Development of a wearable motion capture system using linear encoder

Goh, Young Koon

2009

Goh, Y. K. (2009). Development of a wearable motion capture system using linear encoder. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/19298>

<https://doi.org/10.32657/10356/19298>

NANYANG
TECHNOLOGICAL
UNIVERSITY

**DEVELOPMENT OF A WEARABLE MOTION CAPTURE
SYSTEM USING LINEAR ENCODER**

GOH YOUNG KOON

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2009

**DEVELOPMENT OF A WEARABLE MOTION CAPTURE SYSTEM
USING LINEAR ENCODER**

GOH Y. K.

2009

DEVELOPMENT OF A WEARABLE MOTION CAPTURE SYSTEM USING LINEAR ENCODER

**GOH YOUNG KOON
(G0600304C)**

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirements for the degree of
Master of Engineering

2009

TABLE OF CONTENTS

	Page
ABSTRACT	I
ACKNOWLEDGEMENT	III
LIST OF FIGURES	IV
LIST OF TABLES	VII
LIST OF SYMBOLS	VIII
CHAPTER 1 : INTRODUCTION	1
1.1 Background	1
1.2 Introduction to Motion Tracking	2
1.3 Objective and Scope	4
1.4 Report Organization	5
CHAPTER 2 : LITERATURE REVIEW	6
2.1 Classification of Motion Capture Systems	6
2.1.1 Visual Systems	7
2.1.2 Non-Visual Motion Tracking	10
2.2 Full Body Motion Tracking Systems	15
2.2.1 Measurand	15
2.2.2 Xsens	18
2.2.3 Animazoo Inc.	19
2.3 DataGlove Systems	20
2.3.1 Measurand	21
2.3.2 Immersion	22
2.3.3 Fifth Dimension Technologies – 5DT	23
2.4 Alternative Sensing Technologies for Body Motion Capture	25
CHAPTER 3 : SENSING PRINCIPLE AND SENSOR DEVELOPMENT	28
3.1 Sensing Principle of Joint Rotation	28
3.2 Sensor Development	31
3.2.1 Linear Encoder	32
3.2.2 Linear Code Strip	33
3.2.3 Electrical Hardware for Linear Encoder	34
3.2.4 Wearable Motion Capture System Protocol	35
3.3 Sensor Fabrication	39

CHAPTER 4 : MODELING AND PLACEMENT OF SENSORS	41
4.1 Human Joints	41
4.1.1 Human Body Plane	41
4.2 Sensor Placement on Upper Extremity	43
4.2.1 Elbow	43
4.2.2 Wrist	45
4.2.3 Shoulder	52
4.3 Sensor Placement on Lower Extremity	68
4.3.1 Knee	68
4.3.2 Hip	70
4.3.3 Ankle	75
4.4 Formulation for Multiple Joints	76
4.5 Routing of Sensor System	81
4.6 Sensor Mounting	82
CHAPTER 5 : EXPERIMENTAL RESULTS AND DISCUSSIONS	85
5.1 Powercube™ Experiment	85
5.1.1 Set-Up of Experiment	85
5.1.2 Results	86
5.1.3 Discussion	86
5.2 Calibration of Joint Radius	87
5.2.1 Elbow Joint	89
5.2.2 Discussion	90
5.3 Goniometer Comparison Experiment for 1-DOF Joint	92
5.3.1 Set-Up of Experiment	92
5.3.2 Results of Experiment	94
5.3.3 Discussion	96
5.4 Goniometer Comparison Experiment for 2-DOFs Joint	98
5.4.1 Set-Up of Experiment	99
5.4.2 Results of Experiment	101
5.4.3 Discussion	107
5.5 Placement Range for Linear Encoder Sensor	108
5.5.1 Set-Up of Experiment	109
5.5.2 Results of Experiment	111
5.5.3 Discussion	114
CHAPTER 6 : CONCLUSIONS AND FUTURE WORKS	116
6.1 Conclusion	116
6.2 Advantages and Limitations	119
6.3 Future Works	120
6.3.1 Experiment Setup and Results	120
6.3.2 Sensor Design	123
6.4 Summary of Contributions	124

REFERENCES	126
APPENDICES	128

ABSTRACT

Motion capture is gaining high popularity in recent years in the field of robotics, animation, health care, computer games, virtual reality, security, and entertainment. Through the use of advance motion tracking system, human motion data can be captured, processed and used in potential human-centered environment for the control of humanoid robots and medical assistive devices to perform complex and daunting task. However, the range of possible human motion consist of a very large number of degrees of freedom and the task of motion capturing, generation and control of these biomimetic systems can be very cumbersome and complicated. The challenge faced by modern researchers in the field of motion capture is that there is no single solution that can address the shortcomings faced by various commercial motion capture systems available and these systems are usually very expensive and are intricate in the setting up and application process.

Hence, the focus of this project is on the development a novel yet cheap sensing technology with high performance un-tethered wearable human motion processing system that is used for real-time sensing and processing of anatomical motion data. Embedded sensing techniques for the detection of individual joint movement, ergonomics and placement of the sensing system addressing wearability issue and the performance of the sensors will be the main research topics. Major applications of this human motion capturing system will be in the instantaneous control and manipulation of virtual figures in a 3-D virtual environment such as interactive media, games and films, and also the control of articulated physical biomechatronic systems, such as humanoid robots and rehabilitation devices.

In this project, a new type of sensors was developed to detect bending and warping of limbs and joints as the fundamental element of the body motion processing system. The sensing device is to be free from signal interference, obstruction or shadow effect, these sensor strips can be woven into a web directly worn by the human or embedded into the clothing. The patterns of the strip sensor web can be configured for a specific application as well as customized based on the biometric data of the user. An embedded processing unit will handle the bending information of all strip sensors to produce the complete body motion data based on the patterns of the strips and biometric data of the user in

real-time. The real-time motion data can be used for control and manipulation of physical and virtual systems through wireless communication capability built into the system.

Keywords :

Humanoid Robot, Wearable, Exo-skeletons, Biomechatronics, Motion Capture, Human Motion Processing

ACKNOWLEDGEMENT

The author would like to express his heartfelt thanks and gratitude to the following people and organization for their efforts and support to the successful completion of the project.

Associate Professors Yeo Song Huat, Chen I-Ming and Duh Been-Lirn for their ever encouraging support, guidance, patience and valuable advices. Their expertise in technical background of this research has immensely contributed to the completion of this thesis.

Mr Lim Kwang Yong, Mr Dong Wei, Mr Nguyen Kim Doang and Mr Li Kang for their beneficial studies and research work on the optical liner encoder, tilt sensors and programming. Their roles are important in guiding me in the fulfillment of this research project. Also to Mr Eric Goh Jie Quan for conducting experiments on those sensors to verify the accuracy. Thanks to Mr Lim Hup Boon for his assistance and loan of the Noraxon™ Electrogoniometer System which greatly assist me in the completion of this report.

Staff of Robotics Research Centre: Mr Lim Eng Cheng, Technician-in-charge, for his coordination of the available resources. Ms Agnes Tan for her guidance, support and valuable advice. Mr You Kim San and Miss Toh Yen Mei for their valuable advices and assistance in the test process.

Finally, to friends who have contributed in one way or another, thank you for your continuous support and endless encouragement during this time.

List of Figures

Fig. 1-1: Classification of Human Motion Tracking	4
Fig. 2-1: Classification of Motion Tracking Systems	6
Fig. 2-2: Inertial Sensors used in Xsens Motion Capture suit.....	11
Fig. 2-3: Gypsy 5 Full-body Mocap System	12
Fig. 2-4: Different Sizes of Electrogoniometers.....	13
Fig. 2-5: Measurand ShapeWrap II.....	15
Fig. 2-6: Sensing Principle of the Measurand ShapeTape™	16
Fig. 2-7: Sensor Tapes.....	17
Fig. 2-8: Measurand ShapeWrap II.....	17
Fig. 2-9: Movent System from Xsens	19
Fig. 2-10: GypsyGyro-18	20
Fig. 2-11: Measurand ShapeHand.....	21
Fig. 2-12: Sensing Principle of the CyberGlove II	23
Fig. 2-13: CyberGlove II.....	23
Fig. 2-14: Sensing Principle of the 5DT DataGlove	24
Fig. 2-15: 5DT DataGlove	24
Fig. 3-1: Working Principle of Linear Encoder.....	29
Fig. 3-2: Working Concept for Finger Joint Angle Sensor	30
Fig. 3-3: Kinematic diagram of the linkage.....	30
Fig. 3-4: Mechanical Structure.....	31
Fig. 3-5: Optical Linear Encoder Sensor	32
Fig. 3-6: Principle of Reflective Linear Code Strip.....	32
Fig. 3-7: Out of phase pulses (90°) from channels A and B	33
Fig. 3-8: Linear Encoder Code Strip Layers Construction.....	34
Fig. 3-9: Printed Linear Code Strip.....	34
Fig. 3-10: Block Diagram of Electrical Design.....	35
Fig. 3-11: Electrical Circuitry for Linear Encoder Sensor	35
Fig. 3-12: Chain of Linear Encoder Sensors connected to Data Concentrator	36
Fig. 3-13: Wireless Communication Protocol	37
Fig. 3-14: Tethered Communication Protocol.....	38
Fig. 3-15: Block diagram of hardware fabrication procedure.....	39
Fig. 3-16: Development of Mechanical Hardware for Linear Encoder Sensor	40
Fig. 4-1: Mapping of Human Joints to Manikin.....	42
Fig. 4-2: Human Body Planes	42
Fig. 4-3: Modeling of Elbow Joint.....	44
Fig. 4-4: Recommended Placement of Sensor on Elbow	45
Fig. 4-5: Modeling of Wrist Joint (Frontal Plane).....	47
Fig. 4-6: Recommended Placement of Sensor on Wrist (Frontal)	48
Fig. 4-7: Modeling of Wrist Joint (Sagittal Plane).....	49

Fig. 4-8: Recommended Placement of Sensor on Wrist (Sagittal)	50
Fig. 4-9: Recommended Placement of Sensor on Wrist (Sagittal)	50
Fig. 4-10: Modeling of Circumduction Motion of Wrist	51
Fig. 4-11: Modeling of Shoulder as Spherical Joint	52
Fig. 4-12: Modeling of Shoulder Joint (Frontal)	54
Fig. 4-13: Recommended Placement of Sensor on Shoulder (Frontal)	55
Fig. 4-14: Modeling of Shoulder Joint (Sagittal)	56
Fig. 4-15: Recommended Placement of Sensor on Shoulder (Sagittal).....	57
Fig. 4-16: Transformation of Sagittal Plane to Transverse Plane	58
Fig. 4-17: Modeling of Shoulder Joint (Transverse)	58
Fig. 4-18: Axes Modeling of Shoulder Joint	59
Fig. 4-19: Global and Local Coordinate Systems.....	60
Fig. 4-20: Mapping ROM of Shoulder Joint from Three Different Planes	61
Fig. 4-21: Mapping Volumetric ROM back to Each Plane.....	62
Fig. 4-22: Modeling of Combined Motion of Shoulder	63
Fig. 4-23: View along Anterior-Posterior Axis (Global)	64
Fig. 4-24: View along Medial-Lateral Axis (Global).....	65
Fig. 4-25: Establishing of Local Coordinate System for Analysis.....	66
Fig. 4-26: View along Medial-Lateral Axis (Local)	67
Fig. 4-27: Modeling of Knee Joint.....	69
Fig. 4-28: Recommended Placement of Sensor on Knee	70
Fig. 4-29: Modeling of Hip Joint (Frontal).....	71
Fig. 4-30: Recommended Placement of Sensor on Hip (Frontal)	72
Fig. 4-31: Modeling of Hip Joint (Sagittal)	73
Fig. 4-32: Pelvis/Hip Bone.....	74
Fig. 4-33: Recommended Placement of Sensor on Hip (Sagittal)	74
Fig. 4-34: Mitered Hinge model by Inman and Mann (1973).....	75
Fig. 4-35: Modeling of Ankle Joint (Sagittal)	77
Fig. 4-36: Recommended Placement of Sensor on Ankle.....	78
Fig. 4-37: Mapping of Radius on Upper Body	79
Fig. 4-38: Mapping of Radius on Lower Body	79
Fig. 4-39: Routing of Sensor for Upper and Lower Body.....	81
Fig. 4-40: Classification Scheme for Linear Encoder Sensors.....	82
Fig. 4-41: Linear Encoder Sensor on barebone substrate.....	83
Fig. 4-42: Mounting of Sensor on Velcro Support Brace	83
Fig. 4-43: Transforming Modular System to Full Suit System.....	84
Fig. 5-1: Setup for the PowerCube™ Experiment.....	85
Fig. 5-2: Encoder readings against Rotation Angle.....	86
Fig. 5-3: Test Jig Radius	87
Fig. 5-4: Goniometer Set.....	88

Fig. 5-5: Elbow Joint.....	88
Fig. 5-6: Ankle Joint.....	88
Fig. 5-7: Plot for Elbow Joint.....	89
Fig. 5-8: Flowchart of Goniometer Experimental Procedure (1-DOF)	92
Fig. 5-9: Experimental Setup for Elbow Joint.....	93
Fig. 5-10: Calibration Result for Elbow joint.....	94
Fig. 5-11: Test Results for Elbow Joint (Flexion).....	95
Fig. 5-12: Test Results for Elbow Joints (Oscillation).....	96
Fig. 5-13: Flowchart of Goniometer Experimental Procedure (2-DOFs).....	98
Fig. 5-14: Noraxon™ Electrogoniometer System.....	99
Fig. 5-15: Experimental Setup for 2-DOFs Joint	100
Fig. 5-16: MyoResearch Record Viewer for Noraxon™ Electrogoniometer	101
Fig. 5-17: MyoResearch Results for Slow Abduction motion along Frontal Plane	102
Fig. 5-18: Test Results for Abduction – Frontal Plane.....	102
Fig. 5-19: MyoResearch Results for Oscillation motion along Frontal Plane.....	103
Fig. 5-20: Test Results for Oscillation – Frontal Plane	103
Fig. 5-21: MyoResearch Results for Slow Flexion motion along Sagittal Plane	104
Fig. 5-22: Test Results for Flexion – Sagittal Plane.....	105
Fig. 5-23: MyoResearch Results for Oscillation motion along Sagittal Plane	106
Fig. 5-24: Test Results for Oscillation – Sagittal Plane	106
Fig. 5-25: Experimental Setup for Placement Range	109
Fig. 5-26: Distance between the Ideal and Offset = 25mm.....	110
Fig. 5-27: Distance between the Ideal and Offset = 50mm.....	111
Fig. 5-28: Test Results for Offset Distance = 25mm.....	112
Fig. 5-29: Results for Offset Distance = 50mm.....	113
Fig. 5-30: Error Statistics between Ideal and Offset Case	114
Fig. 5-31: OLE Response (Degree) against Offset Distance.....	115
Fig. 6-1: Full Body Divided into Three Main Segments.....	122
Fig. 6-2: Current Linear Encoder Design	123
Fig. 6-3: Flexible Printed Circuit.....	124

List of Tables

Table 2-1: Comparison of Various Sensing Methods	25
Table 5-1: Joint Radius Calibration Results for Various Joints	90
Table 5-2: Various Joint Motion, Radius and Plane	91
Table 5-3: Error Statistics for Elbow Joint (1-DOF)	96
Table 5-4: Error Statistics for 2-DOFs Joint	106
Table 5-5: Responses and Error Statistics for Placement Range	113

List of Symbols

DOF	Degree Of Freedom
fps	Frames per second
ROM	Range Of Motion
LED	Light Emitting Diode
OLE	Optical Linear Encoder
RMS	Root Mean Square
SD	Standard Deviation
r, R	radius (mm)
d, D	distance (mm)
α	angle (in Degree)

CHAPTER 1

INTRODUCTION

1.1 Background

Human movement analysis aims at gathering information about the mechanics of the musculo-skeletal system during the execution of a motor task. Human motion processing systems are expected to generate real-time data that dynamically represents the changes in pose of a human body or a part of it such as limb movement, are based on well developed motion sensor technologies. Data concerning the motion of the whole-body, relative motion between adjacent bones or joint kinematics can be used as input information for highly articulated biomechatronic systems, such as humanoid robots and physiotherapy devices for real-time control and analysis.

Various tracking devices have been developed to trace the location of the limb in space and the orientation of the limb. A person has to wear a suit containing markers located at each joint on body. Each marker will be traced to identify the position or angle between the markers. The information gain from the markers is then sent for analysis by the motion capture system. The types of markers used like can be acoustical, magnetic, optical, reflective, etc. The system records the position, angle, velocities, acceleration and impulses, providing a digital representation of the motion. Position tracking makes a lot of contribution to entertainment industry and it eliminates the use of sophisticated software to draw the animation. Hence, the cost and time required are greatly reduced. In addition, integration of the human motion and behavior with animation characters make the characters behave more naturally and realistic and hence improve the quality of the animation.

In medical and rehabilitation treatment, it is desirable to continuously monitor a patient's day-to-day activities in the friendly environment such as at one's home, workplace and outside but not in a confined and controlled environment such a clinical laboratory or the doctor's office. This type of monitoring will be beneficial to the therapist as it allows for a better assessment of human motor control and functional use of a body segment over long periods of time. Evaluating a patient's daily life activities

allows a more reliable assessment of a patient's disabilities, and aids in developing rehabilitation treatments and programs, as well as assessing a treatment's effectiveness. The recognizing the deviations in joint movement patterns are essential for rehabilitation specialists and physio-therapists to select and implement an appropriate rehabilitation programme for a patient. Many medical and rehabilitation applications can benefit from the data derived by continuous human motion monitoring.

Employing the use of video and optical motion analysis systems offers the most accurate evaluation of human movement; however measurements need to be restricted within a controlled and confined environment. Body mounted sensors such as accelerometers and pedometers can be used for monitoring daily physical activities, but the shortcoming of these devices are that they are unable to detect the body posture and have a limitation in reliability, repeatability and applicability.

In the recent years, due to their potential applications in human-centered environment such as healthcare, sports medicine, rehabilitation, virtual reality and entertainment, the field of motion tracking is gaining high popularity. However, despite all these growing enthusiasm and interest, there is still a lack of acceptable devices available that is able to capture the motion of the human body in a reliable and non-intrusive way over a long period of time. Due to the large number of applications that require motion tracking, no single technology is able to solve the problems associated with every application.

1.2 Introduction to Motion Tracking

Motion tracking which is also known as motion capture (mocap), is the technique of recording movements for entertainment, sports medicine, and rehabilitation applications through digital means. This technique of recording the actions of human subjects in the real world and using that piece of information to animate digital character models in 3-D animation in the virtual world is refer as motion capture and processing.

Motion capture, which started as a photogrametric analysis tool used in biomechanics research in the 1970s and 1980s, had expanded into the domain of education, sports medicine and most recently, virtual reality animation for

cinematography and console games as the technology matured. The subject is required to wear markers located near each joint that is used to identify the motion by the positions or angles between the markers. Acoustic (including ultrasonic), inertial, LED, magnetic or reflective markers, or combinations of any of these, are tracked optimally at least two times the rate of the desired motion, to submillimeter positions. The motion capture computer software records the positions, orientation, angles, velocities, accelerations and impulses, and thus providing a precise digital representation of the motion.

In the motion capture session, the movements of one or more subjects are sampled many times per second or frames per second. High resolution optical motion capture systems can be used to sample body, facial and finger movement at the same time. A motion capture session records only the movements of the subject but not his visual appearance, these movements are recorded as animation information which are mapped into a Virtual Reality (VR) environment as a 3-D model (human, robot, etc.). A computer is used to process the information and displays the movements of the subject, as inferred from the 3-D position of each marker. After processing, the animation data which is associated with the 3-D model created is exported by the software and it can be used by normal computer animation software to manipulate the virtual model.

In entertainment and cinematography field, this can significantly reduce the costs of animation production which otherwise requires animators to draw each frame, or with more sophisticated software, key frames which interpolation between frames are generated by software. Motion capture saves time and creates more natural movements than manual animation, but is limited to motions that must obey physical laws and are anatomically possible.

In biomechanics, sports medicine and training, real-time data can provide the critical information to diagnose and pinpoint the problems in the execution of a certain action such capturing motions of up to 140 miles per hour for a golf swing¹ or drop jump of a parachutist and suggest ways to improve performance and prevent injuries.

In general, a motion tracking system can be classified as visual which includes marker and markerless based or non-visual which consists of mechanical, magnetic, ultrasonic and etc². Fig. 1-1 illustrates a classification of existing sensor techniques.

Fig. 1-1: Classification of Human Motion Tracking

There are two major drawbacks to state-of-the-art motion tracking systems that prevent them from being more widely used. First, they require an expensive laboratory apparatus that constraints the user to a limited space. Second, the set-up and post-processing times are typically quite lengthy. Having a cost-effective, self-contained motion capture system that does not constrain the user in a limited, laboratory setting or require lengthy set-up/post-processing would allow many applications that are used mainly for research to be more widely available.

1.3 Objective and Scope

The objective of this research is to develop a high performance yet cheap, non-visual based, wire-less wearable human motion sensing system for instantaneous capturing of joint motion data. The development and testing of the sensing system for human movement detection will be the main research topic. Major applications of this sensing system will be in the real-time control and manipulation of virtual figures in virtual reality environment and control of articulated physical biomechatronic systems, such as humanoid robots and physiotherapy devices.

The scope the research project will cover the following:

- Development of a new of tracking sensors using a linear encoder to detect bending and warping of limbs and joints.
- Modeling of the sensors at each limb and joint on the human body
- Calibration setup of the sensors
- Experimental verification of the accuracy of the sensors

1.4 Report Organization

This report is organized as follows:

- Chapter 2 gives the literature review of the relevant research area.
- Chapter 3 describes the development and fabrication of the sensors
- Chapter 4 covers the modeling and placement of sensors on human body
- Chapter 5 presents the set-up procedure and the results for discussion
- Chapter 6 summarizes the research work and describes the future work.

Additional specifications and data sheet are included in the Appendices

CHAPTER 2

LITERATURE REVIEW

In this chapter, the literature review of motion capture technologies is presented. For a comprehensive understanding, different forms of motion tracking systems are described, including a few commercially available full body motion tracking systems and also tracking systems for the hand.

2.1 Classification of Motion Capture Systems

Many sensing methods have been researched to add to the limited number of sensing technologies for motion tracking. Fig. 2-1 shows a classification of available human motion tracking systems based on the sensing techniques:

Fig. 2-1: Classification of Motion Tracking Systems

It is seen that existing motion tracking systems can be classified into two types, the non-visual systems and the visual systems. The sensing techniques in the non-visual systems include the inertial, mechanical, magnetic, ultrasonic and others. The visual systems which are also known as optical systems can either be marker-based or marker-free based. Above and beyond mechanical, inertial, acoustic³, magnetic, optical sensing⁴, innovative techniques such as conductive fibers⁵, inductive fiber mesh⁶, optical fiber

loss⁷ and piezo-resistive fabric⁸ are introduced. Nevertheless, these new sensing methods still cannot achieve the response (200 Hz), accuracy ($\pm 1^\circ$), robustness and low cost required by most applications. In addition, each approach has its advantages and limitations. The limitations include modality-specific limitations related to the physical medium, measurement-specific limitations imposed by the devices and associated signal-processing electronics, and circumstantial limitations that arise in a specific application.

2.1.1 Visual Systems

Visual or Optical sensors (e.g. cameras) are normally applied to improve accuracy and precision in position estimation. Motion tracking systems can be classified as either visual marker or marker-free, depending on whether or not indicators need to be attached to body parts.

Visual systems make use of the data captured from image sensors to extrapolate and triangulate the 3-D position of a subject between one or more cameras calibrated to provide overlapping projections. Data acquisition is traditionally implemented using special markers attached to the subject; however, in recent years, more advance systems are able to generate precise data by tracking surface features identified dynamically for each particular subject. Tracking a large number of test subjects or expanding the capture area is accomplished by the addition of more cameras. These systems produce data with three degrees of freedom for each marker and rotational information must be inferred from the relative orientation of three or more markers; for example, shoulder, elbow and wrist markers providing the angle of the elbow.

Visual Marker Based : Passive Markers

Passive optical system uses markers coated with a Retroreflective material to reflect light back that is generated near the cameras lens. The camera's sensitivity can be adjusted taking advantage of most cameras narrow range of sensitivity to light, so only the bright markers will be sampled ignoring skin and fabric.

The centroid of the marker is estimated as a position within the 2-D image that is captured. The grayscale value of each pixel can be used to provide sub-pixel accuracy. An object with markers attached at known positions is used to calibrate the cameras and

obtain their positions and the lens distortion of each camera is measured. Providing two calibrated cameras see a marker, a 3-D fix can be obtained.

Typically an optical system will consist of around six to twenty over cameras. Extra cameras are required for full coverage around the capture subject. Professional vendors have sophisticated constraint software to reduce problems from marker swapping since all markers appear identical. Unlike active marker systems and magnetic systems, passive systems do not require the user to wear wires or electronic equipment. The markers are usually attached directly to the skin (as in biomechanics), or they are velcroed to a subject wearing a full body spandex/lycra suit designed specifically for motion capture. This type of system can capture large numbers of markers at frame rates as high as 2000fps. The frame rate for a given system is often traded off between resolution and speed, so for a system with higher megapixels (resolution), the operating speed need to run at lower frequency and vice-versa.

Visual Marker Based : Active Markers

Active optical systems triangulate positions by illuminating one LED at a time very quickly or multiple LEDs but sophisticated software to identify them by their relative positions, somewhat akin to celestial navigation. Rather than reflecting light back that is generated externally, the markers themselves are powered to emit their own light. Since Inverse Square law provides $\frac{1}{4}$ the power at 2 times the distance, this can increase the distances and volume for capture. The power to each marker can be provided sequentially in phase with the capture system providing a unique identification of each marker for a given capture frame at a cost to the resultant frame rate. This identification ability is useful in real-time applications. The alternative method of identifying markers is to do it algorithmically requiring extra processing of the data.

Infrared (Visual) Based : Passive/Active Markers

Infrared (IR) based motion capture systems are quite widely used in the industries and they are available as both active and passive markers systems. For passive marker-based optical systems, infrared cameras are used to capture three-dimensional dots placed on something or someone moving in space. The reflective optical motion capture systems use infrared LED's mounted around the camera lens, along with IR pass filters placed over the camera lens to detect the light reflected from markers.

Optical motion capture systems that are based on active markers or pulsed-LED's, measure the Infra-red light emitted by the LED's as the markers in an active system can produce infrared, which is then collected by a camera system.

Visual Marker Based : Semi-passive Imperceptible Marker

One can reverse the traditional approach based on high speed cameras. Systems such as Parkash use inexpensive multi-LED high speed projectors. The specially built multi-LED IR projectors optically encode the space. Instead of retro-reflective or active LED markers, the system uses photosensitive marker tags to decode the optical signals. By attaching tags with photo sensors to scene points, the tags can compute not only their own locations of each point, but also orientation, incident illumination, and reflectance.

These tracking tags work in natural lighting conditions and can be embedded in attire or other objects. The system supports an unlimited number of tags in a scene, with each tag uniquely identified to eliminate marker reacquisition issues. Since the system eliminates a high speed camera and the corresponding high-speed image stream, it requires significantly lower data bandwidth. The tags also provide incident illumination data which can be used to match scene lighting when inserting synthetic elements. The technique is therefore ideal for on-set motion capture or real-time broadcasting of virtual sets.

Marker-free Based : Markerless

Emerging techniques and research in computer vision are leading to the rapid development of the markerless approach to motion capture. Markerless systems do not require subjects to wear special equipment for tracking, thereby eliminating extensive user calibration efforts. Special computer algorithms are designed to allow the system to analyze multiple streams of optical input and identify human forms, breaking them down into constituent parts for tracking. Applications of this technology extend deeply into popular imagination about the future of computing technology. The first commercially available markerless system is designed by Organic Motion.

The marker-free visual based tracking systems exploit visual/optical sensors such as cameras to measure movements of the human body as low cost cameras nowadays can be easily obtained while the camera parameters can be flexibly configured by the user.

These merits encourage cameras to be popularly used in surveillance applications, hence the adaptability of markerless technology in service industries such as patient care wherein a variety of subjects could benefit from motion analysis without the need for extensive user calibrations. A little bit disappointment is that this technique requires intensive computation to conduct 3-D localization and error reduction; in addition to the minimization of the latency of data. Furthermore, high speed cameras are required, as conventional cameras (with a sampling rate of less than sixty frames a second) provide insufficient bandwidth for accurate data representation.

2.1.2 Non-Visual Motion Tracking

Sensors employed within these systems adhere to the human body in order to collect movement information. These sensors are commonly categorized as inertial, mechanical, magnetic, radio or microwave and acoustic based. Some of them have such small footprints that they can detect small amplitudes, such as finger or toe movements.

Inertial Systems

Inertial Motion Capture technology is based on miniature inertial sensors, biomechanical models and sensor fusion algorithms. It is an easy to use and cost-efficient way for full-body human motion capture. The motion data of the inertial sensors (inertial guidance system) is transmitted wirelessly to a PC or laptop, where the full body motion is recorded or viewed. No external cameras, emitters or markers are needed for relative motions. Inertial mocap systems capture the full six degrees of freedom body motion of a human in real-time. Benefits of using inertial systems include: (1) Elimination of the needs to solve complex mathematical function as the sensors need not to be placed in a triangulate positions for detection, (2) Freedom from studios as most systems are portable, and large capture areas. These systems are similar to the controllers used in the Nintendo Wii™ console but are much more sensitive and having much greater resolution and refresh rate. They can accurately measure the direction to the ground within a degree. Base suits tend to be in the \$50,000 range. Fig. 2-2 shows inertia measurement units incorporated into a suit from Xsens.

Fig. 2-2: Inertial Sensors used in Xsens Motion Capture suit

However, the uses of inertial motion capture systems are still restricted because electronic offsets and drifts yield significant tracking errors during the integration of linear acceleration and angular rate^{9,10}. More importantly, inertial trackers alone cannot recover reliably from these errors without introducing external reference information. Luinge¹¹ introduced the design and performance of a Kalman filter to estimate inclination from the signals of a triaxial accelerometer. Empirical evidence shows that inclination errors are less than 2° . Unfortunately, the problem of integration drift around the global vertical direction still appears.

Various technologies including cycle-canceling algorithm, time-frequency analysis, and filter algorithms were applied to eliminate the impact of offsets and drifts^{12,13}. But they also increased computational cost and therefore, end up with a complex system that requires more hardware and software resources.

Motion tracking based on sensor fusion of accelerometers, magnetometers, and gyroscopes^{14,15,16} represents a promising stand-alone technology in those orientations can be measured solely relying upon gravitational and geomagnetic fields which constitute an absolute coordinate frame of reference. Bachmann *et al.*^{14,15} first introduced such a device and developed a quaternion attitude filter for three-degrees-of-freedom (DOF) orientation tracking of rigid bodies. Zhu *et al.*¹⁶ modeled human body motion with a geometric representation and tracked articulated human motion with inertial/magnetic sensors.

Mechanical Systems

Mechanical motion capture systems directly track body joint angles and are often referred to as exo-skeleton motion capture systems, due to the way the sensors are attached to the body. A subject attaches the skeletal-like structure to their body and as they move so do the articulated mechanical parts, measuring the performer's relative motion.

Mechanical motion capture systems are real-time, relatively low-cost, free-of-occlusion, and wireless (untethered) systems that have unlimited capture volume. Typically, they are rigid structures of jointed, straight metal or plastic rods linked together with potentiometers that articulate at the joints of the body. Fig. 2-3 shows the Gypsy 5 on-the-body mocap system using mechanical means for motion tracking. These suits tend to be in the \$25,000 to \$75,000 range plus an external absolute positioning system.

Fig. 2-3: Gypsy 5 Full-body Mocap System

Electrogoniometers as shown in Fig. 2-4 are a form of electro-mechanical based non-visual motion tracking system which is frequently used to measure dynamic, multi-axis joint angle changes in individuals, providing continuous joint movement information. These devices, however, are not desirable for long-term monitoring of daily living, since they are exo-skeletal devices that cross the joint, potentially interfering with movement. Furthermore, any shift from their original placement leads to errors in angle estimations. Such commercially available goniometers can produce erratic readings once the device is detached from the patient body and put back on the same joint in a slightly

different orientation. It is therefore difficult to use these goniometers at home for long periods of time.

Source from
<http://www.sport.uni-stuttgart.de>

Fig. 2-4: Different Sizes of Electrogoniometers

Magnetic Systems

Magnetic systems calculate position and orientation by the relative magnetic flux of three orthogonal coils on both the transmitter and each receiver. The relative intensity of the voltage or current of the three coils allows these systems to calculate both range and orientation by meticulously mapping the tracking volume.

Since the sensor output is 6-DOF, useful results can be obtained with two-thirds the number of markers required in optical systems; one on upper arm and one on lower arm for elbow position and angle. The markers are not occluded by nonmetallic objects but are susceptible to magnetic and electrical interference from metal objects in the environment, like rebar (steel reinforcing bars in concrete) or wiring, which affect the magnetic field, and electrical sources such as monitors, lights, cables and computers.

MIT Architecture Machine Group developed the Polhemus¹⁷ 3-space tracking sensor to trace the location of participant in free space. The sensor worn on the user hand is able to detect the pulsed magnetic field radiated by a stationary source. The system calculates position and orientation with reference to the relative magnetic flux of the sensor to the source. The system traces the sensor with frame rate up to 100 Hz in ranges from 3 to 20 feet and achieves an accuracy of 0.1 inches in position and 0.1 degrees in rotation. However, the response of the sensor will be nonlinear, especially approaching

the edges of the capture area. Yet the signal will be distorted due to the presence of metallic object, like wiring and electrical sources.

Ultrasonic Systems

Ultrasonic transducers are able to measure distance without coming in contact with the object. An ultrasonic sensor works by propagating a sound wave from the sensor to an object and back to the sensor again, the time taken for the sound to travel to and from was measured and the distance can be obtained. The elapsed time for the ultrasonic waves to travel from the emitter to the target and get reflected with the returning waves picked up by a receiver is used to determine the distance to the object. The longer it takes the sound wave to propagate is a tell sign that an object is further away.

Ultrasonic systems collect signals by transmitting and sensing sound waves, where the flight duration of a brief ultrasonic pulse is timed and calculated. These systems are used in medical applications, but have not been used in motion tracking. This is due to the following drawbacks: (1) the efficiency of an acoustic transducer is proportional to the active surface area, hence large devices are required; (2) to improve the detected range, the frequency of ultrasonic waves must be below 10 Hz, but this affects system latency in continuous measurement; (3) acoustic systems require a line of sight between transmitters and receivers.

Other Systems : Optical Fiber

With the development of lasers, optic fiber were used as embedded bend sensors in commercially available body motion sensing suit such as the one shown in Fig. 2-5 by Measurand Inc. The sensors used are specially treated optic fiber and worn as an exo-skeleton around the body to measure the curvature along a given joint. The fiber has been treated such that only one section of the fiber emits the light transmitted through it. As the bend in the fiber increased, more light escapes from the fiber reducing the final intensity detected, thus allowing the extent of the curvature to be measured. However for this system, the exo-skeleton sensor strips prove to be obtrusive to the user movement and the Data Concentrator module which is worn on the body will generate up heat due to the powering up the laser to the optic fiber hence causing discomfort to the user.

Fig. 2-5: Measurand ShapeWrap II

2.2 Full Body Motion Tracking Systems

In order for the ease of monitoring day-to-day activities for multiple subjects, a non-occlusive tracking system is needed. There are currently three major companies that markets body motion tracking devices that can overcome occlusion. This feature allows multi-actors interaction and does not restrict actors to a limited volume for motion capture. The three companies are namely Measurand, Xsens and Animazoo.

2.2.1 Measurand

Measurand (www.measurand.com) pioneered the use of 3D flexible arrays of distributed sensors and specializes in quality manufacture of flexible 1D, 2D, and 3D measuring systems based on fiber optics and other technologies. The Measurand sensor tapes which is known as ShapeTape™, is an array of fiber optic curvature sensors that measure bend and twist in pairs. The tapes are available with different numbers of sensors, with different sensorized zone lengths, with different lead and tip lengths, and some measure bend only, with or without pairing. The ShapeTape™ uses pairs of curvature sensors along its length to measure bend and twist as shown in Fig. 2-6. The number of pairs and the length of the tape determine the spatial density of the sensors, or number of sensors per length.

The spatial sensor density determines the smallest features that may be measured accurately. Generally, it is best to have at least two sensor lengths involved in measuring a monotonic curve. A monotonic curve is one that has all positive or all negative bend, or all positive or all negative twist. This means that unless the tape has many sensors along its length, some detail will be missed. To have both a positive and negative curve (an S shape) within one sensor length, each sensor pair integrates (adds up) the curvature along its length and reports the net angular differences from beginning to end of the sensor pair. The net angular differences are then used to calculate the Cartesian coordinates (x,y,z) of the end of the pair relative to its start.

Fig. 2-6: Sensing Principle of the Measurand ShapeTape™

Using the principle, the Measurand's 2D and 3D sensors are able to measure different shape as the data set of positions and orientations along a curve or throughout an area or volume is been captured. The measurement and control of shapes from static poses to high speed events can be use in many different applications as diverse as virtual reality and geosciences¹⁸.

The Measurand ShapeWrap II offers a mocap system based on ShapeTapes that flex instead of breaking on impact which is great improvement over the conventional rigid exo-skeletons mocap system. The Measurand system is made up of multiple ShapeTapes. Four ShapeTapes make up the ShapeWrap II system (full body system for capturing motion). The system consists of two arm tapes (one tape for each arm that extend to capture hand, wrist and finger movements), and two leg tapes (one for each leg that attaches and adjusts at the waist to capture the full leg movements extending to capture foot, ankle and toe movements¹⁸). Fig. 2-7 shows the four sensor tapes for the ShapeWrap II system while Fig. 2-8 shows the full Measurand suit, ShapeWrap II been worn by a user. The cost of ShapeWrap II system is approximately \$50,000 while the

cost of ShapeHand system (which will be covered later in this chapter) is approximately \$21,000.

Fig. 2-7: Sensor Tapes

Fig. 2-8: Measurand ShapeWrap II

2.2.2 Xsens

Xsens (www.xsens.com) Technologies uses miniature low-cost and highly accurate 3D MEMS inertial sensor technology¹⁹ for the measurement of motion, orientation and position which can be used for different applications such as control, stabilization and navigation of small (unmanned) vehicles, and totally new applications such as inertial full-body human motion capturing (for camera-less character animation, VR training and simulation, sports and health).

For human motion tracking, the inertial motion trackers are placed on each body segment to be tracked. The inertial motion trackers give absolute orientation data such as 3-D linear accelerations which in turn can be integrated to obtain translation estimates of the body segments. Since the rotation from sensor to body segment and its position with respect to the axes of rotation are initially unknown, a calibration procedure is necessary. An advanced articulated body model constraints the movements of segments with respect to each other and eliminates any integration drift.

The MoVeN suit (developed by Xsens Technologies) uses sixteen embedded inertial motion trackers in a stretch suit which locates the sensors on major body landmarks to record corresponding angles. Assuming rigid body dynamics, the angles provide forward kinematics for a skeletal reconstruction of the human body hence able to track the six degrees of freedom (6 DOF) body motion of a human in real-time. The sixteen inertial measurement units (IMU) give absolute orientation information which is used to calculate the 3-D linear position, velocity and accelerations and can be used to gather translation information. A single sensor has an orientation accuracy to 2° RMS; however, with the feedback from a chain of sensors there is minimal position error. The system output is data rich with orientation, velocity and acceleration recorded at 100Hz. Fig. 2-9 shows the MoVeN system suit been worn by the user. The 3D motion measurement units were embedded in the suit that she is wearing. The cost for the MoVeN system is approximately \$110,000.

Fig. 2-9: Moven System from Xsens

2.2.3 Animazoo Inc.

The GypsyGyro-18 by Animazoo (www.animazoo.com) is a motion capture system based on gyro measurements²⁰. Eighteen tiny inertial sensors or gyros were attached to a flexible Lycra suit which allows precision and stability of motion data and measure the exact rotations of the user's bones to pinpoint the 3D location of the joints over time. The gyros can be strategically placed for greater accuracy of measurement from the joint but not the muscle. The GypsyGyro-18 system allows for an extremely large capture area as the subject is free to move in any area he or she chooses. As the system is self contained, there is little possibility of it being affected by outside influences such as light and reflections. As a result of this, it is able to eliminate all the external interferences and distortion of the data obtained.

The gyro-sensor detects changes in an object's angular velocity (the rate of change of angular position of a rotating body). The detected angular velocity is converted to an electronic signal to derive the function required for an electronics product. Position estimates from the gyro-sensor can be acquired by integrating the obtained information from the sensors; once for obtaining the speed, twice for obtaining the traveled distance. However, since measurements are made by integration, the position estimates drift over time, and thus the errors increase without bound. Cleaning up of the data is required to improve the accuracy.

The GypsyGyro-18's inertial gyroscopic sensors are able to directly records the actual rotations of the user's body parts and capture more points on the human body which includes the head, neck, clavicles, ankle and wrist motion. There is no physical constraint of user's movements as all sensors can be worn under normal clothes. Sensors and transmitter can be positioned anywhere on the body allowing increased applications such as rolling around and hugging without suffering the problem of occlusions. However, this system is not really suitable for the sports motion analysis because users may also harm themselves if they were to land awkwardly on one of the trackers. Fig. 2-10 shows the Animazoo GypsyGyro-18 suit been worn by user. The cost of GypsyGyro-18 is approximately \$100,000.

Fig. 2-10: GypsyGyro-18

2.3 DataGlove Systems

For capturing motion of the fingers, a DataGlove system is needed to capture the information of the motion of the individual finger. A search was conducted for some of the commercially available DataGlove systems, generally there are only 3 companies that provide a conveniently, wearable device that is able to capture a human hands' motion to an acceptable level of repeatability. These companies are Measurand, Immersion, and Fifth Dimension Technologies (5DT).

2.3.1 Measurand

Built on the same adaptable platform as ShapeTape™ technology, the Measurand's ShapeHand uses the same sensing tapes that are used for the full body suit. The ShapeHand is a data glove which consists of two components, a data capturing component of sensors and a glove. The glove component is simply a leather sports glove which can be interchanged to accommodate different wearers and sizes and disposed of when desired. The sensors are made up by fiber optical sensors that are capable of not only to track the finger gesture, but also to detect the finger motion using the same sensing principles that were mentioned previously. In addition, the sensor is also capable of capturing full range of finger thumb movement. (i.e. flexion and abduction). There are a total of forty fiber optic bend twist sensors that are used to record the movement of the hand and individual digits.

The ShapeHand is ideal for use in applications like the hand-over because it uses flexible sensors that are not physically built into a glove so it can attach to most hand sizes. The fiber optic tapes of the ShapeHandPlus system attach loosely to the body of the wearer by Velcro straps. The tapes for the hand and fingers are attached to the end and the back of the fingers via Velcro pads attached to a generic (golfing) glove supplied with the system. The tapes are calibrated with predetermined arm and hand positions based on the cardinal body poses. Fig. 2-11 shows the Measurand's ShapeHand DataGlove system.

Fig. 2-11: Measurand ShapeHand

2.3.2 Immersion

The Immersion's (www.immersion.com) Cyberglove uses strain gage to measure the finger flexion²¹. The cyber glove comes with a control interface that enables the user to change the gain and offset for strain gauge through the software. It allow user to custom determine the A/D range that are suitable for them. There are twenty-two sensors on the cyber glove which consist of two bend sensors on each finger, four abduction sensors, plus sensors measuring thumb crossover, palm arch, wrist flexion and wrist abduction, additional sensors are added to measure the flexion of the distal joints on the four fingers. Each resistive sensor is extremely thin yet flexible and being virtually undetectable as it was stitch onto the lightweight elastic glove. 3-D tracking devices can be integrated with the Cyber glove so that the absolute position data such as x, y, z and orientation data such as yaw, pitch and roll are able to be traced. The glove only measures spreading of fingers, not the absolute sideways finger movement or position.

The basic principle of sensing is the measurement of the resistance between two points. Each finger has sensors located in the textile support on the back of the hand, and these sensors are pairs of strain gages. Each pair of strain gages is part of Wheatstone bridge circuits as shown in Fig. 2-12, and their electrical resistance change based on tension/compression which is experienced by the strain gages. The voltage outputs of the Wheatstone bridge circuits are multiplexed then amplified and digitized, such that data can be sent to the host computer running the VR simulation using a data bus. It requires calibration each time it is donned on.

The Cyberglove is able to trace the flexion angle at finger with accuracy of 0.5 degrees and to provide consistence reading with repeatability of 1 degree. It uses a pertaining resistive bend-sensor technology which is linear and robust to accurately measure hand and finger motions and transfer it into real-time digital joint-angle data. Fig. 2-13 shows the CyberGlove II system. The cost of Cyberglove is approximately \$20,000.

Fig. 2-12: Sensing Principle of the CyberGlove II

Fig. 2-13: CyberGlove II

2.3.3 Fifth Dimension Technologies – 5DT

The 5DT (www.5dt.com) Glove package uses flexible optical-bending sensing to track hand and arm movement²². There are quite a few models of the data gloves offered by 5DT. Taking the 5 Ultra as an example, these gloves have five finger sensors in total together with an auxiliary roll and pitch sensor which is mounted at the centre of the back of hand for overall hand position and orientation. Each finger sensor consists of an optical fiber that wraps around the length of the digit, such that the flexion of a finger bends the fiber. In an electronics package attached to the body of the glove, a light source emits light, and photosensors observe the transmission through the fiber. The glove is calibrated based on the principle that as an optical fiber flexes²³; the intensity of a

transmitted light will vary as a linear function of the flexion. This flexion is represented as a single 8-bit byte value to the host. The roll and pitch sensors also produce 8-bit accurate results. The glove is connected to computer via a serial interface such as a USB cable or Series Port (RS232) to the host machine which is as shown in Fig. 2-14. The 5DT Glove 5 Ultra comes with one size that fits many as the glove is made of stretch lycra. Right- and left-handed models are available.

A more advanced version of the 5 Ultra is the 5DT Glove 14 Ultra which comprises of 2 sensors for a finger such that the glove could trace the finger gesture with higher accuracy. In addition, abduction sensor is embedded in the 5DT Glove 14 Ultra in order to trace the abduction between fingers. The 5DT Data Glove 14 Ultra measures finger flexure (2 sensors per finger) as well as the abduction between fingers. Fig. 2-15 shows the 5DT DataGlove system. The cost of DataGlove is approximately \$8,000.

Fig. 2-14: Sensing Principle of the 5DT DataGlove

Fig. 2-15: 5DT DataGlove

2.4 Alternative Sensing Technologies for Body Motion Capture

Currently, commercial systems for capturing motion use sensing technologies based mostly on inertial measurement units, bend-enhanced fiber and strain gages. There are also many other forms of sensing methods for capturing body motion. These methods are, however, not fully developed for commercial release.

After reviewing the available commercial systems for both Full Body Motion Capture systems and DataGlove systems, the various sensing methods can be generally classified into the following:

- Inertia measurement unit (e.g. accelerometers, gyroscopes)
- Piezo-resistive fabric (e.g. lycra coated with PPy)
- Conductive fiber
- Inductive fiber-meshed transducer
- Optical bend enhanced fiber

Table 2-1 shows the comparison of various sensing methods.

Table 2-1: Comparison of Various Sensing Methods

Characteristics	Inertia Measurement Unit	Piezo-Resistive Fabric	Conductive Fiber	Inductive Fiber-Meshed Transducer	Optical Bend Enhanced Fiber	New Proposed Sensor
Dynamic response	Medium to Fast	Slow	Slow	Slow to Fast	Slow to Fast	Slow to Fast
Linearity	Non-Linear	Non-Linear	Non-Linear	Non-Linear	Linear	Linear
Aging	No aging	Yes	Yes	No aging	Slight Deterioration	Slight Deterioration
Fragility	Rugged	May crack	May crack	Not Fragile	Fragile	May crack
Packaging ease	Difficulty in packaging	Difficulty in packaging	Difficulty in packaging	Standard Equipment	Difficulty in packaging	Difficulty in packaging
Manufacturing cost	Low	Low	Low	Low	High	Low
Susceptibility to electro-magnetic interference	No	No	No	Yes	No	No
Signal processing requirement	Savitzky-Golay filter	Regression Methods Required	Kalman Filter	5 th order polynomial fitted with LE	Simple	Simple
Sensors registration	Not self-registering	Not self-registering	Self-registering	Not Self-registering	Can be Self-registering	Can be self-registering
Accuracy	High (rms error = 1.6°)	Low (gesture only)	Low ($\pm 7^\circ$)	High	High	High (target $\pm 1^\circ$)
Form factor rating	4	1	3	3	3	2
Signal to noise ratio	Low	Low	Low	Medium	High	High
Systems	Windows based	Windows based	Windows based	Windows based	Windows based	Windows based

The various characteristics that were evaluated are defined as follows:

- Dynamic response refers to the how fast the sensor can produce a measurement. Sensors such as piezo-resistive fabric may take about 0.5 seconds to produce a useful reading as the sensor suffers from mechanical hysteresis.
- Linearity refers to the relation between measurand and the actual angle to be measured. A linear system demands less processing from the embedded system.
- Aging depicts the ability of the sensor to maintain its' performance over an extended period of time. For example, piezo-resistive fabric ages and its' resistance increases due to oxidation of the piezo-resistive material.
- Fragility refers to how fragile the sensor is. Optical bend enhanced sensor, for example, breaks when bent to below its' minimum bend radius as it is made using glass optical fiber.
- Packaging ease denotes how easy it is to package the sensor so that the sensor will not be damaged during deployment. Sensors such as inertial measurement units are encapsulated in a rugged plastic enclosure and are thus much more durable. Their sizes are, however, larger, resulting in lower form factor rating.
- Manufacturing cost estimates the amount of resources that will be required to produce a single sensor and therefore, it's subsequent cost.
- Susceptibility to electromagnetic interference (EMI) shows if the sensors' is immune to EMI, thus enabling it to be used in environment where strong electro-magnetic waves are generated if the sensor is not affected by EMI.
- Signal processing requirement is related to signal to noise ratio and details the filtering technique employed by researchers to obtain useful signals from their sensors.
- Sensors registration determines if the sensing method adopted can incorporate compensation for variability in gait analysis such as soft tissue artifact, change in weight of the subject, etc.
- Accuracy refers how precise the joint angle can be measured with various methods. Accuracy for different methods can range from $\pm 1.6^\circ$ to $\pm 7^\circ$.

- Form factor rating represents the overall size of the sensor together with the controller unit. This is graded with 5 being the largest and 1 being the smallest.
- Signal to noise ratio shows how susceptible the sensor is to noise generated from undesirable sources such as vibration, temperature, etc. Low signal to noise ratio means the sensor picks up noise easily and will thus need a low pass filter, for example, to filter the noise picked up by the sensor.
- Systems identify the operating systems used for the interface with the mocap system.

Identification of issues to be resolved

From the study of various sensing methods, the following unresolved issues were identified:

- Low accuracy (typically $\pm 2^\circ$)
- High cost of sensing systems (in the range of more than \$2,000 per sensor)
- Difficulty in extending their proposed methods to the entire body (i.e. only provide limited motion such as upper limb only)
- Sensor registration (i.e. repeatable placement of sensor on the human body with every trial)
- Discomfort to patients/subjects while wearing the sensors
- Not able to provide continuous monitoring of human motion while the patients/subjects carry out daily activities

Based on the results of the literature survey, the proposed sensor will require the following specifications:

- High accuracy ($\pm 1^\circ$)
- Low cost (<\$500 per sensor)
- Extendable design (for a single joint or for entire body motion capture)
- Compensation for gait variability such as soft tissue artifact, etc.
- Highly usable (un-obtrusive to user, wireless)
- Wearable over long periods (battery powered over a week or more)

CHAPTER 3

SENSING PRINCIPLE AND SENSOR DEVELOPMENT

3.1 Sensing Principle of Joint Rotation

The concept for the sensing makes use of the basic geometry of the human joint and the stretch of the skin as the joint moves. If the amount of stretch of the skin can be measured, then it can be related to the change in the angle of rotation of the joint. Here, it is assumed that the joint center is fixed during the range of motion and that all the joints can be modeled as circles. In this way, the radii of the circles represent the biometric data of the subject under consideration and can be approximately obtained via physical measurement.

Fig. 3-1(A) shows the schematic diagram of the layout based on the above concept. The circle represents a joint with radius R e.g. the elbow joint. A linear encoder strip will be used to measure the amount of stretch of the skin. The linear encoder is attached to a wire with its end fixed on the forearm while the linear encoder assembly is fixed on upper arm. When the elbow angle is rotated by an angle α , the skin stretches and wire is wrapped along the circumference of the joint as shown in Fig. 3-1(B). This amount of wrap is translated into a linear displacement and is captured by the linear encoder assembly. As the wire is used is bendable yet non-stretchable, the displacement of the wire (D) will cause the linear encoder to be moved by the same amount (Δx):

$$\Delta x = D \quad (1)$$

The radius about the joint (i.e. elbow) is assumed to be constant as the wire wraps around the joint. Hence, the amount of wrap by the wire (D) is:

$$D = \frac{\alpha}{360^\circ} \times 2\pi \times R \quad (2)$$

The rotation angle of the elbow joint can therefore be expressed as:

$$\alpha = \frac{D}{2\pi R} \times 360^\circ \quad (3)$$

Fig. 3-1: Working Principle of Linear Encoder

A search on existing patents was done to see if similar idea has been used to obtain the joint angle information. It was found that a Japanese patent, Publication No. 04143602A, dated 18th May 1992 employed a somewhat similar concept for displacement transducers that are placed on finger joints and the working principles are as illustrated in Fig. 3-2. Here, a linkage is attached to the finger so that the rotation of the finger joint is translated as into the rotation of the linkage. The patent written in Japanese is included in Appendix A.

Source from
Patent Abstracts of Japan,
Publication number: 04143602A

Fig. 3-2: Working Concept for Finger Joint Angle Sensor

The kinematic diagram of the linkage is shown in Fig 3-3. It is seen that the displacement transducer is modeled as a sliding block that is linked to Joint A. The degree of freedom (DOF) of the linkage is one and so the displacement of the slider Δx is directly related to the angular rotation α . Since the linkage is rigidly attached to the finger, its angle of rotation will follow that of the finger joint.

Fig. 3-3: Kinematic diagram of the linkage

From the geometry, the linear displacement is related to the angle of rotation by:

$$\Delta x = \frac{\alpha}{360^\circ} \times 2\pi \times R \quad (4)$$

The joint angle rotation can then be expressed as:

$$\alpha = \frac{\Delta x}{2\pi R} \times 360^\circ \quad (5)$$

It is seen that Equation (5) is similar to Equation (3). However, the main difference is that the R in (5) is the link length whereas it is the joint radius in (3).

3.2 Sensor Development

Fig. 3-4 shows the mechanical structure of the linear encoder unit. A miniature linear encoder is designed to slide over a Delrin™ base structure. The encoder is attached to a flexible stainless steel wire with a diameter of 1mm. A 3mm diameter Teflon™ tube is used to guide the sliding motion of the wire. The linear code strip is adhered to the Delrin™ base structure. The base structure is designed so that the encoder can traverse above the linear code strip while maintaining a constant gap of about 0.43 mm between the code strip and the linear encoder. The linear encoder unit is also called the Optical Linear Encoder (OLE).

Fig. 3-4: Mechanical Structure

Apart from the Delrin™ base structure, the other main components are the linear encoder and the reflective code strips.

3.2.1 Linear Encoder

The linear encoder is a miniature optical sensor that outputs a pulse as it senses an interruption to its reflective path. It has both an infra-red emitter and a receiver built in a single package. Fig. 3-5 shows the Avago™ AEDR-8400-132 miniature linear encoder used. It is a 3VDC quadrature linear encoder with an accuracy of 0.1 mm. The sensor measures only 3mm x 3.28mm x 1.26mm in size.

Fig. 3-5: Optical Linear Encoder Sensor

The infra-red light from the emitter is reflected off a reflective portion of the linear code strip as shown in Fig. 3-6. This linear code strip is 0.1mm apart onto these reflective linear code strips. The reflected light is captured by a receiver.

Fig. 3-6: Principle of Reflective Linear Code Strip

If the light is reflected, the signal processing circuitry will output 2 electrical pulses (i.e. channel A and B) that are 90° out of phase as shown in Fig. 3-7. The 2

electrical pulses that are out of phase will indicate the direction of travel of the sensor with respect to the linear encoder.

Fig. 3-7: Out of phase pulses (90°) from channels A and B

The pulses represent the number of interruptions to the sensors' reflection. This linear code strip, thus provide a means of indicating the distance traveled as the encoder moves over the linear code strip. Each pulse that is read from the linear encoder represents a distance of 0.1mm. The linear code strip, together with linear encoder, forms a distance measurement device.

3.2.2 Linear Code Strip

The optical properties of the 4 layer linear code strip have to be controlled. Fig. 3-8 shows the linear code strip construction. The top layer printed linear code strip is segmented so that the optical sensor can detect the interruptions in its optical path. The second layer optical grade adhesive is to ensure that the optical sensor signal can be transmitted to the reflective layer without much loss. The third reflective strip layer has to be highly reflective so that it can reflect the signal back to the receiver of the optical sensor. The fourth layer adhesive is used as a bonding layer to adhere the code strip module to the base structure. Upon laminating the four layers together, the whole code strip module will be adhered onto the Delrin™ base structure. Fig. 3-9 shows a photo of the actual linear code strip.

Fig. 3-8: Linear Encoder Code Strip Layers Construction

Fig. 3-9: Printed Linear Code Strip

3.2.3 Electrical Hardware for Linear Encoder

A block diagram of the electrical circuitry required to convert the linear distance based on the linear encoder output to a joint angle is shown in Fig. 3-10. The digital signal controller (DSC) used is Microchip's dsPIC33FJ12MC202, a 16-bit digital signal processor based on a RISC architecture. The DSC uses a 16-bit Quadrature Encoder Interface peripheral that has a programmable digital noise filter on input pulses to capture pulses from the linear encoder. After all the signal processing, the DSC package

orientation information with a tracker identification number, and then send them out to the Microchip™ MRF24F40 2.4 GHz transceiver.

Fig. 3-10: Block Diagram of Electrical Design

The linear encoder communicates to the DSC's Quadrature Encoder Interface (QEI). The electrical circuitry was routed on a 2 separated pieces 2-layer Printed Circuit Board (PCB) as shown in Fig. 3-11.

Fig. 3-11: Electrical Circuitry for Linear Encoder Sensor

3.2.4 Wearable Motion Capture System Protocol

The wearable motion capture system as proposed will consist of sensor strips which include a linear encoder and a Digital Signal Controller (DSC). These sensor strips will send the appropriate joint data of each human joint to the gateway (i.e. a Personal Digital Assistant-type device), which will synthesize all the information sent to it from the sensor strips. Using a forward kinematics model embedded into the gateway, the captured motion can then be mapped to a robot, on a virtual reality system or on a personal computer.

There are two methods for the sensor strips to transmit the data to gateway, one way is via wireless transmission protocol and the other is via tethered connection protocol. As the sensor strip is self-contained, it is able to embed the linear encoder and Digital Signal Controller (DSC) and wireless transceiver into one single package.

For the wireless transmission protocol, the sensor strips are arranged in the daisy chain manner and connected to the Data Concentrator as shown in Fig. 3-12. The wireless module which is embedded in the Integrated Circuit (IC) package will transmit data from the linear encoder via the data concentrator to a wireless receiver which is connected to the gateway as shown in Fig. 3-13.

Fig. 3-12: Chain of Linear Encoder Sensors connected to Data Concentrator

For the tethered connection protocol, the sensor strips are arranged in a similar daisy chain manner and linked to the Data Concentrator as shown previously, the mode of operation is the same; the linear encoder will detect the joints movement and send to the information to the Data Concentrator. However, the user can choose either to connect directly to the gateway for immediate output display or control as shown in Fig. 3.14 or the user can choose to use the linear encoder sensor system as-such and store the joints data in the Data Concentrator. After the data collection is over, the user will download

the data by connecting the Data Concentrator to the gateway through the interface to playback the information.

Sensor Strips are daisy chained to one another.

Fig. 3-13: Wireless Communication Protocol

Fig. 3-14: Tethered Communication Protocol

Each strip sensor will be interfaced and packaged with a low power microcontroller. The controller will allow the customization of each sensor according to the patients'/subjects' biometric data and provide either wireless sensor network or tethered interface to the gateway. When the sensors are deployed over the patients'/subjects' entire body, the strip sensors form a sensor mesh network. With this distributed system, it is possible for the entire system to achieve real-time performance coupled with portability over long periods of activity.

3.3 Sensor Fabrication

The fabrication procedure for the mechanical hardware for the Linear Encoder Sensors is as shown by the flowchart in Fig. 3-15. Each process will be explained in details in Appendix B with the equipment and materials needed coupled with step-by-step illustrations.

Fig. 3-15: Block diagram of hardware fabrication procedure

The Mechanical construction of the Linear Encoder base structure has undergone three generations of modification in order to reduce the size and thickness for the ease of mounting on the body and also to reduce mechanical errors such as hysteresis. Fig. 3-16 shows the evolution of the mechanical hardware of the Delrin™ base structure. The Delrin™ base structure is available in 2 sizes, namely 60mm (effective distance 40mm) and 130mm (effective distance 110mm). The detailed drawing of the latest revision of the base structure can be found in Appendix D.

Fig. 3-16: Development of Mechanical Hardware for Linear Encoder Sensor

CHAPTER 4

MODELING AND PLACEMENT OF SENSORS

4.1 Human Joints

The human body consists of 206 bones in adults. Of the 206 bones in the adult human body, just slightly over half are in the hands and feet; 52 are in the feet and 54 are in the hands. A point where two or more bones connect is called a joint. There are two different types of joints in the human body²⁴:

- Movable joints (like ball-and-socket, hinge, gliding and pivot joints)
- Immovable joints (like the bones of skull and pelvis which allow little or no movement).

The human body has over 100 joints²⁵. To capture the motion of all the joints on the human body is a very costly, complex and time-consuming procedure and much of the data are not that required for Body Motion Analysis. For the capturing only the Motion of the Body, the movement of the following joints are taken into consideration:

1. Wrist – 3-DOF Joint
2. Elbow – 1-DOF Joint
3. Glenohumeral Joint (Shoulder) – 3-DOF Joint
4. Hip Joint – 3-DOF Joint
5. Knee – 1-DOF Joint
6. Ankle – 3-DOF Joint

Using a manikin to simplify the modeling of the human body as shown in Fig. 4-1, the modeling of each of the joints will be examined in details.

4.1.1 Human Body Plane

Prior diving into the modeling of each of the six joints that were listed previously, an understanding of the human body planes will be needed as it can be used to simplify the analysis of the complex joint movements of the 2 or more DOF joints into 1-DOF

movement in a single plane. Fig. 4-2 shows the plane convention used for the analysis of the human body.

Fig. 4-1: Mapping of Human Joints to Manikin

Fig. 4-2: Human Body Planes

The three planes used are :

Sagittal – Vertical plane that divides the body into **RIGHT** and **LEFT** parts

Frontal – Vertical plane that divides the body into **ANTERIOR** (Front) and **POSTERIOR** (Back) parts

Transverse – Horizontal plane that divides the body into **TOP** and **BOTTOM** parts

4.2 Sensor Placement on Upper Extremity

4.2.1 Elbow

The elbow-joint is a hinge joint with 1-DOF. Three bones form the elbow joint: the humerus of the upper arm, and the paired radius and ulna of the forearm. Fig. 4-3 shows the modeling and mapping of the elbow joint for movements from neutral/extension to flexion. From the Sagittal Plane, flexing of the elbow causes the skin to stretch resulting in a linear displacement at the Linear Encoder Sensor. The ROM of the elbow joint is from 0° (neutral/extension) to 140° (flexion) and the corresponding stretch ranges from 10mm to 25mm.

With the linear displacement information recorded by the Linear Encoder Sensor and the biometric information i.e. radius of the joint, the angle of bend can be obtained using Equation (3). The average joint radius of the elbow is around 7mm to 15mm depending on the built of the person.

For the placement of the sensor on the arm, the fixed cable end-point can be placed as a reference point on the upper arm while the Linear Encoder Sensor can be placed on the forearm. Note that it is also possible to place the fixed cable end-point on the forearm instead, making it as the reference arm.

Since the stretch due to flexion is estimated at 10mm to 25mm, a 60mm sensor structure is sufficient to record the linear movement of the Optical Linear Encoder. The placement of the sensor, fixed cable end-point together with two pieces of the 3mm diameter Teflon^{TM} tubing to guide the sensor are as illustrated in Fig. 4-4. Taking reference from Point A which is denoted as the notch groove located at the side of the Ulna Bone, the cable end-point can be placed at 55mm to the top taking reference from this point. The sensor should be placed along the line of axis ulna bone to improve the sensitivity of the reading.

Fig. 4-3: Modeling of Elbow Joint

Fig. 4-4: Recommended Placement of Sensor on Elbow

4.2.2 Wrist

The wrist is the flexible and narrower connection between the forearm and the palm. The wrist is essentially a double row of small short bones, called carpals, intertwined to form a malleable hinge. The wrist-joint is a condyloid articulation allowing 3-DOF. The condyloid articulation includes flexion, extension/hyperextension, adduction (Ulna Deviation), abduction (Radial Deviation) and circumduction (consists of a combination of flexion, extension, adduction, and abduction).

The rotating (twist) motion of the hand and wrist which creates movement such as pronation (palm down) and supination (palm up) is achieved by the crossing motion of the radius and ulna bone. Motion Capture Systems, especially optical (visual) and ultrasound sensors, have problem capturing the twist motion. This is because they are unable to differentiate between the positions of the two markers which are closely placed together. Another issue that would be encountered when rotating the hand and wrist is possible blockage restricting the motion to be captured. For other Mocap systems such as Xsens and GypsyGyro-18, as the sensors are placed on the suit, there is a tendency of slippage between the suit and the skin surface hence they are unable to record the rotating motion accurately. Similarly, the Linear Encoder Sensor can only detect motion along a single plane and is not able to use for the twist motion. The Linear Encoder

Sensor can be used to detect flexion, extension/hyperextension, adduction (Ulna Deviation), abduction (Radial Deviation) and circumduction.

(a) Flexion/Hyperextension

Referring to Fig. 4-5, the flexion (moving the palm of the hand toward the front of the forearm) and extension/hyperextension (straightening and moving the back of the hand toward the back of the forearm) of the wrist from the neutral position will cause the skin to stretch resulting in a linear displacement at the Linear Encoder Sensor. The ROM of the wrist joint in the Frontal Plane is from 0°(neutral) to 60° for flexion and from 0°(neutral) to 60° for extension/hyperextension. The corresponding stretch or fold-in ranges around 8mm to 20mm for both flexion and extension/hyperextension motion. The average joint radius of the wrist (frontal) is around 12mm to 18mm.

For the placement on the wrist (frontal), the sensor can be placed either on the front of forearm or at the back of forearm. Depending on the location, the fixed cable end-point must follow accordingly. If the sensor is to be placed on the back of forearm, the fixed cable end-point must be on the back of hand. If the fixed cable end-point is located on the palm of hand, then the sensor has to follow according and be placed on the front of forearm. The direction of travel of the Optical Linear Encoder will be dependent on the placement. Based on Fig. 4-5, when the Delrin^{TM} structure is located at the back of forearm, the sensor will travel backward when the wrist is in hyperextension and forward when the wrist is in flexion. If the sensor is placed on the front of forearm, it will travel forward in flexion and backward in hyperextension which is in opposite direction.

The stretch due to flexion and hyperextension motion is estimated at 8mm to 20mm, a 60mm sensor structure is sufficient to record the linear movement of the sensor. Similar to the elbow, the position of the sensor and fixed cable end-point is interchangeable. However, taking ergonomics, dimension of the Delrin^{TM} structure and stability of sensor placement into consideration, it is recommended that the sensor be placed at the back of forearm and the fixed cable end-point at the back of hand as shown in Fig. 4-6. Taking reference from Point B which is denoted as the bony notch protrusion at the end of Ulna Bone, the cable end-point will be placed at 45mm to the top.

Fig. 4-5: Modeling of Wrist Joint (Frontal Plane)

Fig. 4-6: Recommended Placement of Sensor on Wrist (Frontal)

(b) Abduction/Adduction

Similarly from the Sagittal Plane, the abduction and adduction of the wrist from the neutral position will cause the skin to stretch resulting in a linear displacement at the Linear Encoder Sensor as shown in Fig. 4-7. The ROM of the wrist joint in the Sagittal Plane is from 0° (neutral) to 20° for abduction and from 0° (neutral) to 30° for adduction. The corresponding stretch or fold-in ranges around 3mm to 6mm for abduction and around 7mm to 14mm for adduction motion of the wrist. The average joint radius of the wrist (Sagittal) is around 15mm to 30mm.

For the placement on the wrist (Sagittal), the sensor can be placed either on lateral side of forearm or medial side of forearm with the fixed cable end-point follow accordingly. The direction of travel of the Optical Linear Encoder is dependent on the placement location. It is recommended that the sensor be placed at the medial side of forearm and the fixed cable end-point along the little finger as it is hard to fix the cable end-point on the muscle group between the thumb and index finger.

The stretch due to abduction and adduction motion is estimated at 3mm to 14mm, a 60mm sensor structure is used to record the linear movement of the sensor. The placement of the sensor, fixed cable end-point together with a single piece of the 3mm diameter Teflon^{TM} tubing are as illustrated in Fig. 4-8. Taking reference from Point B which is denoted as the bony notch protrusion at the end of Ulna Bone, the cable end-point will be placed at 45mm to the top.

Fig. 4-7: Modeling of Wrist Joint (Sagittal Plane)

Fig. 4-8: Recommended Placement of Sensor on Wrist (Sagittal)

The 2-DOF of the wrist joint is captured by treating them independently and placing the sensors on the Frontal and Sagittal planes. One of the issues that need to be addresses is the possible coupling effect on the Linear Encoder Sensor at the Frontal plane due to the motion in the Sagittal plane and vice-versa thus creating errors to the sensor readout. To effectively minimize the coupling effect of the joint motion on the two planes, the Linear Encoder Sensors should be placed along the line of axis of the forearm with the Teflon tubing sewed across the assumed joint center to fix the line of movement of the cable (see Fig. 4-9). It is important that the cable with the tubing be fixed securely across the joint center and aligns along the line of axis as any offset will contribute to the coupling errors.

Fig. 4-9: Recommended Placement of Sensor on Wrist (Sagittal)

After modeling the wrist joint on both planes and verifying the working principles, the two planes are then combined together to address circumduction motion

which is a 360° range of motion in a wrist joint which include a combination of flexion, extension, adduction, and abduction as shown in Fig. 4-10.

Fig. 4-10: Modeling of Circumduction Motion of Wrist

4.2.3 Shoulder

The shoulder joint is made up of three bones: the clavicle (collarbone), the scapula (shoulder blade), and the humerus (upper arm bone) as well as associated muscles, ligaments and tendons. The articulations between the bones of the shoulder make up the shoulder joints. There are three joints at the shoulder, namely the glenohumeral, the acromioclavicular, and the sternoclavicular joints. The shoulder joint is flexible and provides a wide range of motion required in the arms and hands, making it the most mobile joint in the human body.

The shoulder motion encompasses a wide range of motion such as flexion, extension/hyperextension, abduction, adduction, transverse abduction/extension, transverse adduction/flexion, medial rotation, lateral rotation and circumduction of upper arm through a full 360° in the Sagittal plane. The three DOF of the shoulder joints can be modeled as a ball-and-socket or a spherical joint as shown in Fig 4-11.

Fig. 4-11: Modeling of Shoulder as Spherical Joint

Similar to the wrist, the Linear Encoder Sensor is not able to capture the twist motion of the upper arm about its axis such as medial rotation and lateral rotation and additional sensor will be required. The main focus here will be the detection of flexion, extension/hyperextension, abduction, adduction, transverse abduction/extension, transverse adduction/flexion and circumduction of the shoulder joint.

The analysis of the shoulder joint can be approached from the three separate planes: the abduction and adduction along the Frontal Plane, the flexion and extension/hyperextension along the Sagittal Plane, and the transverse abduction/extension and transverse adduction/flexion along the transverse plane.

(a) Abduction

From the Frontal Plane, the abduction of the upper arm will cause the skin to stretch resulting in a linear displacement at the Linear Encoder Sensor as shown in Fig. 4-12. The ROM of the shoulder joint in the Frontal Plane is from 0°(neutral) to 90° for abduction. The stretch ranges around 12mm to 25mm. The average joint radius of the shoulder (frontal) is around 9mm to 18mm. For the adduction motion, the upper arm has to cross into an awkward position in order to achieve this motion hence it will not be included.

For the placement on the shoulder (frontal), the sensor can be fixed on the upper arm while the fixed end is placed slightly above the greater tuberosity as shown in Fig 4-12. The concept can still work similarly even if the position of the sensor and fixed end is interchanged. However, since the Delrin^{TM} structure is long and need a stable base, it is advisable to affix the sensor on the upper arm.

The stretch due to abduction motion is estimated at 12mm to 25mm, a 60mm sensor structure is used to record the linear movement of the sensor. The placement of the sensor, fixed cable end-point together with a single piece of the 3mm diameter Teflon^{TM} tubing are as illustrated in Fig. 4-13. Taking reference from Point C which is denoted as the bony notch protrusion at the top of Clavicle Bone, the cable end-point will be placed at 40-50mm to the bottom.

(b) Flexion/Hyperextension

Similarly from the Sagittal Plane, the flexion and hyperextension of the upper arm the motion will cause the skin to stretch resulting in a linear displacement at the Linear Encoder Sensor as shown in Fig. 4-14. The ROM of the shoulder joint in the Sagittal Plane is from 0°(neutral) to 90° for flexion and around 50° for hyperextension. The stretch ranges around 12mm to 25mm. The average joint radius of the shoulder (frontal) is around 9mm to 18mm.

Fig. 4-12: Modeling of Shoulder Joint (Frontal)

Fig. 4-13: Recommended Placement of Sensor on Shoulder (Frontal)

For the placement on the shoulder (Sagittal), the sensor can be fixed on the upper arm while the fixed end is placed around the lesser tubercle as shown in Fig. 4-14. The concept can still work similarly even if the position of the sensor and fixed end is interchanged. However, since the Delrin^{TM} structure is long and need a stable base, it is advisable to affix the sensor on the upper arm.

The stretch due to flexion and hyperextension motion is estimated at 12mm to 25mm, a 60mm sensor structure is used to record the linear movement of the sensor. The placement of the sensor, fixed cable end-point together with a single piece of the 3mm diameter Teflon^{TM} tubing are as illustrated in Fig. 4-15. Taking reference from Point C which is denoted as the bony notch protrusion at the top of Clavicle Bone, the cable end-point will be placed at 55-65mm to the bottom. Taking reference from Point D which is the side of Deltoid Muscle, the cable end-point will be placed 30-40mm to the side.

Fig. 4-14: Modeling of Shoulder Joint (Sagittal)

Fig. 4-15: Recommended Placement of Sensor on Shoulder (Sagittal)

(c) Transverse Flexion/Transverse Extension

By placing the sensor as shown for the Sagittal Plane, the same sensor is applicable for detecting motion along the Transverse Plane such as transverse abduction/extension and transverse adduction/flexion. The Transverse Plane can be viewed as a Sagittal Plane with the shoulder joint in flexion of 90° as shown in Fig. 4-16 since the shoulder joint is modeled as a spherical joint. From the Transverse Plane, when the upper arm moves from neutral to transverse abduction/extension or to transverse adduction/flexion, the motion will cause the skin to stretch resulting in a linear displacement at the Linear Encoder Sensor as shown in Fig. 4-17. The ROM of the shoulder joint in the Transverse Plane is from 0° (neutral) to 135° for horizontal flexion and 45° for horizontal extension. The stretch ranges are the approximately the same as those for the Sagittal Plane.

The modeling of the Shoulder Joint from Transverse Plane is as shown in Fig. 4-17. The placement on the Sagittal Plane also takes into the consideration of the motion in the Transverse Plane.

Frontal Plane View

Fig. 4-16: Transformation of Sagittal Plane to Transverse Plane

Source from
<http://www.dartmouth.edu/~anatomy/>

Fig. 4-17: Modeling of Shoulder Joint (Transverse)

(d) Circumduction/Combined Motion

For circumduction or combined motion of the shoulder joint, the muscles play an important role in the shoulder motion control. As such, an analysis strategy based on the axis of rotation is deployed for the investigation of the shoulder joint for circumduction/combined motion. As shown in Fig. 4-18, the shoulder joint can be viewed from the three axes which are related to the human planes.

Fig. 4-18: Axes Modeling of Shoulder Joint

The three axes are :

Medial-Lateral Axis – axis that runs perpendicular to the **SAGITTAL** plane

Anterior-Posterior Axis – axis that runs perpendicular to **FRONTAL** plane

Longitudinal Axis – axis that runs perpendicular to **TRANSVERSE** plane

For analysis, a Local coordinate system attached to the shoulder joint and a Global coordinate system are defined as shown in Fig. 4-19. The position of the upper arm can then be defined with respect to the global coordinate system which can be thought of as an absolute reference frame.

Fig. 4-19: Global and Local Coordinate Systems

Fig. 4-20 and 4-21 show the ROM for the shoulder joint from the three different planes respectively. A volumetric 3-Dimensional ROM that is detectable by the linear encoder sensor can be obtained experimentally and plotted for the analysis of combined motion. For motions outside the volumetric ROM, the linear encoder sensors will not be able to effectively determine the joint angles as such motions involve significant movement of the scapula bone and muscle. This will result in a shift of the joint center and the assumption of a single fixed center of rotation will no longer valid. Further work will be needed to address on this issue.

Fig. 4-20: Mapping ROM of Shoulder Joint from Three Different Planes

Fig. 4-21: Mapping Volumetric ROM back to Each Plane

Consider a position of the upper arm with 45° of abduction (to the side) and 35° of flexion (to the front) as shown in Fig. 4-22. The analysis starts off by looking along the Anterior-Posterior Axis (Global) as shown in Fig. 4-23. It is seen that along the Anterior-Posterior Axis (Global), the joint angle can be detected by the linear encoder through projection along the axis and onto the Frontal plane. R_{Frontal} which is joint radius of the shoulder (Frontal) consists of bones and muscles group around the shoulder and can be pre-determined by a calibration process. With the joint radius and the readout of the linear encoder sensor, the abduction motion of the upper arm along Frontal plane can be determined.

Fig. 4-22: Modeling of Combined Motion of Shoulder

For the flexion motion angle, the position of the upper arm can be viewed along the Medial-Lateral Axis (Global) as shown in Fig. 4-24. It should be noted that the Sagittal plane where the linear encoder sensor was initially placed has been tilted by 45° due to the abduction motion, causing the circular shape (originally used to represent the shoulder joint) to change into an elliptical one.

Fig. 4-23: View along Anterior-Posterior Axis (Global)

In order to determine the joint angle due to flexion motion, a Local coordinate system can be established by rotating the coordinate axes by the amount caused by abduction along the Anterior-Posterior Axis (Global) as shown in Fig. 4-25. Viewing along the Medial-Lateral Axis (Local), the plane along which the linear encoder sensor lies can be considered as a circle with $R_{Sagittal}$, the joint radius of the shoulder (Sagittal) as shown in Fig. 4-26. The joint radius can then be used to determine the joint angle due to flexion motion. By recognizing the fact that any motion or position of the upper arm that are located within the detectable ROM is made up of flexion/hyperextension and abduction, the above analysis can be done simply by decoupling the combined motion and looking at the motion at any one axis at any one time.

Fig. 4-24: View along Medial-Lateral Axis (Global)

As motion of the shoulder is seldom purely flexion/hyperextension or transverse abduction/extension, there is a need to have a strategy to capture circumduction or combined motion of the shoulder, consisting of a combination of flexion, hyperextension, abduction and transverse abduction or adduction. If the position of the upper arm is located within the detectable ROM, the approach for capturing such information is by looking at one axis at any one time, starting with the Anterior-Posterior Axis to determine the amount of abduction and then looking along the Medial-Lateral Axis to determine the amount of flexion/hyperextension.

Fig. 4-25: Establishing of Local Coordinate System for Analysis

Fig. 4-26: View along Medial-Lateral Axis (Local)

4.3 Sensor Placement on Lower Extremity

4.3.1 Knee

The knee-joint is the lower extremity joint connecting the femur, fibula, patella, and the tibia. The knee joint permits the following movements: flexion, extension, as well as slight medial and lateral rotation. The knee can be overall modeled as a one-DOF joint like the elbow joint of the upper extremity because the main movement of the knee joint is flexion and extension. From the Sagittal Plane, as the knee flexes, it causes the skin to stretch over the kneecap area. Since the cable of the Linear Encoder Sensor is placed over the kneecap, it will move the Optical Sensor by a proportional amount.

The modeling and mapping of the knee joint when it moves from neutral/extension to flexion is shown in Fig 4-27. The ROM of the knee joint is 0° for neutral/extension position while flexion is permitted up to 160° . The stretch ranges around 15mm to 45mm. The average joint radius of the knee is around 10mm to 20mm depending on the built of the person.

For the placement of the sensor on the knee, the fixed cable end-point can be placed on the thigh while the Linear Encoder Sensor can be placed on the lower leg. The placement could also work with the Linear Encoder Sensor on the thigh while the fixed cable end-point on the lower leg making it the reference limb.

The stretch due to flexion is estimated at 15mm to 45mm. A longer sensor length of 130mm is needed in order to fully record the linear movement of the Optical Linear Encoder. The placement of the sensor, fixed cable end-point together with two pieces of the 3mm diameter Teflon^{TM} tubing that were to guide sensor in a single DOF movement are as illustrated in Fig. 4-28. Taking reference from Point E which is denoted as the notch groove located at the side of Patella Bone, the cable end-point will be placed at 90mm to the top taking reference from the Notch Groove at the side of Patella Bone.

Fig. 4-27: Modeling of Knee Joint

Fig. 4-28: Recommended Placement of Sensor on Knee

4.3.2 Hip

The hip is the bony projection of the femur and the hip joint, scientifically referred to as the acetabulofemoral joint which is the joint between the femur and acetabulum of the pelvis. The primary function of the hip is to support the weight of the body in both static (e.g. standing) and dynamic (e.g. walking or running) postures. The hip joint is a synovial joint formed by the articulation of the rounded head of the femur and the cup-like acetabulum of the pelvis. It is classified as a ball and socket joint. It forms the primary connection between the bones of the lower limb and the axial skeleton of the trunk and pelvis. The modeling of the hip joint and analysis involved is similar to that of the shoulder joint as it is also a ball and socket joint. However, due to the shape of the hip bone the ROM is much limited as compared to the shoulder joint.

(a) Abduction

From the Frontal Plane, when the thigh moved from neutral to abduction, the ROM of the hip joint is 0° for neutral position and 30° to 40° for abduction. The stretch ranges around 17mm to 27mm. The average joint radius used for the hip (frontal) is around 20mm to 35mm. Fig. 4-29 shows the modeling involved for the hip joint from the frontal plane.

Fig. 4-29: Modeling of Hip Joint (Frontal)

Fig. 4-30: Recommended Placement of Sensor on Hip (Frontal)

The modeling divides the whole hip into two spherical joint and that the sensor is modeled to be placed on either the lateral or medial side of the femur bone. However, since the sensor is to be placed physically on the skin, therefore it has to be positioned on the lateral side of the thigh. As the thigh abduct outward, the sensor will travel forward. The stretch due to abduction motion is estimated at 17mm to 27mm, a 130mm sensor structure is used to record the linear movement of the sensor. The placement of the sensor, fixed cable end-point together with a single piece of the 3mm diameter Teflon^{TM} tubing are as illustrated in Fig. 4-30. Taking reference from Point F, the cable end-point will be placed at 60-70mm to the bottom from the reference point and around 30-40mm to behind the reference mark. The sensor should be placed along the axis of the femur bone.

(b) Flexion/Hyperextension

Similarly from the Sagittal Plane, the flexion and hyperextension of the thigh from neutral will cause the skin to stretch, resulting in a linear displacement at the Linear Encoder Sensor as shown in Fig. 4-31. The ROM of the hip joint in the Sagittal Plane is from 0°(neutral) to 110° for flexion and around 30° for hyperextension. The stretch ranges around 20mm to 42mm for flexion and around 3 to 12mm for hyperextension. The average joint radius of the hip (Sagittal) is around 12.5mm to 25mm.

Fig. 4-31: Modeling of Hip Joint (Sagittal)

Looking at the pelvis bone structure, the center of the ball-and-socket joint is located off the Bony Notch Protrusion at the end of Ilium Crest as shown in Fig. 4-32. Hence based the analysis, the placement of the sensor, fixed cable end-point together with a single piece of the 3mm diameter Teflon^{TM} tubing are as illustrated in Fig. 4-33. Taking reference from Point F which is denoted as the Bony Notch Protrusion at the end of Ilium Crest (Hip/Pelvis Bone), the cable end-point will be placed at 80-90mm to the side of the reference point and about 60-70mm to the bottom from the reference point. The sensor should be placed along the axis of the femur bone.

Fig. 4-32: Pelvis/Hip Bone

Fig. 4-33: Recommended Placement of Sensor on Hip (Sagittal)

4.3.3 Ankle

The ankle joint is formed where the foot and the leg meet. It is a synovial hinge joint that connects the distal ends of the tibia and fibula in the lower limb with the proximal end of the talus bone in the foot. The bones which constitute the ankle are the two long bones of the lower leg (tibia and fibula), which articulate with a short ankle bone called the talus. This is an 'uniaxial', or hinge joint, which allows flexion and extension movements. In the case of the ankle these movements are called dorsiflexion (sole of the foot up) and plantarflexion (foot down) respectively. The sub-talar joint (below the ankle) permits movements of the sole of the foot inward (inversion) and outwards (eversion) i.e. rotation of the foot. The sub-talar joint can be likened to the action of a mitered hinge as shown in Fig. 4-34.

Fig. 4-34: Mitered Hinge model by Inman and Mann (1973)²⁶

The ankle joint is considered as a limited 3 DOF joint. However, if for a subject who is walking or jogging on normal flat ground, the main motion of the ankle is dorsiflexion and plantarflexion along the Sagittal Plane from Heel Strike to Toe Off instant.

Fig. 4-35 shows the modeling involved for the ankle joint. From the Sagittal Plane, when the ankle moves from neutral to plantarflexion, the ROM of the ankle joint is from 0° to about 30° or 40°. The skin stretch ranges around 7mm to 21mm. As the ankle moves from neutral to dorsiflexion, the ROM of the ankle joint is from 0° to about 20° or 30°. The corresponding skin stretch ranges around 5mm to 17mm. The average joint radius for the hip is around 22mm to 37mm. Since the stretch limit is less than 50mm, a 60mm sensor structure is used to record the linear movement of the sensor.

The placement of the sensor, the fixed cable end-point and a single piece of the 3mm diameter Teflon™ tubing are as illustrated in Fig. 4-36. The Teflon™ is placed over stretch/folding region of the ankle to prevent buckling of wire. Taking reference from Point G which is denoted as the Bony Notch Protrusion at the end of Fibula Bone, the sensor should be placed along the axis of the femur bone with the cable end-point located at 40mm to the bottom from the reference point.

4.4 Formulation for Multiple Joints

The Linear Encoder Sensor can be used individually to detect motion of one joint or it can be linked up to detect motion of a group of joints. Having all the joints on the body been mapped out, all the Linear Encoder Sensors can be placed on the respective joints and form a wearable suit to capture the human motion. In order to analyze the human body motion, an analysis model can be used to compute all the joint angles on the body if the radius of each joint can be determined. Consider dividing the human body into two half (Left and Right) by the Sagittal Plane, each half of the body will consist of equal number of joints. Consider N Linear Encoder Sensor for measuring N joints on the one side of the human body. The analysis model can be expressed as:

$$\alpha = GD \quad (6)$$

where $\alpha = (\alpha_1 \ \cdots \ \alpha_N)^T$ denotes the $N \times 1$ vector matrix for the joint angles, G is a $N \times N$ matrix constant multiplier and $D = (D_1 \ \cdots \ D_N)^T$ is the $N \times 1$ vector of corresponding sensor readings in millimeters.

The actual readout from the Linear Encoder Sensor is in terms of numbers of lines which is spaced 0.1mm apart. The following equation can be used to convert the Linear Encoder readout to millimeters:

$$D = Pd \quad (7)$$

where $d = (d_1 \ \cdots \ d_N)^T$ denotes the sensor readings in No. of Lines and P as a scalar Multiplier of 0.1 magnitude.

Fig. 4-35: Modeling of Ankle Joint (Sagittal)

Fig. 4-36: Recommended Placement of Sensor on Ankle

The matrix G contains diagonal elements among multiple joints which can be obtained by the following equation:

$$G = qR \quad (8)$$

where

$$G = \begin{bmatrix} G_{11} & 0 & \cdots & 0 \\ 0 & G_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & G_{NN} \end{bmatrix} \quad (9)$$

is the $N \times N$ diagonal matrix constant multiplier, q is a scalar multiplier, magnitude of $\frac{360^\circ}{2\pi}$ while R denotes the radius on each joint

$$R = \begin{bmatrix} \frac{1}{r_{11}} & 0 & \cdots & 0 \\ 0 & \frac{1}{r_{22}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{r_{NN}} \end{bmatrix} \quad (10)$$

r_{ij} denotes the joint radius on one side of the human body as illustrated in Fig. 4-37 and Fig. 4-38, showing the overall human body structure model with all the radii on the body indicated.

Fig. 4-37: Mapping of Radius on Upper Body

Fig. 4-38: Mapping of Radius on Lower Body

By determining the joint radius r_{ij} on the human body, the joint angle α_i can be obtained easily based on the sensors readout D_i . Hence, the joint radius parameters have to be specified prior collecting data. However, the joint radius varies from human body to human body. Therefore, the $N \times N$ R diagonal matrix has to be experimentally determined in order to relate the inputs and the outputs.

One way to overcome the constant need to determine the joint radius parameter is to do a statistical study on a population of test subjects which is sufficiently large enough and create a detailed lookup table based on the age group, sex, race and build of the person (e.g. weight, height, limbs length and etc). This method of data collection and analysis is very detailed as all the data will be compiled into a database which will be used for the joint angle calculations. Before the user puts on the network of sensors on the body, all the parameters have to be recorded and input into a system which it will in turn do a search on the lookup table for the appropriate sets of joint radius to be used.

Alternatively, using the same statistical data analysis, the build of a person can be categorized into three bands, namely Small, Average and Large. By segregating the human body build into bands, each band will be allocated a specific set of joint radius data that will be used for calculation in determining the joint angles during movement. The user has to input his/her build into system based on certain guidelines which will tag them into one of the three bands and the appropriate sets of radius data can be used.

One last method is to use a single average value that is assigned for the respective joint for analysis. This method assumes that the data collected follows a normal distribution and that there is no relationship between the build of the human and the joint radius. Based on that assumption, the data collected for the each joints are averaged respectively and the resulting joint radius parameter was obtained. By using an average value for each joint, the sensor suit detects mainly motion but it is unable to reflect the true value of the joint angle as accurately as compared to the previous mentioned methods of analysis.

4.5 Routing of Sensor System

To form a complete body motion sensing suit, one issue that needs to be addressed is the routing on the sensor systems. The proposed routing method is as shown in Fig. 4-39. The groups of sensors are linked together in a daisy chain manner and the data will be transmitted to and stored in the Data Concentrator. Besides acting as data storage, the Data Concentrator also acts as a beacon to transmit signal so as to synchronize the timing of the sensors.

Fig. 4-39: Routing of Sensor for Upper and Lower Body

Based on Fig. 4-39, the Linear Encoder Sensors were classified by their location, sensor length and also respective joint. The classification scheme is as illustrated in Fig. 4-40.

Fig. 4-40: Classification Scheme for Linear Encoder Sensors

4.6 Sensor Mounting

In order to facilitate accurate sensing and easy tracking, a backing material such as fabrics in the form of a suit or brace/substrate is needed to improve the placement for the sensors.

For long duration monitoring of joint information, the sensors can be mounted on fabrics in form of apparel which can provide better comfort and look to the user. The apparel can be support braces which are modular for each joint or it can be a full body suit similarly to those worn by sportsmen/sportswomen.

By mounting the sensors onto a backing material as shown in Fig. 4-41, it can help to improve the accuracy of the sensor by restricting undesired mechanical errors such as buckling and kinking of the Nylon Coated Wire when the fabrics is stretched over the joints during bending. Another advantage is for ease of aligning as the linear encoder sensors are sewed firmly on the fabrics. Acting like the seams on the clothing, this helps the wearer to align the sensors at the various joint locations.

Fig. 4-41: Linear Encoder Sensor on barebone substrate

A modular approach will be to sew Velcro on both the support brace and the linear encoder sensor as shown in Fig. 4-42, providing the user with the flexibility to place the sensor at the desired joints and also to adjust the sensor. The user can remove the sensors easily after monitoring by separating them from the support brace. The modular system can also be mapped onto a Full Suit System as shown in Fig. 4-43 for whole body motion capturing.

Fig. 4-42: Mounting of Sensor on Velcro Support Brace

Fig. 4-43: Transforming Modular System to Full Suit System

CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSIONS

5.1 Powercube™ Experiment

5.1.1 Set-Up of Experiment

This experiment is to verify the repeatability and accuracy of the concept that an average radius can be used to measure the rotation angle based on the Equation:

$$\alpha = \frac{D}{2\pi R} \times 360^\circ$$

Fig. 5-1 shows the setup of the experiment. A precise rotary joint, Powercube™ from Amtec™, is used as the reference for the angular rotation. It has 2000 pulse per revolution encoder which translates into 0.18° per pulse. The linear encoder assembly is mounted onto a jig that is attached to the Powercube™. Measurements of displacement are recorded from the linear encoder via the DSC as the Powercube™ rotary module is programmed to rotate from 0° to 90° at intervals of 10°.

Fig. 5-1: Setup for the PowerCube™ Experiment

5.1.2 Results

For repeatability, three readings are taken from the linear encoder for each rotation angle. Fig. 5-2 shows the plot of the linear encoder readings in unit of number of lines against the angle of rotation of the Powercube™. It is seen that there is a linear relationship. A straight line with an R-squared value of 0.9996 can be fitted, showing a linear relationship between the encoder readings and the angle of rotation. Hence, the linear encoder is effective in measuring the rotation angle.

Fig. 5-2: Encoder readings against Rotation Angle

5.1.3 Discussion

From the experimental results, the initial assumption of using some basic geometry such as a circle with a single fixed center point to model the human body joint is acceptable. This forms the basis of the working principle of the linear encoder sensors as denoted by Equations (2) and (3) in Chapter 3.

Referring on the graph plotted, the straight line equation based on the experimental results is given as $y = 5.5021x$. Note that the distance between two lines on the linear encoder coder is 0.1mm. Hence the distance traveled (D) can be found by

multiplying the number of lines (y) by 0.1mm. The variable x is the angle of rotation or angle α . The working radius can be obtained as shown below:

$$\alpha = \frac{D}{2\pi R} \times 360^\circ$$

$$\frac{D}{\alpha} = \frac{2\pi R}{360^\circ}$$

$$\therefore 0.55021 = \frac{2\pi R}{360^\circ}$$

$$R = 31.525\text{mm}$$

Based the calculation, the constant radius derived from the experimental graph is found to be 31.5mm which is close to radius of the test jig of 30mm as shown in Fig. 5-3.

Fig. 5-3: Test Jig Radius

5.2 Calibration of Joint Radius

The experiment involves the determination of the different joint radius so as to calibrate the Linear Encoder Sensor to suit the test subject. The method of calibration is applicable to test subjects of different age group, body built and gender. Once the calibration is done and the radii for the different joints are determined, the Linear Encoder Sensor will be able to detect the amount of stretch/fold-in and output the readout in terms of degrees.

In this experiment the goniometer, the medical standard for joint angle measurement, is used as the reference (see Fig. 5-4). The calibration is carried out by

having the test subject to move through pre-determined angles with both the Linear Encoder Sensor and the goniometer attached across the joint as shown in Fig. 5-5 and Fig. 5-6.

Fig. 5-4: Goniometer Set

The test subject is made to move the joint under investigation slowly from a rest position (assume 0°), through small angle incremental of either 5° or 10° to a suitable position based on the range of motion (ROM) of the respective joints. As the joint moves through the angle increments, the test subject is required to hold at that angle for a while before moving on to the next. Once the ROM is reached, the joint is slowly returned back to the initial position. For each joint, three repetitions are performed to ensure consistency and accuracy of the data collected.

Fig. 5-5: Elbow Joint

Fig. 5-6: Ankle Joint

The calibration is conducted for all the joints and their respective motion range to obtain the joint radii parameter:

- Elbow
- Wrist (*Flexion, Hyperextension, Abduction, Adduction*)
- Shoulder (*Flexion, Hyperextension, Abduction*)
- Knee
- Hip (*Flexion, Hyperextension, Abduction*)
- Ankle (*Plantarflexion, Dorsiflexion*)

5.2.1 Elbow Joint

Using the elbow as an example, the elbow is moved from a straighten position of 0° to an approximate angle of 35° before returning back. The readout from the Linear Encoder Sensor, in unit of number of lines, is plotted against the readout of the goniometer in degrees. Fig. 5-7 shows a linear relationship between the two parameters with an R-squared value of 0.9664. The equation of the line fitting through the data points is given as $y = 4.0814x$.

Fig. 5-7: Plot for Elbow Joint

The procedures and graphs for the other joints can be found in Appendix E.

5.2.2 Discussion

Table 5-1 summarizes the experimental results for all the joints with the values of the joint radii listed.

Table 5-1: Joint Radius Calibration Results for Various Joints

Joint and Motion	Range Of Motion (ROM)			Stretch / Fold-in (mm)	Equation of Line	R ² -Value	Radius (mm)
	Min	Test Range	Max				
Elbow	0°	35°	140°	13.3	4.0814	0.9664	23.385
Wrist - Flexion	0°	25°	60°	9.5	3.7855	0.9947	21.689
Wrist - Hyperextension	0°	20°	60°	8.0	3.7867	0.9779	21.696
Wrist - Abduction	0°	15°	20°	6.0	3.7857	0.9817	21.690
Wrist - Adduction	0°	25°	30°	10.0	3.7855	0.9630	21.689
Shoulder - Flexion	0°	50°	90°	26.0	5.1982	0.9882	29.783
Shoulder - Hyperextension	0°	25°	50°	13.5	5.1927	0.9580	29.752
Shoulder - Abduction	0°	50°	90°	25.0	5.1855	0.9873	29.711
Knee	0°	50°	120°	25.0	4.8527	0.9683	27.804
Hip - Flexion	0°	30°	110°	23.8	8.0198	0.9990	45.950
Hip - Hyperextension	0°	15°	30°	12.1	8.0571	0.9987	46.164
Hip - Abduction	0°	25°	40°	19.2	8.0218	0.9864	45.962
Ankle - Plantarflexion	0°	25°	40°	12.1	4.7491	0.9831	27.210
Ankle - Dorsiflexion	0°	20°	30°	9.2	4.7467	0.9906	27.197

The R²-value of the straight line corresponds to the correlation coefficient between the two measurement parameters. The average R²-value is around 0.9817 which indicates that close approximation between these two systems. This implies that the output of the Linear Encoder Sensor is able to match the readings of the goniometer.

Having to calibrate the Linear Encoder Sensors, it is noted that the radii obtained in a single plane but for two different motions are not exactly the same value as shown in Table 5-2. Depending on the accuracy needed, joint radii as obtained can either be taken using the average of two values for the same joint and same plane or using the actual value as derived for each motion. The prior method of using the average between two values produces nine sets of joint radius which still gives a reasonable accuracy as the differences between the values are quite insignificant. For a more precise accuracy, it will be advisable to use the individual radius as acquired for each separate motion for

analysis. For cases where the differences in the radii for the same joint, same plane but different motion is large, it is also advisable to use the separate radii for calculation.

Table 5-2: Various Joint Motion, Radius and Plane

Joint and Motion	Radius (mm)	Test Plane
Elbow	23.385	Sagittal
Wrist - Flexion	21.689	Frontal
Wrist - Hyperextension	21.696	Frontal
Wrist - Abduction	21.690	Sagittal
Wrist - Adduction	21.689	Sagittal
Shoulder - Flexion	29.783	Sagittal
Shoulder - Hyperextension	29.752	Sagittal
Shoulder - Abduction	29.711	Frontal
Knee	27.804	Sagittal
Hip - Flexion	45.950	Sagittal
Hip - Hyperextension	46.164	Sagittal
Hip - Abduction	45.962	Frontal
Ankle - Plantarflexion	27.210	Sagittal
Ankle - Dorsiflexion	27.197	Sagittal

For the same joint and within same plane, the two motions permissible are direct contrary with each other, e.g. Flexion is opposite of Hyperextension, Adduction is opposite of Abduction. In the same way, the Linear Encoder Sensor is able to detect the direction of travel within the single plane, the direction of travel will help to indicate the motion within that plane and hence the respective radius can be utilized for calculation of that particular motion. Additional programming efforts are needed for such a situation.

After obtaining the joint radii, the calibration process is completed as the readings of the Linear Encoder Sensor are converted directly from number of lines into angular degree.

5.3 Goniometer Comparison Experiment for 1-DOF Joint

The experiment compares the accuracy and response of the new linear-sensor against a Biopac™ TSD130A twin-axis goniometer. The test procedure is as illustrated by the flowchart in Fig. 5-8.

Fig. 5-8: Flowchart of Goniometer Experimental Procedure (1-DOF)

5.3.1 Set-Up of Experiment

The performance of the linear sensor are evaluated against that of the Biopac™ TSD130A twin-axis goniometer for a single DOF elbow joint. The goniometer system measures the change in the position of a joint via change of resistance in a set of strain gages. The readout of the goniometer serves as a reference for the elbow bend angle.

In the experiments, the goniometer is attached to the lateral side of the upper arm while the linear encoder sensor is strapped to the posterior of the elbow joint where the ulna bone is located. As shown in Fig. 5-9, the goniometer is attached to the arm using

double adhesive tapes while the linear encoder sensor is incorporated onto a barebone substrate design for the comfort of the user to put on and remove.

Fig. 5-9: Experimental Setup for Elbow Joint

Three healthy male subjects are recruited for the experiments. Each of the subjects is required to perform two set of experiments. For the first experiment, each subject is seated and asked to do a simple elbow flexion motion from 0° to 90° and back to 0° continuously for a few cycles at a slow pace. For the second experiment, the test subjects are required to flex the forearm in a fast oscillating motion to simulate high frequency motion. The subjects are asked to flex the forearm while keeping the upper arm still throughout the experiment. They are reminded that regular and repeated movements are preferable. Any twisting motion due to the bones under the skins will be avoided or minimized.

Prior to the actual experiment, a calibration test is needed to determine the radius about the elbow. For the calibration test, a set of readings from 5° to 80° , with 5° intervals are taken with three repetitions. Using the results from the goniometer as a reference of the elbow bend angle, the output from the linear encoder sensor, in units of number of lines are recorded and are plotted against that of the goniometer reading as shown in Fig. 5-10.

Fig. 5-10: Calibration Result for Elbow joint

By drawing a best fit straight line through the points as showed in Fig. 5-10, a correlation coefficient of 0.9834 is computed. The radius of the elbow joint can be obtained as described in section 5.1.

5.3.2 Results of Experiment

After the calibration process and getting the radius of the joint under consideration, the subjects are ready for the actual experiment. For the first set of experiment, the subjects are required to slowly flex their forearm from a straighten position at 0° to 90° and then back to 0° for a few cycles of around 0.1 to 0.3 Hz which is one complete cycle in 3 to 5 seconds. This is to assess the response of the Linear Encoder Sensor performance at low test frequency.

Fig. 5-11 illustrates that the readings of the linear encoder sensor as compared to that of the goniometer system. From the figure, a close relation of the performance between the goniometer and the sensor can be deduced. A statistical analysis of the performance and error between the two systems is carried out via Mathlab^{TM} and Table 5-3 shows that the Root Mean Square (RMS) error of the elbow joint angle is 3.8044° with a standard deviation of 3.8355° .

In statistics, the correlation ratio is a measure of the relationship between the statistical dispersion within individual categories and the dispersion across the whole population or sample. It is the descriptions of association and statistical significance of a trend in the data. By doing a correlation analysis between the two sets of readings, the amount of similarity between the measurement systems can be determined. The correlation ratio for the flexion motion is 0.9955. That is to say that the output from the OLE sensor is able to match up to 99.55% similarity of the goniometer output.

Fig. 5-11: Test Results for Elbow Joint (Flexion)

For the second set of experiment, the subjects are required to flex their forearm to 45° and oscillate around that range and continue up to 90° and holding it there before straightening back to 0° for a few cycles. For the oscillation part, the frequency of test is around 0.5 to 2 Hz which is around one cycle within a time frame of 1 to 2 seconds. For the holding portion of the experiment, it is to check for any sign of drifting in the sensor response.

Fig. 5-12 illustrates that the outcomes of the linear encoder sensor as compare to that of the goniometer system for high frequency motion, Table 5-3 show that the RMS error of the elbow is 3.4786° and the standard deviation is 3.4629° . In addition, based on

the graph, the sensor performance is observed to be able to handle high frequency excitation. The correlation ratio for the oscillation motion is 0.9901 which indicate that even at high frequency excitation; the OLE sensor is able to match the speed of detection of the goniometer with only 1% difference.

Fig. 5-12: Test Results for Elbow Joints (Oscillation)

Table 5-3: Error Statistics for Elbow Joint (1-DOF)

Experiment	Approximate Frequency (Hz)	Root Mean Square (RMS)	Standard Deviation	Correlation Ratio
Flexion Motion	0.18	3.8044°	3.8355°	0.9955
Oscillation Motion	2.13	3.4786°	3.4629°	0.9901

5.3.3 Discussion

For this experiment, it can be observed that the Linear Encoder Sensor had displayed an interesting set of characteristics in comparison against the goniometer. During the first test, when the subjects were asked to slowly flex their forearm from a straighten position to 90° position and then back for a few cycles at around 0.18 Hz, it can be seen that the Linear Encoder Sensor does not have a smooth turning point as compared with the goniometer. The error between the Linear Encoder Readout and

goniometer as recorded at around the turning point is around 2° to 4° which gives a Root Mean Square of 3.8044° . The measure of spread as denoted by the standard deviation is 3.8355° which shows a wide spread hence more improvements are needed to enhance the performance of the OLE sensor to reduce the variation.

However, during the second test, it is noted that the Linear Encoder Sensor is able to match the high excitation rate of around 2.13 Hz during the oscillation phase with negligible error even though it display error of about 3° to 5° in magnitude at plateau portion of the experiment when the subject was asked to hold still. Besides that, there are region of unsmooth transient noted at those turning point. Despite all these, the readout display close similarity to that of the goniometer results which give a Root Mean Square of 3.4786° while the spread also reduces to 3.4629° which indicate a better performance while compared to slow flexion motion.

The correlation ratios yield from both the flexion and oscillation experiments are 0.9955 and 0.9901 respectively. This shows a high resemblance of the OLE output to that of the goniometer which indicates that the Linear Encoder Sensor is able to replicate the output of the goniometer with 1% of discrepancy.

The discrepancies as noted for the Linear Encoder Sensor could be due to the mechanical construction of the sensor. Since the basic design and sensing principle is based on the mechanical portion of the sensor, the Linear Encoder Sensor is susceptible to mechanical error such hysteresis, inertia and friction.

As the elbow start moving from a resting position, it caused the sensor to move from its initial static position to a new position during which it has to overcome the initial friction and inertia. This could account for the region of unsmooth transient that are noted at those turning point which can be observed in both flexion and oscillation experiments. Other factors that could be possibly present are buckling of the Nylon Coated Wire which occurs when subject goes from a bended position to a straighten position which might cause a latency in the mechanical responses.

5.4 Goniometer Comparison Experiment for 2-DOFs Joint

The experiment involves the determination of the accuracy and response of the new multi-sensor used on a 2-DOFs joint which completes the set of limbs, hence the shoulder joint was selected for the experiment so as to complete the upper limb. The Linear Encoder Sensor is compared against a Noraxon™ twin-axis Electrogoniometer. Even though the goniometer is not ideal for the shoulder joint, it serves as an initial works and stepping stone for further investigation so as to assess the performance of the Linear Encoder Sensor to see if it suffers the similar shortcomings as the goniometer. The experiment procedure is similar to that used for a 1-DOF joint and is as shown in Fig. 5-13.

Fig. 5-13: Flowchart of Goniometer Experimental Procedure (2-DOFs)

5.4.1 Set-Up of Experiment

The performance of the linear sensor is evaluated against that of the Noraxon™ Plug-In Sensor Series Goniometer. The NorAngle Electrogoniometer System provides clear, dual, biaxial angle signals for up to two axis angles per joint. The NorAngle is designed specifically to be tethered to Noraxon's MyoSystem fixed-cable SEMG instruments. The NorAngle may also be used as a stand-alone electrogoniometer package as shown in Fig. 5-14. The lightweight, belt-worn interface pack comes with an extremely flexible, twenty-foot long tether and the analog output can be connected to any acquisition system for storage and/or analysis of the angle data.

Fig. 5-14: Noraxon™ Electrogoniometer System

In the experiments, two set of goniometers and linear encoder sensors are attached side by side to the anterior and lateral side of the upper arm while the other end were attached to Trapezius muscle which is a large superficial muscle which extends longitudinally from the occipital bone to the lower thoracic vertebrae, and laterally to the spine of the scapula (shoulder blade). The goniometers and linear encoder sensors are attached to the arm and shoulder using double adhesive tapes as shown in Fig. 5-15.

Goniometer 1 which is attached to the anterior side of the upper arm is used to record the abduction motion while Goniometer 2 which is on the lateral side of the upper

arm is used mainly for detecting flexion motion. The placement of the Linear Encoder Sensor is opposite to that of the goniometers. OLE sensor 1 which is stick on the anterior side of the upper arm is used to record the flexion motion while OLE sensor 2 which is used to detect abduction motion is adhere to the lateral side of the upper arm.

The test subject is required to perform four set of experiments to test the accuracy of the sensor been used for a 2-DOFs joint. Before commencement of the experiments, calibration is done to determine the joint radii for the shoulder for flexion and abduction motion. The results of the calibration will be used for converting the output of the Linear Encoder Sensor from number of lines into angular degrees so as to compare against that of the reading of the goniometers which is in term of degrees.

Fig. 5-15: Experimental Setup for 2-DOFs Joint

For the first experiment, the subject is seated and asked to do a simple upper arm flexion motion along the Sagittal Plane from 0° to 45° and back to 0° continuously for a few cycles at a slow pace. The test subject was asked to flex the upper arm while attempting to lock the forearm straightened throughout the experiment. Slow, regular and repeated movements are preferable. Any abduction motion to the side is kept at a minimal.

For the second set of experiment, the test subject was required to oscillate his upper arm along the Sagittal plane from 0° to 30° and holding it there before straightening back to 0° . The same two sets of experiments were repeated for Frontal Plane for abduction motion and oscillation. Precautions were taken to avoid excessive side swaying and to keep the motion within the same plane.

5.4.2 Results of Experiment

The results from the goniometers were capturing using the authorized software MyoResearch as shown in Fig. 5-16 which is delegated for use with the NorAngle Electrogoniometer System. The outputs from the goniometers were compared against that from the Linear Encoder Sensors for the specific motion along the particular plane so as to assess the capability of the sensor for detecting motion on 2-DOFs joints.

Fig. 5-16: MyoResearch Record Viewer for Noraxon^{TM} Electrogoniometer

The subject was asked to lift his arm by the side to around 40° and back to 0° for a few cycles at a low test frequency of 0.15 Hz. Fig. 5-17 shows the output from the MyoResearch Record Viewer for Goniometer 1. The graph which is emphasized by the red box is the region of interest and was compared against the output from the linear encoder OLE 2 shown in Fig. 5-18. Due to the method of calibration and placement of the NorAngle Electrogoniometer, the data extracted is in negative terms hence additional processing is needed to convert the data to positive for comparison purposes.

From Fig. 5-18, a close relationship between performance of Goniometer 1 and OLE sensor 2 can be derived. By doing a statistical analysis on error between the two systems, the RMS error of the shoulder joint angle for abduction motion is 3.9038° and the standard deviation is 3.8832° . However the correlation ratio is 0.9652 which indicates around 3.5% of discrepancies between the output response of the goniometer and OLE sensor.

Fig. 5-17: MyoResearch Results for Slow Abduction motion along Frontal Plane

Fig. 5-18: Test Results for Abduction – Frontal Plane

For the second set of experiment, the subject has to abduct the upper arm to 30° and oscillate for a few cycles at around 1.09 Hz and holding it there before relaxing back to 0° . The reason why only a small angle range was tested is because the cables and rest

of the peripheral for the Noraxon™ Goniometer system were sticking out and quite obtrusive to the test subject. The output as captured by the MyoResearch system is as shown in Fig. 5-19. Similar processing of the data was applied to convert the polarity of the readings from negative to positive.

Fig. 5-19: MyoResearch Results for Oscillation motion along Frontal Plane

Fig. 5-20: Test Results for Oscillation – Frontal Plane

Comparisons were made between the outcome for the OLE and goniometer systems, the readings were plotted side-by-side as shown in Fig. 5-20 and statistical analysis on the amount of error were carried out and yield the following results. The RMS was found to be 3.0348° while the standard deviation is 3.0333° . The correlation ratio was calculated to be 0.9620.

Having to complete the abduction motion along the Frontal plane, the next test to be conducted is the flexion of the upper arm along the Sagittal plane at a low frequency of around 0.16 Hz. The output of Goniometer 2 as reflected by the red box in Fig. 5-21 was compared against that of the OLE sensor 1. The yield from Goniometer 2 indicates a positive angular displacement because of the sensor placement orientation and calibration method hence no further processing is needed. The figures as derived from the OLE sensor were plotted directly and compared against the output of the goniometer as shown in Fig. 5-22.

The error statistics as attained from the comparison analysis done via Mathlab^{TM} are as follows, the error RMS was calculated to be 3.9546° and the standard deviation was recorded at 3.4870° . The correlation ratio was worked out to be 0.9549. A sample of the Mathlab^{TM} programme used for the error statistics comparison analysis can be found in Appendix F.

Fig. 5-21: MyoResearch Results for Slow Flexion motion along Sagittal Plane

Fig. 5-22: Test Results for Flexion – Sagittal Plane

Next, the test subject was asked to flex his upper arm forward to an angle of 30° and oscillate for a couple of cycles at around 1.00 Hz and hold at 30° prior releasing back to neutral position. The end result as captured on the MyoResearch programme are as illustrated in Fig. 5-23, no further processing of the data are needed and it was used as reference of comparison for the OLE sensor.

By running the error statistics analysis using Mathlab^{TM} yields the deduction on the performance of the Linear Encoder Sensor as follows in Fig. 5-24, the error RMS deduced is 2.8779° and the standard deviation was registered at 2.8090° while the correlation ratio was worked out to be 0.9529.

Table 5-4 summarized the test error statistics as captured for the four sets of data comparison for both flexion and abduction motion and oscillation motion along the Frontal and Sagittal plane.

Fig. 5-23: MyoResearch Results for Oscillation motion along Sagittal Plane

Fig. 5-24: Test Results for Oscillation – Sagittal Plane

Table 5-4: Error Statistics for 2-DOFs Joint

Experiment	Approximate Frequency (Hz)	Root Mean Square (RMS)	Standard Deviation	Correlation Ratio
<i><u>Abduction</u></i>				
Slow Motion	0.15	3.9038°	3.8832°	0.9652
Oscillation Motion	1.09	3.0348°	3.0333°	0.9620
<i><u>Flexion</u></i>				
Slow Motion	0.16	3.9546°	3.4870°	0.9549
Oscillation Motion	1.00	2.8779°	2.8090°	0.9529

5.4.3 Discussion

For the 2-DOFs joint comparison, the performance of the Linear Encoder Sensor can be seen to be quite good, accurately capturing the joint movement patterns over time as the response graphs of the Linear Encoder Sensors display similar characteristics to the goniometers for motion along both Frontal and Sagittal plane.

The error statistics analysis indicates that significantly larger errors results as the frequency of test is low for both flexion and abduction motion at around 0.1 to 0.2 Hz yield a larger RMS value at around 3.9° . The measure of statistical dispersion shows that the data points are spread far from the root mean square as the standard deviation is large. Hence better experimental controls have to be instilled to ensure consistency in the experiment. The correlation ratio denotes that there are around 3.5% to 4.5% of differences in the movement patterns.

From Fig. 5-18 and 5-22, it can be observed that there is a fairly big difference in the readings at the turning point when upper arm was either moving from 40° to 0° or vice versa, the error range is around 3° to 5° for abduction and 1° to 2° for flexion. Same similarities were noted as the 1-DOF experiment is that the turning points for the OLE sensors were not as smooth as the response of the goniometers. So while not perfect, but still the OLE sensors were able to give a fairly accurate prediction of the joint angle for slow test frequency.

It is critical that these OLE sensors are able to capture higher frequency motion which is set for a 2-DOFs joint. From the results as indicated in Table 5-4, it is seen that the sensors are able to track the oscillation motion of around 1 to 1.2 Hz and yield much better results while compared to low test frequency. The test subject was unable to produce a much higher test frequency of around 2 Hz as the cables that were connected the goniometers and OLE sensors are obtrusive to the test subject. If the test frequency is too high, it might cause the sensors to fall out.

The average error root mean square between both systems is around 2.9° for high frequency movement along both Frontal and Sagittal plane while the spread of the data shows a reasonable pattern of around 2.9° . The OLE sensors illustrate better performance

during high frequency in which same observations were made for the 1-DOF experiment. However, there is an increase in the correlation ratio that is around 4% to 5% of differences in the movement patterns.

Similar observations as the low frequency tests were noted at the turning point of the oscillation motion for both Frontal and Sagittal plane as demonstrated in Fig 5-20 and 5-24. The unsmooth transient point seems to be inherited for both high and low frequencies tests but it is not as significant during the high frequency excitation.

In comparison with the 1-DOF experiment, the Linear Encoder Sensors are able to function as well for a 2-DOFs joint. However, the placement of the sensors is really important as it will add on another source of variability which is on top of the intrinsic mechanical errors such as hysteresis, inertia and friction which cause latency in the mechanical responses. The “zeroing” and calibration of both goniometers and OLE sensors are another potential source of error, during the testing phase, the results might have drifted slightly due to settling in of sensors. Other possible sources of error will include non-robust de-coupling of motion along both Frontal and Sagittal plane. On top of that, there might be other uncertainties such as material or other processes that cannot be accurately monitored or modeled and are present in both measurement systems.

5.5 Placement Range for Linear Encoder Sensor

The experiment involves determining the range of placement for the linear encoder sensors and also the response of the sensors if it is placed off-center from the ideal proposed location. A pair of Optical Linear Encoder sensors placed side by side is compared against a Noraxon™ twin-axis Electrogoniometer using it as the reference of comparison. One of the Optical Linear Encoders is placed at the recommended location while the other is placed x mm away as shown in Fig. 5-25. By varying the distance between the two Optical Linear Encoder sensors and examining the response of the sensor which is placed off-center, a relationship between the distance and corresponding response can be established and examined.

Fig. 5-25: Experimental Setup for Placement Range

5.5.1 Set-Up of Experiment

The off-center response of the linear encoder sensor is compared against the standard response set which is in turn evaluated against a reference system which is the Goniometer. In the experiments, two linear encoder sensors are attached side by side to the posterior of the elbow joint where the ulna bone is located while the goniometer is strapped on the lateral side of the upper arm. The goniometer and linear encoder sensors are attached to the upper arm and forearm using adhesive tapes.

In order to determine the effect of off-center placement of the linear encoder sensor, the distance x mm is varied at 25mm and 50mm. The results are recorded and evaluated against the standard output and goniometer readings. The test subject is required to perform three set of motions to verify the accuracy and repeatability of the

sensors. Before commencement of the experiments, calibration is done to determine the joint radius for the elbow. The results of the calibration will be used for converting the outputs of both Linear Encoder Sensors from number of lines into angular degrees.

For the first experiment, the offset distance x is set at 25mm as shown in Fig. 5-26. The subject is seated and asked to do a simple elbow flexion motion from 0° to 45° and back to 0° continuously for a few cycles at an average pace. For the second experiment, the offset distance x is set at 50mm as shown in Fig. 5-27 and the test subject was asked to repeat similar elbow flexion motion from 0° to 45° and back to 0° continuously for a few cycles at an average pace of 0.3 to 0.5 Hz. Observing similar precaution, the upper arm is kept still throughout the experiment while the forearm is flexed in regular and repeated motions.

Fig. 5-26: Distance between the Ideal and Offset = 25mm

Fig. 5-27: Distance between the Ideal and Offset = 50mm

5.5.2 Results of Experiment

The outputs from both Linear Encoder Sensors were plotted and compared against that of the goniometer for each placement of the linear encoder sensors. For the 25mm offset, the graph in Fig. 5-28 shows a close match between the output from the goniometer and the OLE sensor which is located at the ideal position. A test frequency of 0.3 Hz was recorded and a statistical analysis on error between the two systems was performed. It was found that the RMS error is 2.5808° and the standard deviation is 2.5052° . For the response of the OLE sensor with a 25mm offset, the corresponding graph showed that there was a significant difference in the responses. The average output angle from the offset sensor is 25° when the actual bend angle is around 45° . The RMS

error between the offset sensor and goniometer was found to be 11.8923° with a standard deviation of 7.2300° .

Fig. 5-28: Test Results for Offset Distance = 25mm

For the second experiment with an offset of 50mm, the responses captured are shown in Fig. 5-29. Again, it is seen that there is a close match between the results from the goniometer and the OLE sensor which is located at the ideal position. The RMS error is 3.0480° and the standard deviation is 2.5473° . For the response of the 50mm offset OLE sensor, the corresponding results show that the average output angle is 8° when the actual bend angle is around 45° . The RMS error between the offset sensor and goniometer is found to be 21.8983° with a standard deviation of 13.4446° .

Fig. 5-29: Results for Offset Distance = 50mm

Table 5-5 summarized the responses for both the ideal and offset OLE sensors in term of degree as compared with the goniometer and also the test error statistics as captured for the two sets of experiments data which can be used to establish the relationship between the distance offset and OLE sensors output.

Table 5-5: Responses and Error Statistics for Placement Range

Experiment	Approximate Frequency (Hz)	Bend Angle (Average Estimation)	Root Mean Square (RMS)	Standard Deviation
<u>25mm Offset</u>				
Goniometer		45°	-	-
Ideal	0.3	45°	2.5808°	2.5052°
Offset (25mm)		25°	11.8923°	7.2300°
<u>50mm Offset</u>				
Goniometer		45°	-	-
Ideal	0.3	45°	3.0480°	2.5473°
Offset (50mm)		8°	21.8983°	13.4446°

5.5.3 Discussion

From the experiments, the performance of the Linear Encoder Sensor which is positioned at the best position for both cases can be seen to display similar characteristics to the goniometer. This demonstrates the ability of the OLE sensor to accurately capturing the joint movement patterns over time. The error statistics analysis indicates the error present to be around 2.5808° to 3.0480° . However, it can be observed that a very different set of results were yield for those sensors which were offset of the ideal position. As shown in Fig. 5-30, starting with the 25mm offset, it can be seen that the root mean square of the error increased by four times to 11.8° as compared to the standard response and the spread of the data becomes bigger with a value of 7.2° . For the case where the offset is 50mm, the error root mean square increased to 21.8° which is almost double of that for the 25mm offset.

Fig. 5-30: Error Statistics between Ideal and Offset Case

Plotting the output of the Linear Encoder Sensors in terms of bend response angle (measured in degree) against offset distance, taking the ideal position as 0mm offset, the plot as shown in Fig 5-31 illustrates a decreasing relationship between response angle and offset distance. It can be observed that as the sensor is placed further and further away from the ideal location, the lesser is the amount of stretch/fold-in detected. This is the case which can be observed physically. As the joint bends, there are some regions

around the joint where the skin and muscles hardly exhibit any form of stretch/fold-in which correspond to the experiment results.

Fig. 5-31: OLE Response (Degree) against Offset Distance

Depending on the accuracy required and the amount of error acceptable, the sensor placement is best recommended to be positioned along the ideal specific location with a tolerance of 3mm to 5mm. The placements as recommended are suitable for all types of people of different size and build as the sensors will just need to be placed along the regions where the skin and muscles stretch/fold-in are maximum to be fully effective in capturing the data. Some form of scaling might be needed to improve the placement of the sensors for those petite or massive build so as to increase the sensitivity of the sensors.

By establishing the relationship between the response angle and offset distance, a clear indicator for the amount of error present in the system if the sensor is placed off-center is documented. By determining the amount of offset error for the different joints, a compensation table can then be set up to address those cases where the sensors are not placed along the center line of the skeleton and be used to compensate for the readouts from sensors.

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

6.1 Conclusion

In this project, the study and design of a wearable body motion sensor system begin with an investigation on the different type of motion capture systems and their limitations. Through reviewing all these available Body Motion Tracking Systems, a characteristics comparison table is made in which the expected characteristics of a new sensor system are proposed. Using linear encoder that outputs a pulse as it senses an interruption to its reflective path coupled with the concept of skin stretch and fold-in over the movable joints, the working principle of the Linear Encoder Sensor is formulated.

Through design and modification, the Linear Encoder Sensor has evolved from a few versions in order to achieve optimum size and thickness so as to attain the target of been light, un-obtrusive and wearable. Most of all, by simplifying the design and fabrication method of the sensor, the cost of producing the sensors can be kept at minimum hence making it cheap and affordable.

One important feature of the project is the conversion of linear data to angular information. This is attained by assuming that each of the joints can be modeled using a circular or elliptical shape with a finite radius and that the joint center is a single fixed point instead of multi-movable points. With these two assumptions, a radius about the joint is assumed to be constant as the wire wraps around it. Based on the linear distance traveled by the Optical Encoder and with the joint radius information, the angular data can be obtained via a backwards calculation.

Hence in order for the Linear Encoder Sensor to function properly, the sensors have to be placed at strategic locations on the body in order to maximize on the skin stretch and fold-in information around the movable joints. The modeling and placement of the sensors on the respective joints are examined in details which proposed locations for the sensors to be fixed firmly to.

Tests are conducted to verify the accuracy and repeatability of the Linear Encoder Sensor. Comparisons made against a Powercube^{TM} rotary module shows positive results of the performance of the Linear Encoder Sensor. A linear relationship with correlation coefficient of 0.9996 is obtained between the Powercube^{TM} and Linear Encoder Sensor. By using the gradient of curve derived from the experiment, the radius of the test jig can be accurately determined.

The second experiment is to determine the joint radii that are used for calibration of the Linear Encoder Sensor. Using a standard medical measurement system i.e. goniometer for benchmark, the number of lines from the OLE sensor is matched against the corresponding rotation angle of the respective joint. The results are plotted on graphs and the gradients of the curves are determined using the best fit line through the points. Once the calibration of the Linear Encoder Sensor is done, the radii of various joints determined can be used for converting the output of the OLE sensor into angular information directly.

After verifying the accuracy and repeatability of the OLE sensor, the 1-DOF tests are conducted on the elbow joint by using Biopac^{TM} TSD130A twin-axis goniometer as a reference. It is found that the Root Mean Square Error for low frequency test range of 0.1 to 0.3 Hz is 3.8044° with a standard deviation of 3.8355° and a correlation ratio of 0.9955. For higher frequency test range of 0.5 to 2 Hz, the error RMS is calculated to be 3.4786° and the standard deviation is 3.4629° while the correlation ratio is 0.9901. It is noted that the Linear Encoder Sensor shows a better performance at high frequency excitation than at low frequency. The causes of discrepancies in performance could be due mainly to the design of the sensor as it is prone to mechanical drawbacks such as hysteresis, inertia and friction.

The next test to be conducted is the verification of the Linear Encoder Sensors used on a 2-DOFs joint. The shoulder joint is selected for the test by using Noraxon^{TM} Plug-In Sensor Series, NorAngle Electrogoniometer System for measurement which the Linear Encoder Sensor is compared against. The test is conducted by considering movement along one plane at any one time, this is to ensure that coupling effect is isolated and not confounded in the test results. A total of four sets of experiments are

conducted for the shoulder joint which include a good mix of high and low frequency movement for abduction (motion along Frontal Plane) and flexion (motion along Sagittal Plane). It has been found that the Root Mean Square Error for abduction at low frequency of 0.15 Hz is 3.9038° with a standard deviation of 3.8832° and correlation ratio of 0.9652. For high frequency abduction of 1.09 Hz, the error RMS is registered as 3.0348° with a standard deviation of 3.0333° and correlation ratio of 0.9620. For low frequency flexion of 0.16 Hz along Sagittal Plane, the error RMS recorded is 3.9546° and the calculated standard deviation is 3.4870° with a correlation ratio of 0.9549. For a high frequency excitation of 1.00 Hz where the test subject flexed his upper arm up and down while keeping the whole arm locked and straightens, the error RMS value obtained is 2.8779° , standard deviation of 2.8090° and correlation ratio of 0.9529.

In comparison with the 1-DOF experiment, it can be observed that the Linear Encoder Sensor shows a common trend of better performance at high frequency than at low frequency. In addition, it can be seen that there is a drop in the correlation ratio for the 2-DOFs experiments as compared against the 1-DOF experiments. The discrepancies could be attributed to the placement of the sensors and also the calibration method of both goniometers and OLE sensors which might cause the results to have drifted slightly due to settling in of sensors. Another reason for the discrepancies could be due to the coupling of movement between the Frontal and the Sagittal plane.

While evaluating the Linear Encoder Sensor against an established measurement system such as goniometer, it can be observed that the output from the OLE sensor differ by 2° to 4° from the readings of the goniometer which could be due to the following factors :

1. Inherent mechanical design error such as hysteresis, inertia and friction on the Delrin^{TM} housing and buckling of Nylon-coated wire.
2. Non-ideal linearization for calibration curves
3. Different sections of a motion will exhibit slightly different amount of skin stretch or fold-in

The data points used for the calibration curves are assumed to have a perfect linear relationship between the output from Linear Encoder Sensor and reading from the

goniometer which might not be ideally the case. The amount of skin stretch or fold-in might not be direct proportional to the joint angles as the limbs moved through a motion. Despite all these sources of ambiguity and discrepancies, it is still possible to calibrate the Linear Encoder sensors and achieve acceptable joint measurements with minimal errors. These ill effects can be minimized through careful consideration during the fabrication process and when placing the OLE sensor on the human body. On top of that, during the analysis of the data, care should be exercised in order to detect any errors due to sensor drift or inherent design issue.

The final test to be conducted is to determine the acceptable range of placement for the OLE sensor and also the impact of offsetting the sensor from the ideal specified location. The results show a fairly linear negative trend relationship between the response output and offset distance which display similar characteristics to that of the skin and muscles group that surrounds the joint. For those regions, the skin and muscles hardly exhibit any form of stretch/fold-in which correspond to the experiment results.

6.2 Advantages and Limitations

Each and every measurements has their strengths and weaknesses, the linear encoder is no exception even though it managed to address most of the characteristics of an ideal Motion Tracking System. The advantages and limitations of the Linear Encoder Sensors will be discussed in details in this section.

The advantages of the Linear Encoder Sensors include the following:

1. Simplicity design
4. Ease of fabrication
5. Cheap and Low manufacturing cost
6. Self-contained – No external parts to be mounted in environment
7. Immune to occlusions - No clear line of sight to anything
8. Fairly accurate
9. Reasonably fast

From the experimental results, it is seen that the sensors are able to track the joint motion up to a frequency of 2 Hz and beyond. Since most human motion that occurs in a typical day-to-day operation would usually takes place not beyond than these frequencies⁵, the sensors can be considered to be reasonable responsive and suitable for everyday normal maneuver measurements, but such limitation should be taken into consideration if more accurate measurements are desired.

The limitations of the sensor are:

1. Unable to track rotation motion
2. Prone to Mechanical errors
3. Sensitive and highly dependent on sensor placement

The issue of not being able to track rotation motion is a common issue with most motion capture systems. For visual-based motion capture systems, the rotation motion e.g. for the forearm, will cause the cameras to mistaken the position the markers as they will be swapped out of place due to the rotation motion. Even for the inertia-based motion capture system such as Xsens or GypsyGyro-18, as the sensors are placed on top of the fabrics instead of direct contact with the skin, it is unable to capture correctly the rotation motion of the forearm due to slippage between the fabric and the skin.

For the issue of wearability of the Linear Encoder Sensor, the sensors and wires are highly compact and lightweight, which the weight negligible to the wearer. Once the wireless design is completed, the Linear Encoder Sensor is better than a typical goniometer as it required no additional peripheral or devices for sensing and data processing.

6.3 Future Works

6.3.1 Experiment Setup and Results

The report outlines the development of the Linear Encoder Sensor from the initial investigation to working prototype with supporting evidences that the performance is able to match that of a typical goniometer. However, further improvements can be made to the installation and experimental procedures to minimize the adverse effect of experimental

errors and the experimental results can be further refined by taking precautions and recommendations. Future effort is also needed to further improve the sensor design and response in order to achieve a robust, comfortable and wearable joint monitoring device.

Some of the future works of the project include :

1. Establishing experimental results for 1-DOF and 2-DOFs joints for lower portion of the human body e.g. for knee and hip
2. Design and conduct experiments for higher frequencies > 5 Hz
3. Comparison of performance for the Linear Encoder Sensors against Visual or markers based motion sensor systems e.g. Vicon
4. Development of a Full body motion sensor suit including inertia or position sensors for head, upper and lower torso to determine orientation of body plane
5. Establishing a lookup table and database for all joint radii based on age, race, gender and build of users.

Having experimental results for the elbow (1-DOF joint) and shoulder (2-DOFs joint) on the upper limb, the linear encoder sensors can be place on corresponding 1-DOF and 2-DOFs joints such as knee and hip on the lower limb to obtain results so that comparison in terms of performance and characteristics can be made and observed. In addition, testing setup and procedure for performance verification of the sensors for accuracy and repeatability at higher frequencies of more than 5 Hz should be established even though normal daily human activities will not exceed 2 Hz. The evaluation of performance for the sensors at higher frequencies is desired so as to understand the response latency and determine the sensitivity limit of the sensors.

Having to establish the baseline performance of the linear encoder sensor against a goniometer, more test data will be needed to further evaluate the performance of the linear encoder sensors against other motion capture systems such as Visual based mocap system e.g. Vicon in terms of response accuracy, repeatability and resolution. Besides establishing more tests and experiments, future works also include developing a Full-body Motion Sensor System which includes inertia or position sensors to detect the orientation and position of the head, upper and lower torso. The full-body is split into three main segments as shown in Fig. 6-1 where the rest of the limbs are attached to. By

introducing the orientation and position of the upper and lower torso, the data from the linear encoders that are placed on the respective joints will have a more meaningful representation on the location of the limbs. The addition of the inertia or position sensors acts as a platform for the linear encoder sensors to build on the angular information and to complete the motion capture system as a whole.

The development of a lookup table or database for all joint radii information based on age, race, gender and build of users is to eliminate the need for calibration process for the sensors. The users just need to input some biostatistics data such as age, race, gender, height and weight and a recommended set of joint radii information which will be used to convert the linear encoder output directly into angular information. Test subjects of different age group and body build will be taken as sample to obtain the recommended joint radius via the Linear Encoder Sensor for setup of the lookup table or database. For medical or precision applications, additional information such as limb length may be required.

Fig. 6-1: Full Body Divided into Three Main Segments

6.3.2 Sensor Design

The current dimension of the linear encoder sensor as shown in Fig. 6-2 is 7.80mm in thickness and 20mm in width which is still rather big. Hence besides improving on the performance of the linear encoder, the size of the sensor should be further minimized making it less obtrusive to the users for future works. The desired thickness of the linear encoder should be around 3-4mm thick and 10-12mm in width which is around half the size of the current design.

Fig. 6-2: Current Linear Encoder Design

In order to miniaturize the linear encoder sensor, the main issue that needs to be addressed on will be the smallest size that the circuitry package can be reduced to and also the feasibility to have the circuitry printed on a Flexible Printed Circuit (FPC) as shown in Fig. 6-3 instead of using conventional Printed Circuit Board (PCB) design.

The thinnest thickness achievable by the PCB is around 1mm depending on the number of layers, while the average thickness of the FPC is around 0.25mm. The reduction in thickness and size of the circuitry can bring about the miniaturization of the linear encoder sensor. However, this will lead to an increase in the cost of the linear encoder sensor as the fabrication method for both the FPC and sensor housing has become more complicated.

Source from
<http://www.flexiblecircuit.com/products/flex-printed/index.php>

Fig. 6-3: Flexible Printed Circuit

A feasibility study can be conducted to compare the linear encoder sensor design against the unit cost in order to achieve an optimum design in terms of dimensions and fabrication method. In this way, the unit cost of the sensor can be kept within a competitive range yet still achieving the desired dimensions and aesthetic design in terms of look. The sensors should be non-obstructive to the user and have the ease to be incorporated into a brace or suit for motion capture.

6.4 Summary of Contributions

A wearable body motion sensor design has been presented that uses Optical Linear Encoder placed in Delrin^{TM} housing and attached to a non-stretchable nylon coated wire for sensing purposes by placing it across the joint. Displacement of the Optical Linear Encoder caused by the skin fold-in and stretch as the joint is moved can be related to angular joint position by assuming each joint can be modeled using a circular or elliptical shape which the radius of the circle or ellipse and that a linear relationship exists between the skin fold-in or stretch and the angular position.

After verifying the accuracy and repeatability of the Linear Encoder Sensor, a one-time calibration procedure is performed by the user and the radii for the joints under consideration can be determined. This will enable direct conversion of the output readings of the Optical Linear Encoder from number of lines (in terms of 0.1 millimeters) to angular displacement in degrees. Continuous joint angle measurement can be made during daily activities as the sensors are designed in such a way that it is non-intrusive to the user and will not hinder the movement of the wearer.

After the preliminary experiments involving 1-DOF and 2-DOFs joints on the upper limbs, it is evidenced that the Linear Encoder Sensor is feasible for monitoring joint motion of the elbow and shoulder. The shoulder joint which is a multi-DOFs joint is modeled as a 2-DOFs joint, where each sensor is placed strategically along both Frontal and Sagittal plane to detect joint angle changes along those planes. The design of the OLE sensor therefore produces a simple, cheap and wearable joint monitoring device which is tactically placed across the body joints for effective monitoring.

A study on the effect of positioning the Linear Encoder Sensor away from the ideal proposed location was also conducted to determine the impact of offsetting the sensor from the best position. Based on the data, it is evidenced that the sensor working principle is very similar to skin stretch or fold-in over the joints and that the sensor should be positioned where the amount of skin stretch/fold-in is the maximum.

The works as presented is two and a half years of effort contributed the author and his team of researchers. The report outlines the development of the Linear Encoder Sensor from initial idea to working prototype through initial studies of various commercially available measurement systems, understanding the cons and pros of each system and through experiments to determine the performance of the OLE sensors. Future effort is needed in developing a completely wearable, highly accurate sensor which includes making the sensors wireless and therefore “tether-free” and also self-calibration of the sensors through either a look-up table or by performing a set of simple gestures. A more robust design modification and precise manufacturing techniques would also be required to further reduce the experimental measurement errors.

REFERENCES

- ¹ Madusudanana Sathia Narayanan, “**Analysis of Parallel Manipulator Architectures for Use in Masticatory Studies**”, *State University of New York at Buffalo*.
- ² Huiyu Zhou, Huosheng Hu, “**Human Motion Tracking for rehabilitation – A Survey**”, *Brunel University & University of Essex*.
- ³ V. Lympourides, D.K. Arvind and Martin Parker, “**Fully Wireless, Full Body 3-D Motion Capture for Improvisational Performances**”, *University of Edinburgh*.
- ⁴ Guodong Liu, Jingdan Zhang, Wei Wang, Leonard McMillan, “**A System for Analyzing and Indexing Human-Motion Databases**”, *University of North Carolina at Chapel Hill*.
- ⁵ Peter T. Gibbs and H. Harry Asada, “**Wearable Conductive Fiber Sensors for Multi-Axis Human Joint Angle Measurements**”, *Journal of NeuroEngineering and Rehabilitation*, vol. 2, pp. 7, 2005.
- ⁶ Wijesiriwardana, R, “**Inductive Fiber-Meshed Strain and Displacement Transducers for Respiratory Measuring Systems and Motion Capturing Systems**”, *Sensors Journal, IEEE*, vol. 6, issue 3, pp. 571 – 579, June 2006.
- ⁷ L. A. Danisch, K. Englehart, and A. Trivett, “**Spatially continuous six-degrees-of-freedom position and orientation sensor**,” presented at Fiber Optic and Laser Sensors VII, Boston, MA, USA, 1999.
- ⁸ A. Tognetti, F. Lorussi, R. Bartalesi, S. Quaglini, M. Tesconi, G. Zupone, and D. De Rossi, “**Wearable kinesthetic system for capturing and classifying upper limb gesture in post-stroke rehabilitation**,” *Journal of NeuroEngineering and Rehabilitation*, vol. 2, pp. 8, 2005.
- ⁹ B. S. Davis, “**Using Low-Cost MEMS Accelerometers and Gyroscopes as Strapdown IMUs on Rolling Projectiles**,” *Proc: Position Location and Navigation Symp.*, pp. 594-601, Apr. 1998.
- ¹⁰ A. T. M. Willemssen, J. A. Van Alste, and H. B. K. Boom, “**Real-time Gait Assessment Utilizing a New Way of Accelerometry**,” *J. Biomech.*, vol 23, no. 8 (1990), pp. 859-863.
- ¹¹ H. Luinge, “**Inertial sensing of human movement**,” *Ph.D. Thesis*, Twente University Press, Netherlands, 2002.
- ¹² J. R. W. Morris, “**Accelerometry – a Technique for the Measurement of Human Body Movements**,” *J. Biomech.*, vol. 6, no. 7 (1973), pp. 29-36.
- ¹³ K. Aminian, C. Trevisan, B. Najafi, H. Dejnabadi, C. Frigo, E. Pavan, A. Telonio, F. Cerati, E. C. Marinoni, P. Robort, and P. F. Leyvraz, “**Evaluation of an Ambulatory System for Gait Analysis in Hip Osteoarthritis and After Total Hip Replacement**,” *Gait and Posture*, vol. 20 (2004), pp. 102-107.
- ¹⁴ E. R. Bachmann, I. Duman, U. Usta, R. McGhee, X. Yun, and M. Zyda, “**Orientation tracking for humans and robots using inertial sensors**,” in *Proc. Int. Symp. Computational Intelligence in Robotics and Automation (CIRA)*, 1999, pp. 187-194.
- ¹⁵ E. R. Bachmann, X. Yun, D. McKinney, R. B. McGhee, M. J. Zyda, “**Design and Implementation of MARG Sensors for 3-DOF Orientation Measurement of Rigid Bodies**,” *Proc. of the 2003 IEEE Intl. Conf. on Robotics and Automation (ICRA)*, Taipei, Taiwan, Sept 2003, pp. 14-19.
- ¹⁶ R. Zhu and Z. Y. Zhou, “**A Real-Time Articulated Human Motion Tracking Using Tri-Axis Inertial/Magnetic Sensors Package**,” *IEEE Trans. on Neural Systems and Rehabilitation Engineering*, Vol. 12, No. 2, 2004.

-
- ¹⁷ Kazutaka Mitobe, Takaaki Kaiga, Takashi Yukawa, Takeshi Miura, Hideo Tamamoto, Al Rodgers and Noboru Yoshimura, “**Development of a Motion Capture System for a Hand Using a Magnetic Three Dimensional Position Sensor**”, *Akita University, Warabi-za Co., Akita Keizaihoka University, Polhemus*.
- ¹⁸ Lee Danisch, Kevin Englehart and Andrew Trivett, “**Spatially Continuous Six Degree of Freedom Position and Orientation Sensor**”, *Measurand Inc., University of New Brunswick and Trivett Technologies Inc.*
- ¹⁹ Daniel Vlastic, Rolf Adelsberger, Giovanni Vannucci, John Barnwell, Markus Gross, Wojciech Matusik, Jovan Popovic, “**Practical Motion Capture in Everyday Surroundings**”, *Computer Science and Artificial Intelligence Laboratory, Mitsubishi Electric Research Laboratories, ETH Zurich, Massachusetts Institute of Technology*.
- ²⁰ Joelle Tilmanne, Raphael Sebbe and Thierry Dutoit, “**A Database for Stylistic Human Gait Modeling and Synthesis**”, *Enterface’08 August 4th – August 29th, Orsay-Paris, France*.
- ²¹ Michele Sama, Vincenzo Pacella, Elisabetta Farella, Luca Benini and Bruno Ricco, “**3dIB: A Low-Power, Low-Cost Hand Motion Capture Device**”, *DEIS University of Bologna*.
- ²² Igor Labutov, “**Design and Development of a Low-Cost Wireless Data Glove for Remote Robotic Hand Operation**”, *The City College of The City University of New York*.
- ²³ Stephen McGuire, Joel Richter, Kevin Sloan, “**A Modular Multi-Function Rover and Control System for EVA**”, *The Penn State Mars Society*.
- ²⁴ Joseph E. Muscolino, “**Kinesiology: The Skeletal System and Muscle Function**”, January 10, 2006.
- ²⁵ D.Dan, “**Finite Element Simulation of the dynamic response of human joints**,” *Theoretical Issues in Ergonomics Science*, Vol. 6, No. 3 & 4 (May 2005), pp 343-348.
- ²⁶ Inman VT, Mann RA, “**Biomechanics of Foot and Ankle**”, *In: Du Vreys’ Surgery of the foot*. Ed. 3, CV Mosby, St. Louis, 1973.

APPENDICES

Page

APPENDIX A: PATENT ON FINGER JOINT ANGLE SENSOR.....	129
APPENDIX B: FABRICATION PROCEDURE FOR LINEAR ENCODER SENSOR.....	135
Step 1: Linear Encoder Code Strip Preparation.....	135
Step 2: Sensor Sliding Block Preparation.....	138
Step 3: Adhere Code Strip to Delrin ^{TM} Housing	144
Step 4: Insert Ribbon Cable into Sliding Assembly Connector.....	144
Step 5: Install Sliding Block into Delrin ^{TM} Housing	145
Step 6: Securing of PCB onto Delrin ^{TM} Housing	145
APPENDIX C: TECHNICAL BULLETIN FOR DAITAC #8612FPW	146
APPENDIX D: MECHANICAL ENGINEERING DRAWINGS FOR LINEAR ENCODER SENSOR.	147
APPENDIX E: CALIBRATION OF JOINT RADIUS.....	155
E.1 Wrist.....	155
E.2 Shoulder	158
E.3 Knee	159
E.4 Hip.....	161
E.5 Ankle.....	163
APPENDIX F: MATHLAB ^{TM} PROGRAMMING FOR ERROR STATISTICS.....	165

APPENDIX A: Patent on Finger Joint Angle Sensor

(19)

JAPANESE PATENT OFFICE

PATENT ABSTRACTS OF JAPAN

(11) Publication number: **04143602 A**(43) Date of publication of application: **18.05.1992**(51) Int. Cl. **G01B 7/30**

B25J 15/08, G01B 5/24, G01B 7/30

(21) Application number: **02209457**(22) Date of filing: **07.08.1990**(71) Applicant: **YASKAWA ELECTRIC CORP**(72) Inventor: **ONIKI KIYOSHI**(54) **FINGER JOINT ANGLE SENSOR**

(57) Abstract:

PURPOSE: To make a sensor small in size and light in weight, to improve the fitting property thereof and to enable linear detection of an angle of a joint of a finger by converting the angle of the joint into a change in a peripheral length on the back side of the finger and by obtaining a linear output of the joint angle of the finger.

CONSTITUTION: Displacement transducers 1a (T1), 1b (T2) and 1c (T3) are disposed on the back-side surface of a finger 10 so that they correspond to a middle interphalangeal joint MP, a proximal interphalangeal joint PIP and a distal interphalangeal joint DIP respectively. On the occasion, wires 2 are fixed to the opposite ends in the length direction of the displacement transducers 1a to 1c respectively and connected together, thereby the displacement transducers 1a to 1c are put in a form of being connected longitudinally, and the opposite free ends of the connected wires 2 are fixed on the back-side surface of the finger 10

by double-sided pressure sensitive adhesive tapes 4a and 4b respectively. In order to apply a tension set beforehand on the back of a hand so as to prevent slackening of the wires 2, a spring 3 is inserted, connected and fixed between the displacement transducer 1a and the adhesive double coated tape 4a, for instance.

COPYRIGHT: (C)1992,JPO&Japio

⑬ 日本国特許庁(JP)

⑭ 特許出願

⑯ 公開特許公報(A) 平4-14

⑮ Int. Cl. ⁶	識別記号	庁内整理番号	⑰ 公開 平成4年(1992)
G 01 B 7/30	C	9106-2F	
B 25 J 15/08	J	8611-3F	
G 01 B 5/24		8605-2F	
7/30	1 0 1 A	9106-2F	
			審査請求 未請求 請求項の数 2

⑱ 発明の名称 指関節角度センサ

⑲ 特 願 平2-209457

⑳ 出 願 平2(1990)8月7日

㉑ 発 明 者	鬼 木 清	埼玉県入間市大字上藤沢字下原490番地 株式
		機製作所東京工場内
㉒ 出 願 人	株式会社安川電機	福岡県北九州市八幡西区黒崎城石2番1号
㉓ 代 理 人	弁理士 佐藤 一雄	外3名

明 細 書

1. 発明の名称

指関節角度センサ

2. 特許請求の範囲

1. 指の関節角度を、指背側の周長変化に変換し、

指の関節角度と線形な関係の出力を得るようにした

ことを特徴とする指関節角度センサ。

2. 両端にワイヤを固定した複数個の変位トランスジューサを、ワイヤを介して線状に接続し、

3. 発明の詳細な説明

(産業上の利用分野)

本発明は、例えば遠隔制御ロボット等のクノロジーの一つであるマスタースレーに係る指関節角度センサに関する。

(従来の技術)

従来から利用されている装置として平式ゴニオメータ(指関節角検出機構)〔これを「従来例①」という〕があり、この図を第4図に表し、その第4図(a)は平基本構成図、第4図(b)は指が屈曲して平の原形態の側断面図、第4図(c)は指関節角を角度θ屈曲したときの平行リン

特開平4-1436

置は不変であり、固定端部48は背側表面にピッタリと固定である。

その指10が屈曲前の水平状態が第4図(b)に表されている。

第4図(e)は指10の最先端の関節を角度 θ 屈曲したときの状態が示されており、そのとき固定端部は48'の形態となり、平行リンク41～47は図示のように平行リンクを保ちながら、原状態から角度 θ 屈曲する。

この角度 θ を電気的に変換して検出している。

また、従来例②として米特許第4,542,291号公報がみられる。

〔発明が解決しようとする課題〕

しかしながら、従来例①にあつては、第4図から明かなように、人の手の指の背側表面に平行リンクを搭載する機構をマスターとしてその動きを検出する手段では、かなりのスペースを必要とし、操作性も悪い。

特に、多指ハンドへの適用を考えると、非常に装着性が悪い。

両方のワイヤのそれぞれの自由端を指の背側表面に配置固定するとともに、

変位トランスジューサから指の関節の屈曲した角度に対応する検出電圧を導出する
前項に記載の指関節角度センサである。

〔作 用〕

本発明は、上記の構成であるから、

ワイヤが指の背側表面に配置固定されて、指の回動をこのワイヤの伸縮に変換され、関節角度とワイヤの動きが線形な関係となり、このワイヤの伸縮を超小型変位トランスジューサで検出するようにしてあり、装着性のいい、線形で誤差が少なくなる。

これを解決するものとして従来例②これは光ファイバケーブルを手袋に用いる曲りによる光損失を検出しものであるけれども、検出値に非線形が複雑であるという、これまた違った難がある。

ここにおいて、本発明は、これら各の不具合を払拭した小型軽量で、装着しきも検出値が関節角度と線形な関係の検出センサを提供することを、その目的〔課題を解決するための手段〕

上記目的を達成するために、本発明は指の関節角度を、指背側の関節変位指の関節角度と線形な出力を得ることを特徴とする指関節角度センサであり、かつ

両端にワイヤを固着した複数個の変位トランスジューサを、ワイヤを介して連続した一端部のワイヤの一部にバネを連続しワイヤに予め設定された張力を与え

$D1P = D2$ とする。

ところで本発明は、この指10の各指関節(MP,PIP,DIP)に各変位トランスジューサ1a[T1],1b[T2],1c[T3]を配置するのであるが、この変位トランスジューサ1a,1b,1cにはワイヤ2を長さ方向の両端に固着して、ワイヤ2を連続し、各変位トランスジューサ1cは連続した形態をとり、ワイヤ1の一端は両面粘着テープ4a,4bにより背側表面に固定する。

そして、手の甲側にてワイヤ2が引っ張られ、予め設定された張力(プリテンション)を維持する。

間の中間部位に位置決めすることが望ましい。

第2図は変位トランスジューサ1a, 1b, 1cを例示する形態図であり、第2図(a)は差動トランス、第2図(b)はリニア可変抵抗器を表す。

第2図(a)の差動トランス11は、ソレノイド状の差動トランスコイル11bに一定交流電圧を与え、鉄心11aの両端部にワイヤが固着接続されそれぞれの自由端にワイヤ2へ接続するためのワイヤ接続リング11cを設けている。

各指関節(MP, PIP, DIP)の回転角に対応して、鉄心11aが差動トランスコイル11bの内腔部を左右に移動するから、磁場のリアクタンスが変化し、これを電流変化として検出するようにしてある。

第2図(b)のリニア可変抵抗器12は、図形線状の両端にサポート12fを携え、その上部に可動子12eを固着した棒状の摺動バー12gを挿通する孔が穿孔されており、その下部には一定電圧の直流電源12g(正), 12h(負)を接続し、摺動バー12gの中程に設けた可動子12eには

$$\theta 3 = \Delta \theta 3 / D3 \quad \dots\dots (3式)$$

【ただし、 $\Delta \theta 1, \Delta \theta 2, \Delta \theta 3$ は各変位トランスジューサ1a, 1b, 1cで検出されたワイヤ2の伸縮量、

$D1, D2, D3$ は各指関節(MP, PIP, DIP)の等価関節円直径であり、ここでの等価関節円直径 $D1, D2, D3$ は校正時に指定されるものである。】

の演算がなされて、各指関節(MP, PIP, DIP)の回転角が電圧信号 $\theta 1, \theta 2, \theta 3$ として導出され、ここに検出がなされたことになる。

この検出電圧 $\theta 1, \theta 2, \theta 3$ でスレーブを動作させればよい。

特開平4-143602

電圧検出端子12dならびに摺動抵抗12eと摺動接触するブラシ12bを持ち、可動の両端部のワイヤ接続端子12cにワイヤ接続することで、電圧検出端子12dから(MP, PIP, DIP)の回転角に対応した直流電圧が検出できる。

この各指関節の回転角を演算導出するを、第3図に示す。

それぞれの変位トランスジューサ1aからの検出電圧は、信号処理回路5にお関節(MP, PIP, DIP)の回転角算導出されるが、まず前処理回路51の51a, 変位計2の51b, 変位計3の51cえられ、ここで演算に適した電圧値に変換回路52が携える計算・換算器5252eを介して、

$$\theta 1 = (\Delta \theta 1 - \Delta \theta 2 - \Delta \theta 3) / \dots\dots ($$

$$\theta 2 = (\Delta \theta 2 - \Delta \theta 3) / D2 \quad \dots\dots ($$

ので、関節角度とワイヤの動きが単純な関係となり、線形による検出誤差が極めなるとともに、このワイヤの伸縮を微小ランスジューサで検出するようにしていい接着性のいい、かつコンパクトな理想的角度センサが得られ、例えば宇宙や特殊の産業用ロボットなどの利用で、遠隔制御したマスタスレーブハンド操作技術スレーブハンドの指令の作成手段としての卓越した効果を奏することができる。

4. 図面の簡単な説明

第1図は本発明の一実施例における人

特開平

- 4a, 4b ... 両面粘着テープ
5 ... 信号処理回路
51 ... 前処理回路
52 ... 演算回路
11 ... 差動トランス
12 ... リニア可変抵抗器
MP ... 中手指節関節
PIP ... 近位指節関節
DIP ... 遠位指節関節。

出願人代理人 佐 藤 一 雄

特開平4・

APPENDIX B: Fabrication Procedure for Linear Encoder Sensor

Step 1: Linear Encoder Code Strip Preparation

Materials and Tool Required :   2 x Optical Grade Adhesive
 (as shown in Fig. B-1)   1 x Printed Linear Code Strip
                                                  1 x Reflective Cellophane Paper
                                                  Roller

Fig.B-1: Materials and Tools needed for Code Strip Fabrication

The Optical Grade Adhesive used is Daitac #8612FPW, the Technical Specification are as attached in Appendix C. The Adhesive construction as shown in Fig. B-2 consists of a top and back release film liner which is used to protect the adhesive and have to be removed when used.

Fig. B-2: Construction of Adhesive

The whole flow process for the Code Strip fabrication is as illustrated in Fig B-3.

Fig. B-3: Procedure for Code Strip fabrication

- a) Remove top liner on adhesive and use a roller to roll over the adhesive to prevent air entrapment when adhering adhesive on printed strip.

- b) Remove back liner of adhesive.

- c) Place reflective cellophane paper over adhesive and use a roller to roll over to prevent air entrapment.

- d) Remove top liner on the other adhesive and roll over the adhesive using roller onto the reflective cellophane substrate.

- e) Cut the Code Strip Substrate to appropriate size.

Step 2: Sensor Sliding Block Preparation

Materials and Tool Required :

(as shown in Fig. B-4)

- 4 x Locating Pin (SPSHT-D1-L3-P0.9-B2.0)
- 2 x Locating Pin (SPSNS2-L0.0-P1.0-B2.0-H2.8-T1.0)
- 1 x Sleeve
- 1 x Delrin™ Sliding Block
- 1 x Optical Sensor PCB
- 1 x Nylon Coated Wire
- Wire Cutter
- Long Nose Plier

The Locating Pins were purchased from Misumi and the part numbers are as specified. The whole flow process for the Sensor Sliding Block fabrication is as illustrated in Fig B-5.

Fig. B-4: Materials and Tools needed for Sensor Sliding Block Fabrication

Fig. B-5: Procedure for Sensor Sliding Block fabrication

- a) Use long nose plier to insert locating pins (x 4) into the Delrin™ Sliding Block. Ensure that the flat ends of the locating pins are inserted Sliding Block with the rounded end facing outward.

- b) Use long nose plier to screw the locating pins (x 2) to secure the Optical Sensor PCB onto the Delrin™ Sliding Block.

- c) Use long nose plier to insert sleeve into the Sliding Block Assembly.

- d) Insert Nylon Coated Wire through the Sleeve.

- e) Use long nose plier to crimp the sleeve and wire so as to secure the wire onto the Sliding Block.

Step 3: Adhere Code Strip to Delrin™ Housing

Remove the back liner of the adhesive which is on the Linear Encoder Code Strip Assembly and adhere it onto the Delrin™ Housing.

Step 4: Insert Ribbon Cable into Sliding Assembly Connector

Pry open the Connector catch which is on the Optical Sensor PCB for the insertion of the ribbon cable. The ribbon cable is for connection to the electrical hardware which will be installed on top of the Delrin™ housing.

Step 5: Install Sliding Block into Delrin™ Housing

Slide the Sensor Sliding Block into the Delrin™ Housing and this complete the mechanical hardware of the Linear Encoder Sensor.

Step 6: Securing of PCB onto Delrin™ Housing

Link the Ribbon Cable up to the Connector catch which is located on one of the 2-layer Printed Circuit Board (PCB) and secure the PCBs to the Delrin™ Housing as shown and the whole Linear Encoder Sensor is complete.

APPENDIX C: Technical Bulletin for Daitac #8612FPW

技術資料

TECHNICAL BULLETIN

PN-017 EN

DAINIPPON INK & CHEMICALS, INCORPORATED. TACK TECHNICAL REPORT

DAINIPPON INK & CHEMICALS, INC.
Pressure-Sensitive Adhesive Materials Div.

DAITAC Good heat resistant & transparency tape

DAITAC #8612FPW

CONSTRUCTION

Tape
thickness
0.06mm

CHARACTERISTIC

- Excellent heat resistant 150°C.
- Good discoloration, reflow ability, smooth.
- Good for die cutting as the different thickness release liner.

APPLICATION

- For surface film of LCD module (touch panel).
- For lens of LCD module, reflection sheet, glass.

PROPERTY

		Unit	# 8612FPW
Peel strength at 180° angle	SUS	N/20mm	8.8
	EPOXY RESIN		8.3
	PET		9.8
	GLASS		8.8
	EPOXY RESIN		8.3
Holding power	150°C :Q 5kg	hr	> 24
Ball tack		No.	4

STANDARD SIZE 1200 mm in max width / 50 m in length

DAINIPPON INK AND CHEMICALS, INC. Pressure-Sensitive Adhesive Materials Div.

DIC Building, 16-2, Sotokanda 2-chome, Chiyoda-ku, Tokyo, Japan Phone 03-5256-3221

The information contained herein are reference based on careful tests and accurate to best knowledge, but not guaranteed specification. All recipes and processes should be modified, if necessary to conform with particular application.

2000. 11

APPENDIX D: Mechanical Engineering Drawings for Linear Encoder Sensor

- 154 -

APPENDIX E: Calibration of Joint Radius

E.1 Wrist

The ROM for the wrist can be divided into four sections, namely, Flexion, Hyperextension, Abduction and Adduction. Tests were performed to evaluate the joint radii for each motion. Care was taken to ensure that the effect of coupling was minimal so as not to confound the reading from one plane to the other.

Flexion

The wrist moved from a straighten neutral position of 0° and downward along the Frontal plane to an angle of 25° before returning back to neutral position. The wrist was positioned alongside a vertical flat structure to restrict the motion along the Sagittal plane so as to ensure minimal coupling effect due to movement. Fig. E-1 shows a similar pattern in the readings as for the Elbow. By assuming a linear relationship and running a straight line through the points, the R-squared value of the line is found to be 0.9947 which indicates a close correlation between the two systems. The equation of the line is given as $y = 3.7855x$.

Fig. E-1: Number of Lines against Degree (Wrist – Flexion)

Hyperextension

Using the same procedure previously for the wrist flexion motion, the wrist was hyper-extended by moving the back of the hand upward to an angle of 20° before returning back to neutral position. Fig. E-2 indicates that the equation of the line is given by $y = 3.7867x$; the R-squared value is 0.9779 which show a fairly accurate result can be obtained using the Linear Encoder.

Fig. E-2: Number of Lines against Degree (Wrist – Hyperextension)

Abduction

By placing the wrist on a horizontal flat surface, the wrist was moved slowly inwards (moving the thumb side of the hand toward the lateral side of the forearm) to an angle of 15° before returning back to normal position. Fig. E-3 indicates that the R-squared value of the line is given by 0.9817 which show very close correlation between the Linear Encoder and goniometer with the equation of the line given as $y = 3.7857x$.

Adduction

With the wrist still place on the horizontal flat surface, the wrist was moved slowly outwards (moving the little finger side of the hand toward the medial side of the forearm) to an angle of 25° before moving back to neutral position. Fig. E-4 indicates

that the R-squared value of the line is given by 0.963 which correspond to a reasonable correlation between the two measurement systems and the equation of the line is given by $y = 3.7855x$.

Fig. E-3: Number of Lines against Degree (Wrist – Abduction)

Fig. E-4: Number of Lines against Degree (Wrist – Adduction)

E.2 Shoulder

The ROM for the shoulder can be divided into three sections, namely, Flexion, Hyperextension and Abduction. Similar precautions used for the evaluation of 2-DOF joints were taken when tests were conducted to assess the joint radii for each motion as so to avoid motion from one plane affecting the results of the other plane.

Even though the goniometer is not ideal for the shoulder joint, it was still used as a benchmark system for the Linear Encoder Sensor. The results from the experiments will serve as an initial work and stepping stone for further investigation. Care should be taken when analyzing the data.

Flexion

The arm (upper and forearm) was kept straight and slowly move upward from a relaxed position with the hand pointing downward in the initial position, then moving to an angle 50° toward the front before returning back to the initial neutral position. As shown in Fig. E-5, the correlation coefficient which is related to the R-squared value is found to be 0.9882 and the line equation is $y = 5.1982x$.

Fig. E-5: Number of Lines against Degree (Shoulder – Flexion)

Hyperextension

Keeping the arm still straightens; the test subject was asked to slowly move the arm backward to an angle of 25° before returning back to the initial neutral position. The arm was restricted to move in a single plane to avoid introducing unwanted variable that will affect the readout from the sensor. The correlation coefficient of the line as show in Fig. E-6 is 0.958 while the line equation is $y = 5.1927x$.

Fig. E-6: Number of Lines against Degree (Shoulder – Hyperextension)

Abduction

The test subject was placed against a vertical wall while he slowly lifted his arm up by his side to an angle of 50° before returning back to the initial neutral position. The arm was maintained in a straighten manner and side swaying motion were kept at a minimal as a precautionary measure. Fig. E-7 indicates that the equation of the line is $y = 5.1855x$ while the correlation coefficient is 0.9873.

E.3 Knee

For the testing of knee, the test subject was allowed to sit on a chair while the experiment was conducted. The thigh was supported on another chair while the lower leg was moved from a straighten position of 0° to an approximate angle of 50° before straightening back. Fig. E-8 shows that the best fit line has an R-squared value of 0.9683 and equation of the line is given as $y = 4.8527x$.

Fig. E-7: Number of Lines against Degree (Shoulder – Abduction)

Fig. E-8: Number of Lines against Degree (Knee)

E.4 Hip

The hip joint is much like the shoulder joint, the ROM for the hip can be divided into three sections, namely, Flexion, Hyperextension and Abduction. For this set of experiment, the test subject is required to stand up instead of sitting down while the test is conducted. Similar precautions used for the evaluation of 2-DOF joints were taken when tests were conducted to assess the joint radii.

Flexion

The test subject was asked to lift his thigh forward while keeping the back straightened by leaning his back against a flat wall, the knee was locked to keep the lower limb straightened. The thigh was lifted to an angle of 30° before returning back to the original neutral position. The correlation coefficient of the line as shown in the Fig. E-9 indicates that a linear relationship with 0.999 accuracy between the goniometer and Linear Encoder Sensor system. The equation of the line was found to be $y = 8.0198x$ which can be used for the calculation of the joint radius.

Fig. E-9: Number of Lines against Degree (Hip - Flexion)

Hyperextension

For hyperextension of the thigh, the test subject was turned around and the back was kept straighten by having the stomach and pelvis flat to a flat wall. The thigh was slowly hyper-extended to the back to an angle of 15° before resuming back to normal position. From Fig. E-10, the correlation coefficient of the line as shown is found to be 0.9987 and the line equation is $y = 8.0571x$.

Fig. E-10: Number of Lines against Degree (Hip - Hyperextension)

Abduction

The test subject was turned around to his back and support was given to maintain a straight and upright posture before lifting the thigh slowly to the sideway to an angle of 25° before restoring back to a normal standing posture. Fig. E-11 indicates the correlation coefficient of the line to be 0.9864 with the equation $y = 8.0218x$.

Fig. E-11: Number of Lines against Degree (Hip - Abduction)

E.5 Ankle

The ankle is treated as a single plane movement joint and the ROM can be divided into namely, Plantarflexion and Dorsiflexion. For this set of experiment, the test subject is allowed to sit on a chair while the test is conducted.

Plantarflexion

With the lower leg supported, the top of the foot was moved slowly away from the lower leg starting from a neutral position to 25° for plantarflexion. The motion of the ankle was kept within a single plane by placing the ankle close to a flat vertical structure to prevent rotation motion being confounded. The results as shown in Fig. E-12 give a correlation coefficient of 0.9831 with the line equation $y = 4.7491x$.

Fig. E-12: Number of Lines against Degree (Ankle - Plantarflexion)

Dorsiflexion

For Dorsiflexion motion, the top of the foot was moved slowly toward the lower leg starting from a neutral position to 20°. Fig. E-13 shows the results which indicate that the correlation coefficient of the line is 0.9906 and the line equation $y = 4.7467x$.

Fig. E-13: Number of Lines against Degree (Ankle - Dorsiflexion)

APPENDIX F: Matlab™ Programming for Error Statistics

The original data from the Noraxon™ Plug-In Sensor Series NorAngle Electrogoniometer System and the output from Linear Encoder Sensor which was captured using C Programming are all in text format. The data were imported and saved as spreadsheet using Microsoft Excel programme before used.

After opening the Matlab™ programme, the data from the NorAngle Electrogoniometer and OLE sensor were imported and the following programme was run for analysis. The variables as underlined in Red are changeable depending on the imported data.

t= <u>Gon1 (1:37201, 1)</u>	; Import time variable
Gon2= <u>Gon1 (1:37201, 5)</u>	; Import Goniometer variable
time1= <u>10. 6: ((35. 4-10. 6)/37200):35. 4</u>	; Create time variable for OLE
OLE2= <u>OLE1 (1:934, 4)</u>	; Import OLE variable
time= <u>10. 55: ((35. 438-10. 55)/933):35. 438</u>	; Create time for spline function
y3 = interp1(t, Gon2, time1, 'spline')	; Convert data to spline function
y4 = interp1(time, OLE2, time1, 'spline')	; Convert data to spline function
err=y3-y4	; Calculate error between data
sqrt(mean(err.^2))	; Calculate RMS
std(err)	; Calculate Standard Deviation
corrcoef(y3, y4)	; Calculate Correlation Ratio