Simulation-Based Functional Evaluation Of Anthropomorphic Artificial Hands

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Abstract

This thesis proposes an outline for a framework for an evaluation method that takes as an input a model of an artificial hand, which claims to be anthropomorphic, and produces as output the set of tasks that the hand can perform. The framework is based on studying the literature on the anatomy and functionalities of the human hand and methods of implementing these functionalities in artificial systems. The thesis also presents a partial implementation of the framework which focuses on tasks of gesturing and grasping using anthropomorphic postures. This thesis focuses on the evaluation of the intrinsic hardware of robot hands from technical and functional perspectives, including kinematics of the mechanical structure, geometry of the contact surface, and functional force conditions for successful grasps. This thesis does not consider topics related to control or elements of aesthetics of the design of robot hands.

The thesis reviews the literature on the anatomy, motion and sensory capabilities, and functionalities of the human hand to define a reference to evaluate artificial hands. It distinguishes between the hand's construction and functionalities and presents a discussion of anthropomorphism that reflects this distinction. It reviews key theory related to artificial hands and notable solutions and existing methods of evaluating artificial hands.

The thesis outlines the evaluation framework by defining *the action manifold of the anthropomorphic hand*, defined as the set of all tasks that a hypothetical ideal *anthropomorphic* hand should be able to do, and analysing the manifold tasks to determine the hand capabilities involved in the tasks and how to simulate them. A syntax is defined to describe hand tasks and *anthropomorphic* postures. The *action manifold* is defined to be used as a *functional* reference to evaluate artificial hands' performance.

A method to evaluate anthropomorphic postures using Fuzzy logic and a method to evaluate anthropomorphic grasping abilities are proposed and applied on models of the human hand and the InMoov robot hand. The results show the methods' ability to detect successful postures and grasps. Future work towards a full implementation of the framework is suggested.

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List of Acronyms

BSL	British Sign Language
CMC	Carpometacarpal joint
CNS	Central Nervous System
CoM	Centre of Mass
DH	Denavit–Hartenberg
DIP	Distal Interphalangeal joint
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DoF	Degree(s) of Freedom
EMG	Electromyography
EP	Exploratory Procedures
FIS	Fuzzy Inference System
FSR	Force Sensing Resistor
GP-LVM	Gaussian Process Latent Variable Models
HF	Hard-Finger
HIT	Harbin Institute of Technology
IH	Integrated Hand (arm-hand integrated system)
IMC	Intermetacarpal joint
IP	Interphalangeal joint
IT	Intrinsic Tactile sensor
JPL	Jet Propulsion Laboratory
LARM	Laboratory of Robotics and Mechatronics
MCP	Metacarpophalangeal joint
MH	Modular Hand
MIT	Massachusetts Institute of Technology

NAIST	Nara Institute of Science and Technology
PCA	Principle Component Analysis
PIP	Proximal Interphalangeal joint
PwoF	Point-contact-without-Friction
RC	Radio-Controlled
RoM	Range of Motion
SAH	SCHUNK Anthropomorphic Hand
SDH	SCHUNK Dexterous Hand
SF	Soft-Finger

Publications

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- M. Sayed, J. C. Diaz Garcia, and L. Alboul. Texture Recognition Using Force Sensitive Resistors. In *17th Towards Autonomous Robotic Systems (TAROS-16)*, Sheffield, UK, June 28-30, 2016, Proceedings, vol. 9716 of Lecture Notes in Artificial Intelligence, pp. 288-294, Springer, 2016.

1

Introduction

This thesis studies anthropomorphic artificial hands and methods to evaluate their performance. This chapter outlines the research and its approach. This chapter distinguishes two views on human and artificial hands: the physical and the functional view, and describes how they shape our research. Finally, it describes some terminology used throughout the thesis.

Introduction

This thesis proposes an outline for a framework for an evaluation algorithm that takes as an input a model of an artificial hand, which claims to be anthropomorphic, and produces as output the set of tasks that the hand can perform and the set of tasks which it cannot perform. The thesis also presents a partial implementation of the framework which focuses on tasks of gesturing and grasping using anthropomorphic postures.

The importance of the human hand in our daily life is undeniable. We continuously use our hand to interact with our surroundings and other individuals. Therefore it is only natural that the field of robotics would aim to replicate its capabilities.

However, the progress in developing capable artificial hands has been slow compared to the development of devices to replicate other human capabilities such as vision. Several factors contribute to this phenomenon, including the variety of tasks the hand can do, construction complexity, and low public demand for artificial hands compared to, for example, the demand for cameras.

One particular factor; the variety of hand tasks, leads to many devices being designed for particular tasks to minimise development costs. This functional compromise means that the device may not necessarily perform all the tasks that a user desires.

In order to address this limitation, this thesis studies the construction and uses of human and artificial hands and methods to evaluate and optimise their performance in order to develop a tool that allows developers and users to determine if an artificial hand can perform the tasks they desire.

1.1 Motivation

This thesis focuses on evaluating the gesturing and grasping performance of anthropomorphic artificial hands. Evaluation can be used during a design process to compare different iterations, or to determine whether an optimisation process resulted in performance enhancement. It also allows users to determine if a specific artificial hand will be suitable for an intended application prior to buying the device and without having to write device-specific code to test each functionality.

Anthropomorphism is required for many applications of artificial hands, Melchiorri and Kaneko (2008) describe four cases where anthropomorphism is desired in an artificial hand:

- If the device will operate in human-oriented environment, where tasks can be carried out by both humans and robots
- If the device will be teleoperated by a human operator, and it is required that the artificial hand reproduce the same movements as the human counterpart
- If human-likeness is specifically required, as in entertainment applications
- For prosthetic limbs

Also, studies investigating the phenomena known as "the uncanny valley" indicate that anthropomorphism is a major factor affecting the "acceptance" of robots by the humans.

1.2 The approach

Given the focus on anthropomorphism, the thesis begins by studying the human hand. It then reviews existing artificial hands and solutions. By combining the knowledge of the two areas, the thesis proposes a concept of the "ideal" anthropomorphic hand, which reflects how the human hand would be like if it was constructed using existing artificial components. This concept is used in this thesis as a reference for evaluating artificial hands.

Next, the thesis reviews existing methods of evaluating hands in an effort to identify their strengths and shortcomings. It then proposes a simulation-based approach to evaluating hands. The approach relies on modelling hands and tasks then attempting to execute the tasks using the modelled hand. Task modelling is based on studies reported in the literature involving human subjects as well as the mathematical analysis of different aspects such as kinematics and forces of the tasks. To verify the approach, a computer simulation environment is implemented and used to perform the proposed simulations on a model of the human hand as well as a model of an artificial hand.

Views on the hand

In the analysis of the available knowledge on human and artificial hands, this thesis makes a distinction between two views: the *physical* view and the *functional* view. The physical view refers to looking at the *construction* of the hand, whether its physical existence - human anatomy and artificial hardware - and the *capabilities* that arise from this construction as described by models and specifications such as kinematic models. The functional view looks at the types of tasks performed by the hand, how they are performed, and applications of artificial hands.

1.3 Structure of the thesis

Chapter 2 conducts a review of the anatomy, capabilities and functionalities of the human hand. It looks into the hand's construction, surface properties and sensory capabilities. It also reviews functionalities of active sensing, prehension, and non-prehensile skills and describe task characteristics such as motion and contact with external objects.

Chapter 3 reviews the efforts made towards replicating the capabilities and functionalities of the human hand in artificial systems. It reviews the components, capabilities and applications of artificial hands. It also reviews the concepts of endo and exoskeletal structure and the mathematics involved in various tasks, especially tasks of grasping and manipulation.

Chapter 4 reviews existing methods of evaluating human and artificial hands and propose an approach that combines the strengths of existing methods and provides solutions for their shortcomings. Since the proposed approach is simulation based, some of the existing computer simulation tools are reviewed to determine which existing tools can be used for our evaluation method and what new tools are required.

Chapter 5 analyses the tasks of the human hand in order to identify how they can be incorporated into our evaluation method. It proposes a task description format that allows modelling of various hand tasks and can be used with our evaluation method. The format is also useful for robot programming.

Chapter 6 implements a simulation environment and perform the proposed simulations of the evaluation method on hand models. The thesis is concluded in Chapter 7 by discussing the overall results of this thesis's approach and proposing future work.

1.4 Scope of research

The field of robot hand development is very wide and can include many sub-fields, this thesis focuses on the evaluation of the intrinsic hardware of robot hands from technical and functional perspectives. This includes different properties of the mechanical structure, physical properties of the contact surface and sensory capabilities of the hand. Despite the importance of control aspects to the operation of the hand, this thesis does not consider any topics related to control such as control strategies, coding, and capabilities of electronic processing hardware. It also does not consider elements of aesthetics or how to evaluate the social acceptance of the design of a robot hand.

In the study of the human hand, this thesis does not aim to conduct a comprehensive study of the performance of the human hand itself, nor does this thesis aim to further investigate the hand's biomechanical performance or sensory capabilities. As this thesis only aims to establish a reference for evaluating robot hands, there are parts where it ignores the actual properties of the hand (such as the dynamic properties) and instead focuses on the outcomes of these factors.

Functionalities and capabilities

The term "functionality" is used in the literature with different meanings. It is common to use the term to describe the motion capabilities of the joints regardless of the actual geometry of the biological joint (Grebenstein, 2012). However, this concept relates the low-level functionality of the components of the hand rather than the high-level functionality of the whole hand system. In this research, it is more suitable to refer to a low-level functionality of a hand component as a "capability" of the hand. And use the term "functionality" to refer to the high-level functionality of the entire hand system.

To avoid confusion, this thesis makes a clear distinction between the two terms as used in this research. This distinction applies only to the use of the word in the original contribution of this thesis, and not to references to the literature.

Capability: a certain characteristic of the hand, such as motion or sensory, that exists in the hand - and may take part in tasks - regardless of how it is being used by humans and regardless of the biological mechanisms of its workings. For example; a joint's motion or skin sensitivity are capabilities of the hand.

Functionality: the purposive utilisation of hand capabilities by the human to achieve a certain task. For example; grasping or gesturing are functionalities of the hand.

Anthropomorphism

This thesis focuses on artificial hands that would be installed on a humanoid robot, or used as a prosthetics, and look like the human hand. Therefore, the concept of anthropomorphism is fundamental to this thesis. However, this thesis also acknowledges that anthropomorphism is "neither necessary nor sufficient" to perform the functionalities of the hand (Biagiotti et al., 2004). In fact, the designs of robotic hands which are based on mathematical analysis of grasping functionalities [CITATIONS] suggest that anthropomorphism is not the optimal solution to achieve successful and efficient grasping. With this in mind, it is important to note that the framework proposed in this thesis is to be used only when anthropomorphism is explicitly required. Section 3.4.1 presents a detailed discussion on the concept of anthropomorphism.

1.5 Problem Statement

This thesis investigates possible ways to evaluate the ability of an anthropomorphic artificial hand to perform the functionalities that can be performed using the human hand. The approach of viewing the hand from the physical and functional views suggests that the capabilities of an artificial hand can be directly determined from its physical constructions, while the functionalities involve the utilisation of these capabilities in one way or another to achieve a task. Therefore, the problem statement of this research can be formulated as:

- Given the construction and capabilities of an anthropomorphic artificial hand, can its ability to perform the functionalities of its human counterpart be quantified?

1.6 Contributions

This thesis makes the following contributions:

- A new approach to categorising tasks of hand functionalities based on task aim
- A through analysis of several tasks representing different hand functionalities which shows the hand capabilities involved in each task and how to simulate the task
- An outline of an evaluation framework to evaluate functional performance of artificial hands
- A syntax to describe hand tasks
- A syntax to describe anthropomorphic hand postures
- A method to evaluate anthropomorphism of hand postures using Fuzzy logic
- A method to evaluate anthropomorphic grasping abilities of artificial hands

1.7 Medical terminology

This thesis uses medical terms that may be uncommon in robotics literature.

1.7.1 Anatomical coordinate system

Anatomy literature uses a special coordinate system to describe the location of body parts and the direction of motion. This section reviews the elements of this coordinate system that are relevant to this research.

Standard anatomical position The coordinate system is defined with respect to a static reference position called "standard anatomical position". The hand reference position is; palm facing forward and all fingers extended. Usually with the fingers evenly spread out.

Anatomical planes Anatomy literature utilises three virtual planes dividing a body part (Figure 1.1).

- **Sagittal plane** divides the hand into *radial* and *ulnar* sides (see radioulnar axis below)
- **Frontal plane** divides the hand into front and back, the front side is the palm
- **Transverse plane** divides the hand into "far" and "near" parts

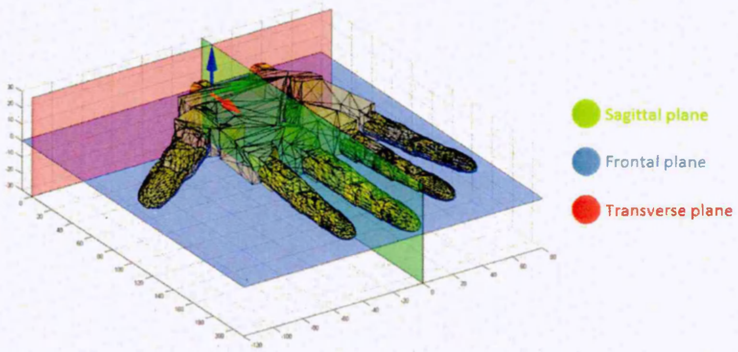


Figure 1.1: Anatomical planes of the human hand

Anatomical axes In the human hand, the three main axes are

- **Proximal/distal** describes body parts and motion direction to be *proximal*, i.e near or towards the arm, or *distal*, i.e far or heading away from the arm. The main proximal/distal axis runs from the base of the hand at the wrist towards the tip of the middle finger. Each finger's local axis similarly runs from the finger's base towards the fingertip, i.e the longitudinal axis. This axis is perpendicular to the transverse plane.
- **Radioulnar** axis describes side direction. As it is confusing to describe "right" and "left" directions in the hand, directions are described with respect to forearm bones (radius and ulna - Figure 2.2). This is an exclusive arm-hand axis that is not used elsewhere in the human body. For example, the thumb is always on the radial side of the hand (Figure 2.1). This axis is perpendicular to the sagittal plane.
- **Dorsopalmar** axis describes the "front" and "back" directions. The palmar direction is out of the palm, the dorsal direction is out of the back of the hand. This is also an exclusive arm-hand axis. This axis is perpendicular to the frontal plane.

Equivalent robotics coordinates It is common to define the coordinates of a robotic system using the right-hand rule. In a robot hand, the x-axis is usually defined along the centre line running from the base at the wrist towards the tip of the middle finger. The z-axis is usually defined perpendicular to the palm, and the y-axis defined according to the right-hand rule. The origin of the coordinate frame is defined at the "hand base" or wrist. Table 1.1 describes the technical coordinate system used throughout this thesis and the equivalent axes in the anatomical coordinates.

Anatomical axis	Robotics axis	Robotics axis positive direction
Proximal/distal	X-axis	Distal direction
Radioulnar	Y-axis	Defined according to right hand rule
Dorsopalmar	Z-axis	Palmar direction

Table 1.1: Anatomical coordinates and the technical robotics equivalent

1.7.2 Anatomical terms of motion

Similar to the coordinate terminology, anatomy literature uses a defined set of terms to describe motion. From a technical point of view, these motions can be categorised into two types: basic motion and compound motion. Figure 1.2 shows different motions of the human hand and their anatomic terminology.

Basic motion is a rotation motion that occurs in one joint about one axis. It is usually easy to associate such motion with one of the three axes defined above.

- **Flexion and extension** occurs about the moving segment's radioulnar axis. Flexion describes moving a segment in the palmar direction, i.e closing a finger. Extension is the opposite motion, i.e opening the finger. *Full extension* refers to extending the fingers so that the hand is as flat as possible. Extending the fingers beyond this position is called *hyperextension*.
- **Abduction and adduction** are sideway movements occurring about the dorsopalmar axis. Due to the thumb's high range of motion, some literature describes two types of thumb motion as "abduction". Radial abduction occurs about the hand's dorsopalmar axis, while palmar abduction occurs about the hand's radioulnar axis. Notably, neither of these motions occur about the thumb's local dorsopalmar axis or radioulnar axis (see Section 2.2).
- **Rotation (pronation and supination)** Rotation, also called pronation and supination at the forearm, describes the rotation of a part about its proximal/distal axis.

Compound motion involves multiple joints, an example of this motion is thumb opposition.

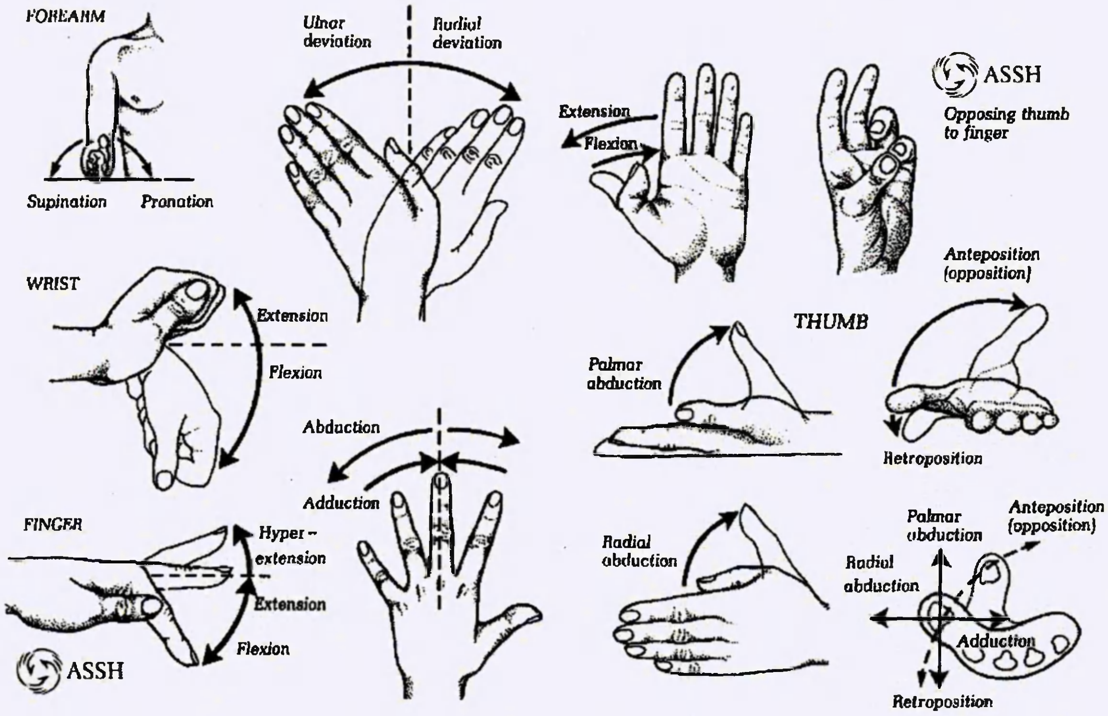


Figure 1.2: Terminology of different hand motions (American Society for Surgery of the Hand)

Equivalent robotics terminology In robotics, a different terminology is used to describe rotation about a given axis. Table 1.2 describes the equivalent robotics terminology taking into account the axes equivalence described in Table 1.1. Note that direction of positive rotation depends on the local axis orientation, there are no direct equivalents that are correct for all cases.

Anatomical terminology	Robotics terminology
Flexion and extension	Pitch (or tilt)
Abduction and adduction	Yaw (or pan)
Rotation	Roll

Table 1.2: Anatomical types of motion and the mathematical equivalent used in robotics

2

The Human Hand

IT IS ESSENTIAL TO UNDERSTAND WHAT IS THE HUMAN HAND before pronouncing any judgement of the state of an artificial hand's proximity to the human hand. This chapter reviews the anatomy, models, motion and sensory capabilities, and functionalities of the human hand.

Introduction

This chapter reviews the literature studying the human hand. It begins by looking at the hand's physical construction and anatomy. Then the motion and sensory capabilities are reviewed. Finally, the chapter looks at the ways humans use their hands.

This chapter aims to develop a comprehensive understanding of the hand by looking at it from different views. This is done to establish a reference that explains what a hand is and what is it used for, which is used throughout this thesis to discuss and evaluate artificial hands.

Section 2.1 reviews the hand's anatomy, including surface anatomy, musculoskeletal structure, sensory aspects in muscles and joints, and the skin. Section 2.2 reviews the hand's motion capabilities and sensitivity. Section 2.3 reviews functionalities of the hand.

In this chapter, any reference to the *hand* without a prefix refers to the human hand. Due to the fact that the human hand is an integrated part of the arm-hand system, and not an independent modular system, parts of the arm are occasionally mentioned.

2.1 Anatomy of the human hand

The hand consists of a palm and five digits: a thumb and four fingers (Figure 2.1). The index and middle fingers are referred to as the *upper* fingers, the ring and small fingers are referred to as the *lower* fingers. The hand has palmar and dorsal surfaces and radial and ulnar borders.

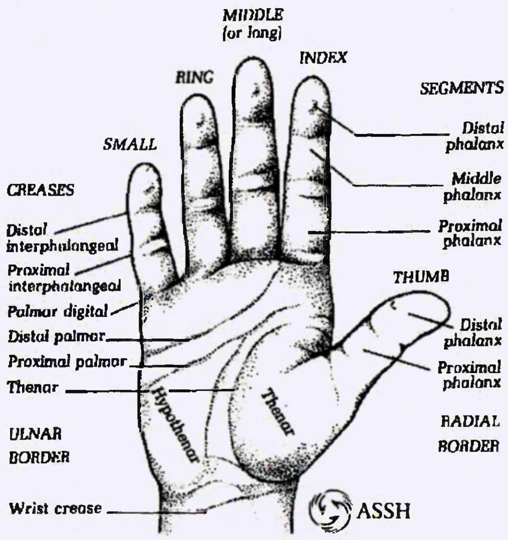


Figure 2.1: Surface anatomy of the hand (American Society for Surgery of the Hand)

2.1.1 Bones and joints

The hand contains eight carpal bones in the wrist, five metacarpal bones in the palm, two phalangeal bones in the thumb and three in each finger (Figure 2.2). The forearm contains two bones called radius and ulna. The bones are held together by ligaments, thus forming the joints.

The Carpometacarpal (CMC) joints connect the metacarpals to the carpal bones. Some sources describe the Intermetacarpal (IMC) joints between the metacarpals. The Metacarpophalangeal (MCP) joints connect the proximal phalanges to the metacarpals. All fingers have two interphalangeal joints: the Proximal Interphalangeal (PIP) and the Distal Interphalangeal (DIP). The thumb has one Interphalangeal (IP) joint.

Sensory elements in joints Senses are mediated through nerves usually ending at the point of information acquisition in sensory *receptors*. *Proprioception* is the ability to estimate relative positions of body parts and muscle effort using only internal information, i.e not vision, from the kinesthetic sense which involves receptors in the joints, muscles, and tendons.

Several types of receptors exist in and around the joints; however, these receptors' provide limited information. Studies on patients with artificial MCP joints indicate that they are redundant and are not the Central Nervous System (CNS) first choice to obtain proprioception information.

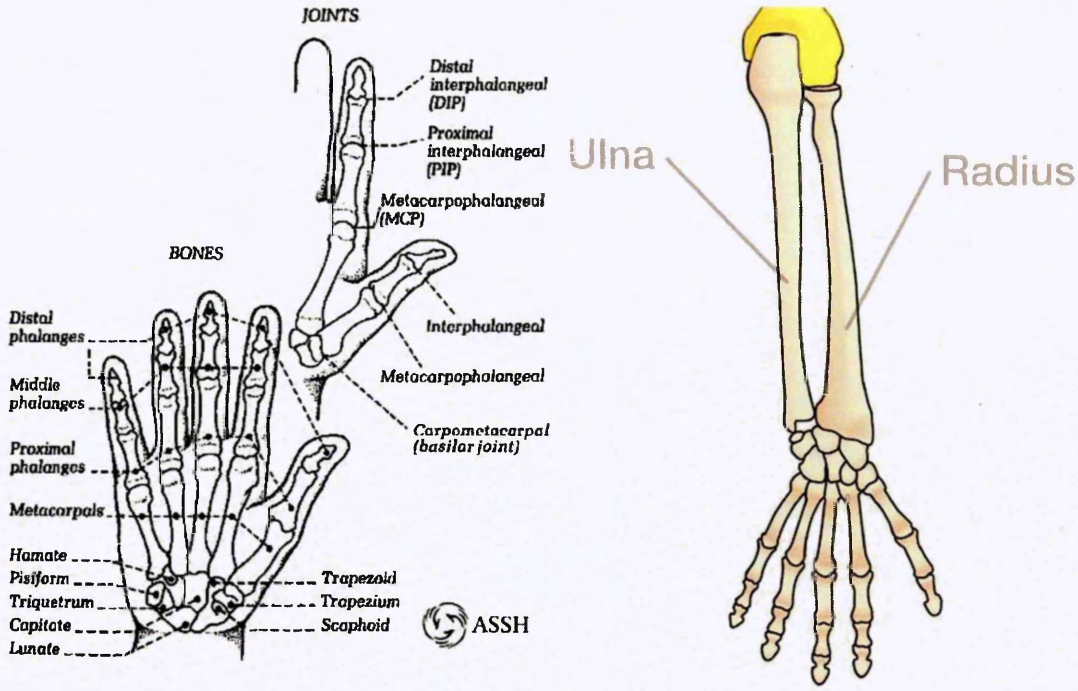


Figure 2.2: Hand and forearm bones and joints (American Society for Surgery of the Hand)

2.1.2 Muscles and tendons

The muscles controlling the hand are categorised based on location into two groups: *intrinsic* and *extrinsic*. Intrinsic muscles are located in the palm, they are involved in the motion of the thumb, small finger, and fingers' abduction. Extrinsic muscles are located in the forearm and control most of the flexion and extension motion. Muscle forces are transmitted to the joints through a complex network of sheathed tendons.

Sensory elements in muscles Receptors that respond to mechanical strain are known as *mechanoreceptors*. Muscles contain three types of mechanoreceptors. The primary and secondary spindle receptors lie in parallel with muscle fibres and signal velocity and direction of motion and static muscle length. A third type, called the Golgi tendon organs, is attached in series between tendons and muscle fibres and are very sensitive to force.

2.1.3 Skin

The *glabrous skin* on the palmar surface of the hand is thicker and more sensitive than the *hairy skin* on the dorsal side. It folds during flexion along the *creases* (Figure 2.1). Some of these creases mark the locations of the joints. The distance from the MCP joint to the *palmar digital* crease is called the *web height* (Alexander and Viktor, 2010). There is no *web height* for the thumb as the crease lies directly above the thumb's MCP joint. Fingertips consist of soft tissue which extends beyond the end of the bone segment. The *tip length* is the distance from the end of the bone to the end of the digit (Alexander and Viktor, 2010).

Sensory elements in the skin There are four types of mechanoreceptors in the glabrous skin. The number and spatial distributing of receptors vary across the hand, with higher density at fingertips followed by phalanges then the palm, this results in improved acuity at denser locations. Two types of free nerve endings in the skin, known as *cold thermoreceptors* and *warm thermoreceptors*, respond to cold and warm thermal stimulation respectively.

2.2 Human hand motion and sensory capabilities

2.2.1 Kinematics of the human hand motion

Many kinematic models have been proposed in the literature for the hand. Stillfried and Smagt (2009) used MRI imaging to analyse the hand motion and proposed a model with 21Degree(s) of Freedom (DoF) for the digits and 3DoF for the palm. The model positions three 1DoF IMC joints between bases of the metacarpals and joins the thumb with a 2DoF orthogonal but non-intersecting joint. A low-polygon skeletal 3D model is implemented in the OpenSim environment and released open source. Gustus et al. (2012) used MRI imaging and optical motion capture to analyse the hand's motion. They describe the same model as Stillfried and Smagt (2009).

Weghe et al. (2004) and Deshpande et al. (2013) proposed a 25DoF model with 4DoF per finger, 5DoF thumb with non-orthogonal and non-intersecting axes, 2DoF at the wrist, and additional 2DoFs for each of the bases of the lower fingers. MCP abduction-adduction axes are inclined by 60° relative to the metacarpal for "more accurate" approximation of the biological motion. DEXMART (2009) researchers used optical motion capture devices and MRI data to construct a kinematic model of the hand. They analysed joints motion and interdependencies and proposed a 25DoF model that includes a 5DoF thumb. Pitarch (2007) analysed the hand articulations and concluded with a 25DoF model. The thumb has 5DoF with orthogonal and intersecting axes, 4DoF for each of the upper fingers, and 6DoF for each of the lower fingers to account for palm motion.

Joints' motion and types CMC joints are capable of flexion and radial-ulnar abduction. Except for the thumb, these joints have a very limited motion that increases from the second to the fifth digit. MCP joints are capable of flexion and abduction. IMC and interphalangeal joints are capable of flexion only. The thumb has higher mobility in the CMC joint than the fingers. Despite the occurrence of axial rotation during thumb opposition, this motion is "constrained" and "not considered a true third degree of freedom" (Jones and Lederman, 2006).

Anatomically, the joints are categorised into three types: *hinge*, *condyloid* and *saddle* joints. *Hinge* joints are 1DoF joints, *condyloid*, and *saddle* joints are 2DoF joints. Interphalangeal and IMC joints are *hinge* joints. CMC and MCP joints are *condyloid* joints, except the thumb's CMC which is a *saddle* joint. The technical equivalent of *hinge* joints are *revolute* joints. The closest technical equivalent of *condylid* and *saddle* joints are *universal* joints.

Anthropometrics Many developers of human hand kinematic models rely on anthropometric data to define link dimensions, joints' Range of Motion (RoM), and axes locations (Deshpande et al. (2013), Pitarch (2007), Kumar (2012)). However, there is much disagreement in the literature considering these values (Deshpande et al., 2013). Hands of different human individuals varies considerably in bone dimensions, proportions, joint position, and RoM with negligible effect on manual abilities (Grebenstein et al. (2010), Alexander and Viktor (2010)).

Special kinematic features of the human hand motion

Interdependencies Hand joints move in patterns due to the complex tendon network. This reduces the number of postures the hand can assume. There are two types of dependency relations: interdigital dependencies between joints of different fingers and intradigital dependencies between joints of the same finger. Santello et al. (1998) studied these relations and proposed a *synergy* model for the human hand based on Principle Component Analysis of grasping postures.

- **MCP axes relations** MCP joint is capable of yaw and pitch. However, yaw range of motion is inversely proportional to pitch angle and turns into axial rotation (roll) at 90° pitch.
- **PIP-DIP coupling** It is common in the literature to correlate the motion of the last two joints of the fingers. This correlation is considered to have a PIP:DIP ratio of 3:2.

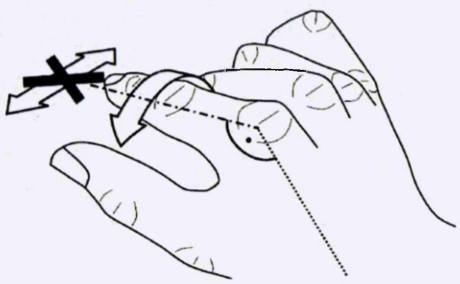


Figure 2.3: MCP yaw motion converts to roll motion at 90° pitch (Grebenstein, 2012)

Palm arching The higher range of motion in the CMC joints of the lower fingers allows the palm to curve over grasped objects with cylindrical or spherical surface, possibly enhancing grasp security (Figure 2.5). The motion of the CMC joints producing this effect is correlated by an approximate ratio of 2:1 for the little to ring finger (DEXMART, 2009).

Inclination of joints Flexion of the fingers' interphalangeal joints results in a slight change in fingertip orientation. At full flexion of PIP joints, the longitudinal axes of all fingers intersect at one point (Figure 2.4). This means that the joint axes are not orthogonal to the sagittal plane. The interphalangeal joints of the ring and small fingers are inclined by about 5°-9° and 10°-14° respectively (Grebenstein, 2012). The change in orientation may serve to enhance the opposition of the fingers to the thumb.

Figure 2.4: Effect of inclination of interphalangeal joints (Grebenstein, 2012)

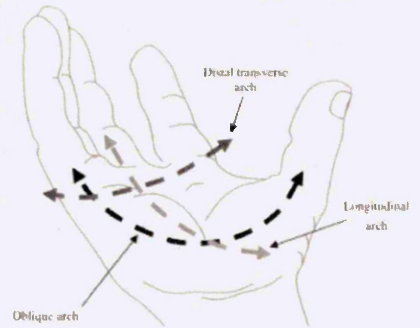


Figure 2.5: arching or cupping of the palm (Sangole and Levin, 2016)

Thumb opposition The high mobility of the thumb's CMC joint allows it to move out of the palm's frontal plane and change orientation to face the fingers. This feature is very important as it provides - along with the fingers - the opposing forces necessary for a successful grasp. Many models have been proposed to explain this motion feature.

The thumb is usually modelled as 4, 5, or 6DoF serial link with three joints. Most literature agrees on 5DoF models. Few models suggest the presence of a constrained sixth DoF: a coupled axial rotation in the proximal phalanx that allows the thumb to change orientation. Recent models explain the opposition feature using non-intersecting and non-orthogonal axes for the CMC and MCP joints (Figure 2.6). These models claim to explain the thumb's motion more accurately than models with intersecting and orthogonal axes.

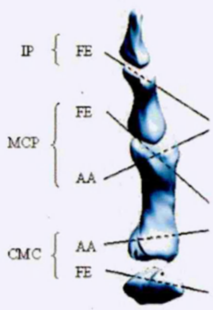


Figure 2.6: Anatomical axes of the human thumb (Chang and Matsuoka, 2006)

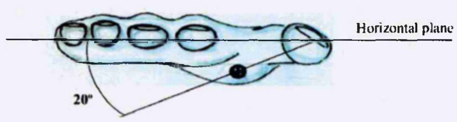


Figure 2.7: Natural twist angle of the human thumb (Saliba and Axiak, 2007)

Thumb twist Unlike the fingers, the thumb's pads at full extension are not parallel to the palm; instead, they are rotated about the thumb axis by about 60°-70° towards the palm (Figure 2.7).

2.2.2 Motion of the skin

The flexibility of the skin, its compliance, and the way it is attached to the bones cause the skin to deform during motion. Therefore, a kinematic model on its own cannot explain the hand's surface geometry at all configurations.

van Nierop et al. (2007) describe a kinematic model covered with a "variable mesh" skin model (Figure 2.8). They divide the surface into different regions with different characteristics. Some areas are modelled using static faces, while areas near the joints and creases are modelled using dynamic faces. The middle finger is modelled in five segments, which are replicated and scaled to create models for other fingers. The palm is modelled in fifteen segments. The model in total comprises forty segments made of 1,000 static faces and 250 dynamic faces.

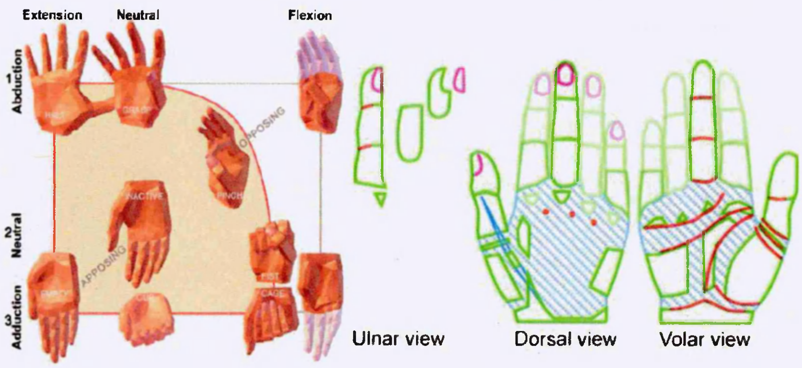


Figure 2.8: Natural Human Hand Model (van Nierop et al., 2007)

2.2.3 Sensory capabilities of the skin

The cutaneous system comprises multiple submodalities. The two submodalities of interest to this thesis are *tactile* and *temperature*. *Tactile* submodality relies on mechanoreceptors and involves perception of *pressure, vibration* and *texture*. *Temperature* submodality uses thermoreceptors to detect warmth and coldness over a certain range.

There are two types of stimulation events described in the literature: stimulating a passive stationary hand with a stationary object, i.e "passive static", and moving an object while in contact with the stationary hand, i.e "passive movement" (Jones and Lederman, 2006). The importance of this distinction relates to the resulting perception and the involved receptors.

Studies make a distinction between two types of parameters: sensitivity and resolution. Sensitivity pertains to intensity related measures, including minimum and maximum detectable values and the smallest detectable variation, i.e *intensity resolution*. Resolution (without the "intensity" prefix) relates to "spatial and temporal resolving capacities".

Tactile submodality Skin sensitivity to pressure varies between body sites. Humans are able to "scale" normal and tangential forces of around 0.15-0.7 N magnitude, though sensitivity to tangential forces is lower than that to normal forces (Jones and Lederman, 2006). The spatial resolution of the skin is "about 2-4 mm on the fingertips and 10-11 mm on the palm". As for temporal resolution, the minimum duration between two successive inputs to be perceived as separate inputs is around 5 ms. There are many perceptual experiences described in the literature that relates to tactile submodality:

- **Touch**: detection of contact with an external stimulus.
- **Pressure**: estimation of the magnitude of pressure/force of the stimulus.
- **Shape**: estimating the local 3D geometry features of the contact area.
- **Vibration**: estimating the vibration frequency of stimulus.
- **Weight**: a limited estimation of weight can be obtained through the perception of *pressure*.

Other perceptions are experienced with a *passive movement* stimulus, such as *motion speed, motion direction,* and *surface texture.*

Temperature submodality Studies indicate that "young adults" were able to detect a change in temperature from a baseline of 33°C "as small as 0.16°C and 0.12°C" on the fingertips and 0.11°C and 0.07°C on the palm for warmth and cold respectively. The hand is more sensitive to cold than to warmth. Temperature sensing exhibits "spatial summation", sensed values are not resolved with high resolution but "summed" across the area of contact.

2.3 Functionalities of the human hand

Sensorimotor continuum Jones and Lederman (2006) describe a framework which "conceptualise hand functions along a continuum that ranges from activities that are essentially sensory in nature to those that have a strong motor component". The "continuum" describes four categories each representing a "comprehensive set of *primary manual functions*" (Figure 2.9).

Tactile sensing refers to sensations resulting from contact between a stationary hand and a stationary or moving surface. These are "not typically used to learn about the properties of external objects" and are more consistent with our definition of *hand capabilities* covered in Section 2.2. Therefore this thesis follows a shorter continuum which excludes *tactile sensing*.

Active haptic sensing refers to tasks where the hand is moved "voluntarily over a surface or object" to learn about its properties. These senses rely on "receptors embedded in skin, muscles, tendons, and joints", hence the use of the term "haptic". *Prehension* category refers to "activities in which the hand reaches to grasp an object". *Non-prehensile skilled movements* is "diverse class of activities" ranging from gesturing to "depressing the keys on a keyboard".

Task characteristics Dollar (2014) describes a taxonomy for categorising "manipulation behaviour" (Figure 2.10). The "hand-centric, motion-centric taxonomy" categorises tasks based on presence of five characteristics. The paper also describes classifying "complex tasks" such as "time-separated sequences", "simultaneous bi-manual tasks", and "simultaneous within-hand

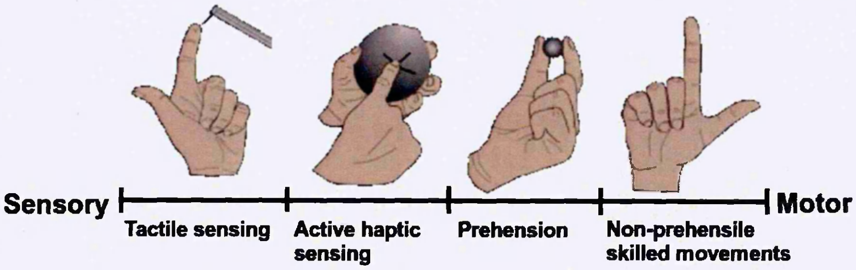


Figure 2.9: Sensorimotor continuum of hand functions (Jones and Lederman, 2006)

tasks". Bi-manual tasks are described "by the individual tasks being performed by each hand". Time-separated sequences and tasks performed simultaneously within-hand, such as "thumb-typing on smartphone", are described as "as the sum of the discrete sub-components". Finally, the paper proposes to describe "dexterous within-hand manipulation" according to "rotation and translation" of the object "along hand coordinate axes" (Figure 2.13).

2.3.1 Active haptic sensing

Klatzky et al. (1985) studied the movements humans performed with their hands during manual exploration of objects and found that the movements were "*purposive* and *systematic*" even as "subjects were unaware of what they did with their hands". They describe six Exploratory Procedures (EP) and the object's property associated with each:

- *Lateral Motion*: repetitive lateral rubbing motion, associated with *texture*.
- *Pressure*: applying normal force to surface or torque about an axis, associated with *hardness*.
- *Static Contact*: stationary contact on surface without molding, associated with *temperature*.
- *Unsupported Holding*: lifting an object of any supporting structure, associated with *weight*.
- *Enclosure*: molding the palm or fingers around an object, associated with *volume*.
- *Contour Following*: dynamic edge following (usually using fingertips), associated with *shape*.

They also describe two other EPs associated with object's "function" and moving parts. These EPs are not considered in the rest of their studies or other literature on the subject.

- *Function Test*: examining the object's "*function*".
- *Part Motion Test*: examining the object's *moving parts*.

Klatzky and Lederman (1993) defined four parameters to differentiate between EPs:

- *Movement*: hand movement during information acquisition period: static or dynamic.
- *Direction of applied force*: normal or tangential to the object's surface.
- *Region* of object explored during performing the EP: edges and/or surface.
- *Workspace constraint*: or position relative to the workspace: "whether there are workspace. constraints - i.e support-surface requirements - on the position of end-effector and object".

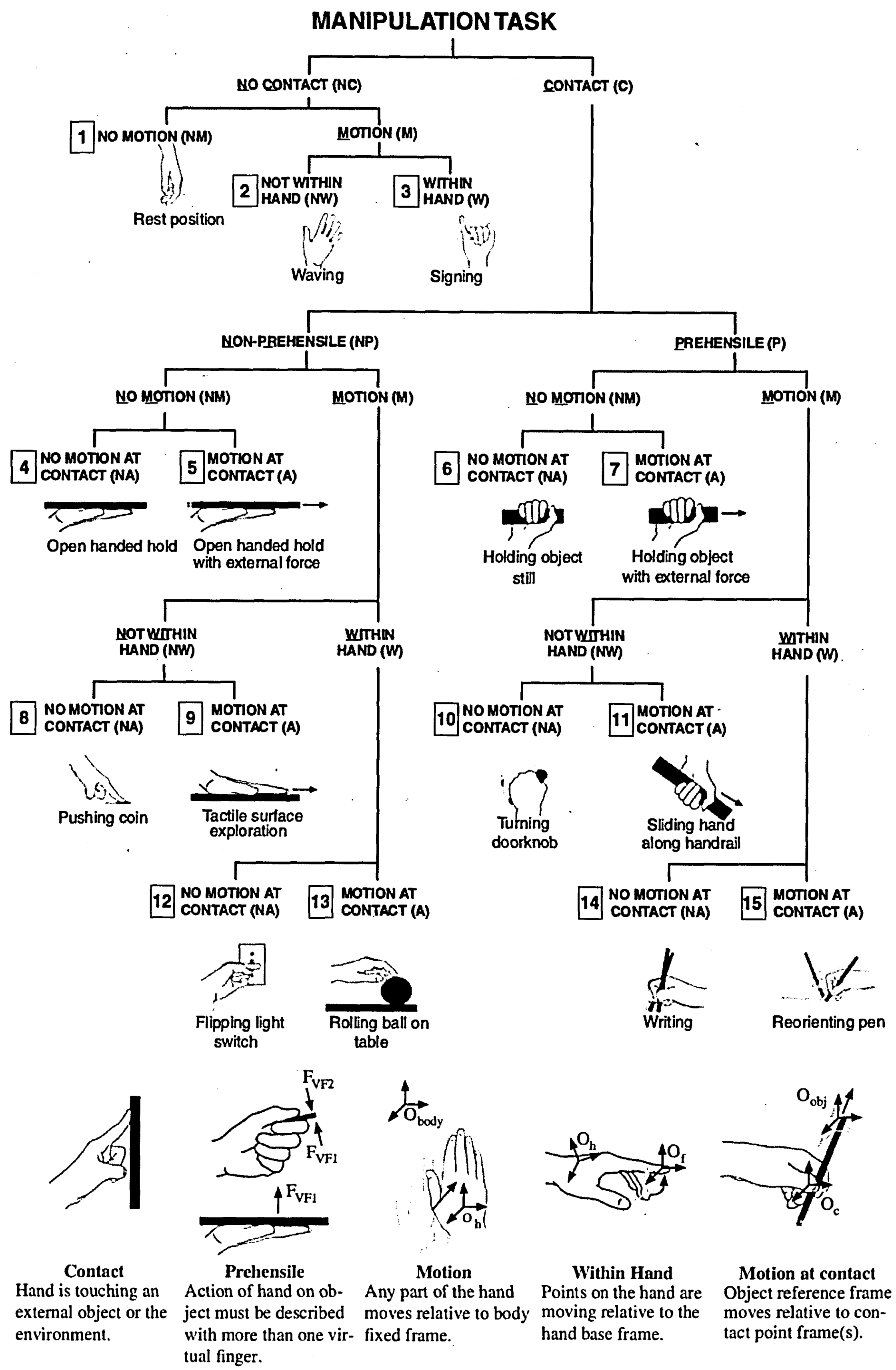


Figure 2.10: Task characteristics and manipulation taxonomy (Dollar, 2014)

They reflect on "the extent to which EPs may be performed in tandem or very close in time". The values of the above parameters (Table 2.1) affect the compatibility between EPs:

> Because the parameters pertain not only to aspects of movement but also to the geometry of the object and the object/workspace relation, our definition of compatibility extends beyond the notion of simple motoric compatibility.

Salience of haptic and visual information Klatzky et al. (1985) found out that subjects would "attend more to material than geometric properties" when performing haptic exploration only, while they would "emphasise the geometric properties more strongly" when vision was used. This indicates that "vision would be considerably more efficient than any haptic EP at extracting geometry but less effective at extracting material properties". The opposite is also true. If subjects are asked to sort objects by touch they would sort based on material properties, if they were asked to sort based on material properties they would use haptic exploration methods.

	Movement	Direction	Region	Workspace Constraint
Lateral Motion	dynamic	tangential	surface	no
Pressure	dynamic	normal	surface	no
Static Contact	static	normal	surface	no
Unsupported Holding	static	normal	surface-and-edges	yes
Enclosure	static	normal	surface-and-edges	no
Contour Following	dynamic	tangential	edges	no

Table 2.1: Values of EPs on the four distinction parameters (Klatzky and Lederman, 1993)

2.3.2 Prehension

This category includes the motion of reaching to grasp an object, the act of actually grasping it, and subsequent manipulation of the object. Studies on the reach-to-grasp tasks are performed independently from studies on grasping and manipulation and emphasises the kinematics component of the hand and arm motion (Jones and Lederman, 2006). Studies on grasping and manipulation

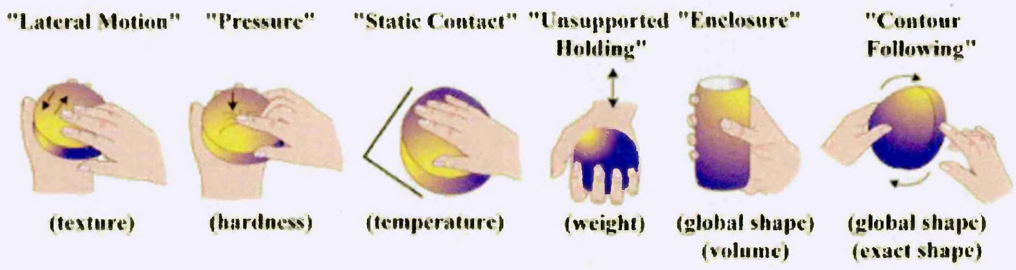


Figure 2.11: Main EPs and their associated properties (Lederman and Klatzky, 1987)

"generally start at the point of contact with the object" and investigates kinematics, dynamics, and sensory aspects of the task.

Reaching to grasp movement Reaching to grasp movement aims to position the hand in a pose that allows the hand to grasp the object. It mainly involves a global positioning motion carried out by the arm. However, during this motion, the hand also assumes an internal posture the brings the contact surfaces of the palm and digits quickly as close as possible to the surface of the object to be grasped. This precedes closing the digits until a successful grasp is obtained.

Grasping and grasp taxonomies Cutkosky (1989) studied human "grasp choices" and categorised them in a hierarchy of seventeen grasps grouped into two grasp types: *power* and *precision* grasps. *Power* grasps refer to holding an object firmly, normally with the palm and all digits wrapped around the object. Precision grasps refer to holding an object using the tips of - all or a subset of - the digits.

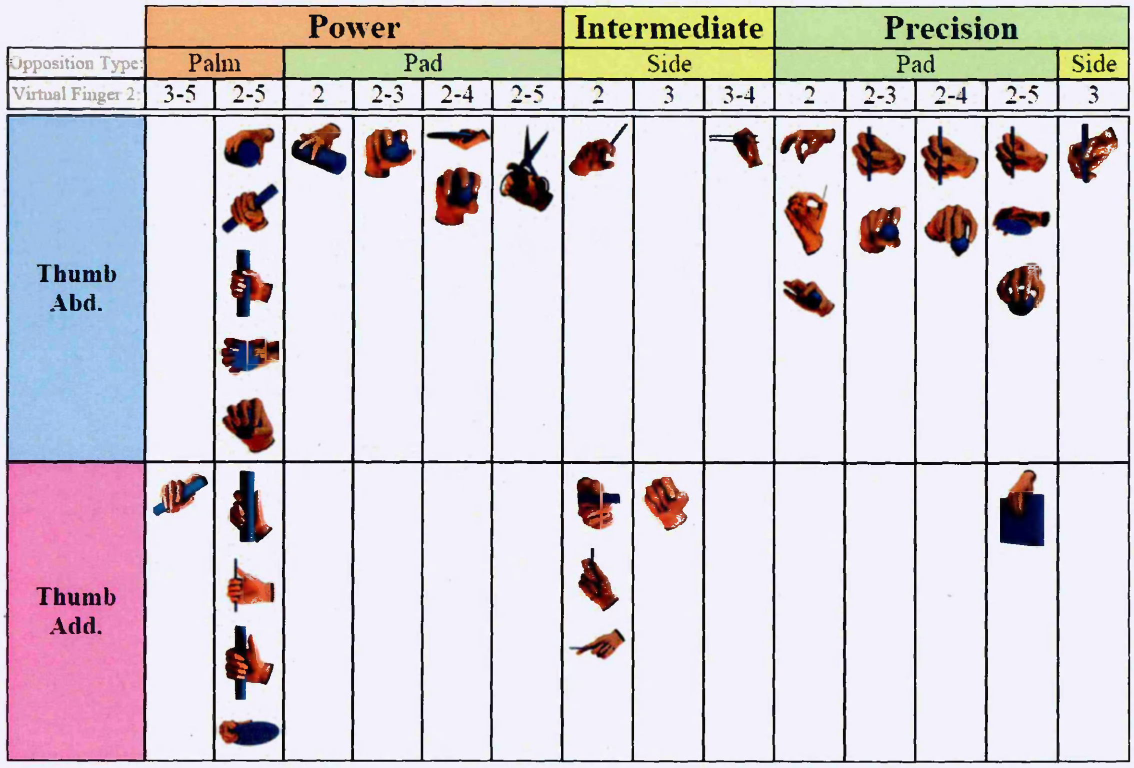


Figure 2.12: Feix grasp taxonomy (Feix et al., 2009)

Feix et al. (2009) surveyed the literature and identified thirty three different grasps (Figure 2.12). They define a grasp as a "very static hand posture with which an object can be held securely with one hand". Therefore they ruled out "intrinsic movement", "bimanual tasks" and two "gravity dependent" grasps found in the literature: the "Flat Hand Grasp" and the "Hook Grasp".

They categories grasps according to grasp type, thumb position, "opposition type", and "virtual fingers" (see Section 3.1). With respect to grasp type, Feix et al. (2009) point out that some grasps are described in the literature as "intermediate". These characteristics are not sufficient to uniquely identify each grasp, but can be used to categorise them into seventeen types.

Within-hand manipulation Dexterous within-hand manipulation refers to moving the digits so as to change the object's pose with respect to the hand's frame while maintaining a precision grasp. Dollar (2014) proposed to categorise within-hand manipulation according to "rotation and translation" of the object "along hand coordinate axes" (Figure 2.13).

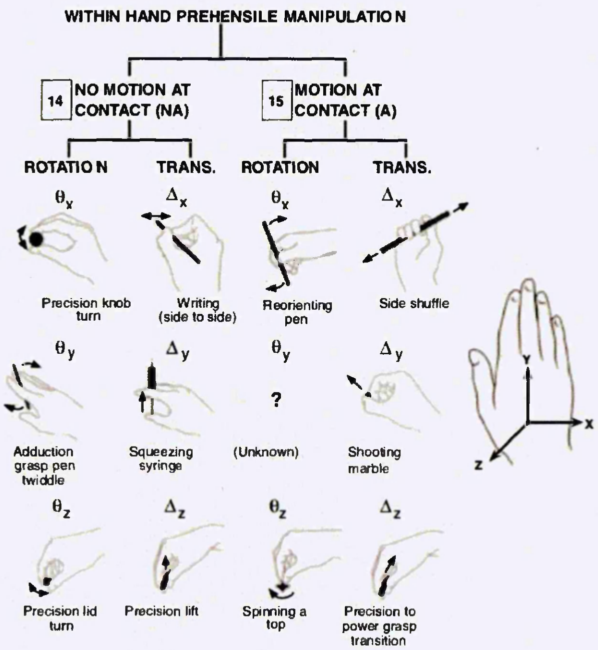


Figure 2.13: Dexterous within-hand manipulation classification (Dollar, 2014)

2.3.3 Non-prehensile skilled movements

The last category on the sensorimotor continuum covers a wide range of hand uses that does not involve prehension. Jones and Lederman (2006) describe four sub-categories (Table 2.2).

Gestures	Pointing and aiming	Keyboard skills	Bimanual music skills
Gesticulations	Pointing	Typing	Playing stringed instruments
Quotable gestures	Aiming	Piano playing	Playing wind instruments
Sign language		Finger tapping	Playing percussion instruments
Finger spelling			

Table 2.2: Non-prehensile skilled movements (Jones and Lederman, 2006)

Gestures and signs Gestures are hand movements that symbolise a meaning. Gestures can be made as part of normal speech which are known as *gesticulation,* used when speech is restricted due to temporary conditions which are called *quotable gestures*, or used as a substitute for speech such as in *sign languages*. Gestures of sign languages are called *signs*. Common words, such as "please" and "apple", are normally represented by a single sign. Uncommon words can be "spelt" using *finger spelling*. Signs have three "components": *location*, *hand shape*, and *movement*. All components occur simultaneously and a change in any component, depending on the language used, could result in a different meaning. The language used in the United Kingdom in known as British Sign Language (BSL). BSL signs are further discussed in Chapter 5.

Pointing and aiming Pointing refers to moving the arm and hand toward the direction of a target defined via visual or proprioceptive feedback. The task may involve contact with the target. Aiming movements differ from pointing in that contact always occurs and - as a result - the task involves higher spatial accuracy constraints. Aiming tasks may also be performed using a grasped tool, i.e a stylus, thou the task itself remains non-prehensile as the tool is not the target of the task.

Keyboard skills The third group contains a set of tasks that involve using the fingers to press keys. *Typing* relates to the task of typing on a keyboard, i.e a computer keyboard or a typewriter. The task requires the ability to press a sequence of keys in a specific order with any force above the force necessary to activate the key. The speed of performing the task is not crucial to the success of the task. *Piano playing* is similar to typing but with higher constraints. In this task, the timing and force of pressing the keys have a significant effect on the task performance. *Finger tapping* relates to tasks where timing is important but the force is not, such as *operating a Morse code transmitter*.

Bimanual music skills The fourth group encompasses tasks of playing stringed, wind, or percussion musical instruments. These tasks require a long time of "explicit training to develop expertise". These tasks "has received very little attention" and are mainly studied from the perspective of tissue damage and effect on the motor and sensory cortices in the brain.

2.4 Discussion

The human hand has a complex *construction* that gives rise to motion and sensory *capabilities*. These *capabilities* are used to perform many *functionalities* in a specific way. This suggests that an *anthropomorphic* artificial hand should approximate the human hand *physically* and *functionally*.

However, given the human hand complexity, it is important to determine the aspects that contribute to *anthropomorphism* and how far an artificial hand needs to approximate the human hand. This requires knowing how the *construction*, *capabilities*, and *functionalities* of the human hand can be artificially replicated. Therefore, Chapter 3 reviews artificial hands and formulates a definition of *anthropomorphism* to be used in this thesis.

2.4.1 Observations on hand functionalities

With regard to *functionalities,* there are two main observations on the task goals and components that are important to the analysis of the hand *functionalities* in Chapter 5 which determines how to simulate the tasks and quantify a hand's performance.

Observations on types of task goals

Tasks of *active sensing functionalities* aim to acquire information about objects. This will be called hereinafter *information exchange* between the hand and object.

Grasping tasks aim is to hold the object in a static position with respect to the hand, although the hand itself may move, i.e *static grasping*. *Within-hand manipulation* aims to hold the object and move it with respect to the hand while holding it.

Tasks of *keyboard* and *bimanual music skills* aim to "manipulate" a target object without holding it. This will be called *force exchange*. "*Gesturing*" and "*pointing and aiming*" tasks do not necessarily involve contact with an object, consequently they do not involve any *force* or *information exchange*. The main aim of *gesturing* tasks is to communicate with other humans. This will be called *visual expression* since the communicated meaning is propagated through the "shape" of the gesture and is meant to be received visually.

Observations on the roles of arm, hand, and controller in manual tasks

Functionalities described in the literature involve tasks that are carried out using the entire arm-hand system. This, and the fact that this thesis focuses on the hand and excludes the arm, introduce the necessity to distinguish between the role of the hand and that of the arm.

Therefore, this thesis uses three terms to make this distinction: *manual task*, *hand task* and *arm task*. *Manual task* refers to a task that is carried out by the arm-hand system. *Hand task* refers to the component of the task that is carried out by the hand itself, i.e digits of the hand. *Arm task* refers to the component of the task that is carried out by the arm. For example, in sign language where a sign contains posture, location, and motion components, the *hand task* includes posture and within-hand motion, while the *arm task* includes location and global motion.

A *controller* is necessary to use the arm-hand system to carry out functionalities. This seemingly contradicts with the thesis focus on the hand and excluding control. To resolve this conflict, a *border* is defined in Chapter 3 between the hand and the *controller* as an interface that conceptualises the hand as an input/output device. It is also necessary to define the hand capabilities required by the *controller* to carry out a task so as to be able to evaluate a hand's ability to perform the task without having to implement a *controller*. This is covered in Chapter 5.

Many tasks are only possible due to the skilful utilisation of hand capabilities by the brain. Therefore, this thesis differentiates between *primitive* and *skillful* tasks. A *primitive task* is defined as any manual task that an adult human would be able to perform without training, such as *grasp-*

ing. A *skillful task* is a task that requires extensive training and usually only performed by specialists, such as playing musical instruments. The remainder of this thesis focuses on *primitive tasks*.

Chapter closure

The purpose of this chapter is to gain a comprehensive understanding of the human hand which explains what constitutes an *anthropomorphic hand*, what it should do, and how. This chapter reviewed the hand anatomy and motion and sensory capabilities. This chapter also reviewed the tasks performed by humans using their hands and some of the notable work done toward analysing and categorising these tasks.

The distinction made in this thesis between the physical aspects of the hand and its functional role allows for a comprehensive understanding of the hand. With these two views in mind, it is concluded that for an artificial device to be considered anthropomorphic it needs to *physically* and *functionally* approximate the human hand. However, given the complexity of the human hand, the extent to which an artificial hand needs to approximate it and what particular aspects contribute to *anthropomorphism* are in question. To address this, the next chapter reviews artificial solutions that aim to replicate aspects of the human hand and defines a concept of *anthropomorphism* which is used as a reference to evaluate artificial hands.

3

Artificial Hands And Solutions

It is necessary to understand the workings of artificial hands in order to compare them with the human hand. This chapter reviews key theory related to artificial hands and notable solutions and discusses the literature in light of the information on the human hand presented in the previous chapter to formulate the definition of anthropomorphism used in this thesis.

Introduction

Artificial hands are extensively studied and developed in academic, industrial, and hobbyist fields. This is done for a variety of applications, including automation of manufacturing processes, understanding the biological counterpart, replacement of lost limbs, and entertainment. The outcomes of these attempts vary considerably depending on the field and application.

This variation, and the complexity of the human hand, gives rise to the question of *to what extent does a device needs to approximate the human hand to be considered anthropomorphic?* To address this question, this chapter reviews and discusses the literature on artificial hands in light of the information on the human hand reviewed in Chapter 2.

Some important background theories are reviewed in Section 3.1. Section 3.2 reviews key *anthropomorphic* artificial hands. Section 3.3 reviews artificial hand applications. Section 3.4 discusses the concept of *anthropomorphism*, the components of artificial hands, and the borders between the hand, arm, and controller.

In this chapter, any reference to the *hand* without a prefix refers to artificial hands.

3.1 General theory

3.1.1 Modelling motion and forces

A common type of robotic mechanisms is the serial link structure, which is commonly modelled using Denavit–Hartenberg (DH) parameters. DH parameters allow describing serial links using only four parameters per link. This results in better computational efficiency; however, it neither allows for modelling exact locations of joints nor defining arbitrary coordinate frames for each link. It is common to model artificial hands as a set of serial link structures, one for each digit.

The motion of a body in Cartesian space can be described as a translational/linear velocity along a direction in a reference frame plus a rotational velocity about the axes of that frame. The translational and rotational velocities are collectively known as the twist of the body. Similarly, forces acting at any point can be described in terms of a linear force and a rotational moment, and the two components are collectively referred to as a wrench.

A manipulator Jacobian matrix allows for mapping the twists and wrenches of the joints of the mechanism to the twists and wrenches of a point of interest, usually the manipulator end-effector.

3.1.2 Contact interfaces

A contact interface, or model, describes the forces and velocities that can be transmitted through a contact as well as the allowed relative motion between the bodies in contact. There are two main categories of contact models: rigid-body models and compliant models. Rigid-body models do not allow deformation at points of contact. Forces in these models could arise from two sources, the incompressibility and impenetrability constraint, and the surface friction. Compliant models allow for surface deformation at points of contact due to external forces. Interaction forces thus depend on a compliance (or stiffness) model that describes the relation between the surface deformation and applied forces. Due to the complexity of accurate and detailed compliant models, it is more common to use a reduces-order quasi-rigid-body model, which allows modelling of compliant materials in a way compatible with conventional robotics analysis methods.

Three types of contact models are commonly used in the literature on artificial hands: Point-contact-without-Friction (PwoF), Hard-Finger (HF) and Soft-Finger (SF). PwoF "is used when the contact patch is very small" and the surfaces in contact are slippery, therefore "only the normal component of translational velocity" and force is transmitted through the contact. HF "is used when there is a significant contact friction but the contact patch is small", therefore all components of translational velocity and force are transmitted through contact. SF is used when "the surface friction and the contact patch are large enough to generate significant friction forces and a friction moment about the contact normal"; therefore, all translational velocity and force components, and the normal component of the angular velocity and moment, are transmitted through the contact. It is common to use the HF and SF models with a Coulomb friction model, which states that to avoid slipping, a contact force must lie withing the "friction cone" whose half-angle is defined as $\beta = tan^{-1}\mu$, where μ is the coefficient of friction between the two surfaces.

Motion between contacting surfaces can be rolling or slipping. Contact motion is rolling if and only if there is zero tangential velocity and acceleration at contact. The motion is slipping is the relative tangential velocity between the contact points is nonzero.

3.1.3 Theory of grasping

Grasping and manipulation are the most studied artificial hands' functionalities. Several methods have been developed to achieve stable grasping and within-hand "dexterous manipulation".

Given a grasp system consisting of a hand and an object making contact at one or more contact points, a *hand Jacobian* allows for mapping the twists and wrenches of the hand joints to the contact points' twists and wrenches. A *grasp matrix* in turn allows mapping the twists and wrenches of the object to the contact points' twists and wrenches.

A *virtual finger* is a conceptual representation of one or more real fingers - or the palm - applying force on an object (Arbib A. et al., 1985). All real fingers of a *virtual finger* act in union to apply the force (Figure 3.1 - left). *Opposition space* is defined as the areas in the hand "where opposing forces can be exerted between virtual finger surfaces" during a grasp (Iberall et al., 1986). Iberall et al. (1986) describe three types of opposition spaces shown in Figure 3.1 (right).

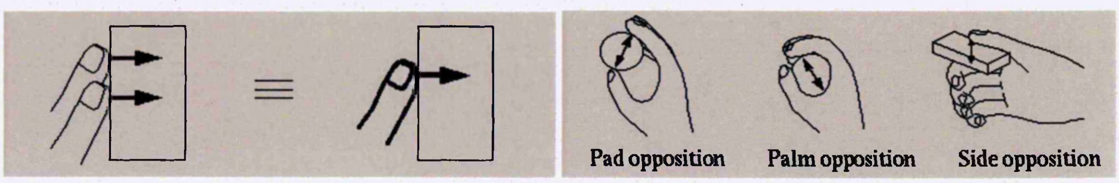


Figure 3.1: Illustration of left) virtual fingers, and right) opposition space (Kang, 1994)

The main aim of a grasp is to restrain the object in order to control its motion. There are two types of grasp restraint: *form closure* and *force closure*. A grasp is in *form closure* if the links of the hand surround the object so as to prevent it from moving in any direction. A grasp is in *force closure* if the hand is applying enough contact forces that can resist - up to a limit - any forces applied on the object. A minimum of two SF or three HF contacts are required to achieve *force closure* (Melchiorri and Kaneko, 2008), all of which must be separate virtual fingers.

There is a chance that for any given hand and object, there is more than one configuration that satisfies the closure conditions. Therefore several "*grasp quality measures*" have been proposed to determine the "best" configuration. Quality measures are categorised into two groups: measures associated with the position of contact points and measures associated with hand configuration (Suárez et al., 2006). The earlier group is further divided into three subgroups. Two groups consider force or form closure conditions but assume that fingers can apply unlimited forces, one considers algebraic properties of the grasp matrix and the other considers geometric relations. A third group considers limits in magnitudes of finger forces.

3.1.4 Mechanical properties of grasping hands

It is hard to build an artificial hand with all the active DoF of the human hand and the same size and weight. Furthermore, the high number of actuators needed to operate such system requires a complex control system and high computational capabilities, which results in high power consumption and pose difficulties for achieving real-time control. The high DoF of a hand gives it the ability to bend around objects during grasping; therefore, researchers study underactuated and adaptive mechanisms to achieve the same ability with less number of actuators and control complexity (Wu, 2013). Two main types of such mechanisms are commonly used: tendon-actuated and linkage-based mechanisms (Ceccarelli et al., 2006). Tendon-actuated mechanisms have the advantage of small size at the cost of low grasping forces and being prone to friction and compliance. Linkage-based mechanisms are more suitable when high grasping forces are needed.

Most artificial hands grasp objects by applying parallel opposite forces on the object's surface because they use mechanisms with fingers that cannot change orientation. This limits the hand's ability to uniformly position contact points around objects with cylindrical surfaces during grasping, which would result in a more secure grasp. To address this limitation, researchers developed mechanisms that can rearrange the fingers and change their orientation (Luo, 2013).

There are four different possible trajectories for gripper fingers: linear translation, curvilinear translation, rotation, and roto-translation (Hugo, 2013). Each trajectory type has different effects on the precision of the relative pose between the gripper and the object to be grasped. Even though trajectories of gripper fingers can be approximated by only four types, there is a variety of gripping mechanisms, each specifically designed for handling a particular set of objects.

Grippers can grasp objects by applying forces on the object's external surface or on the internal surfaces of holes in the object. Objects of the earlier type are classified as "of external action", objects of the latter type are classified as "of internal action" (Hugo, 2013).

Another mechanical factor which plays an important role in grasping performance of an artificial hand is stiffness (Carbone, 2013). The stiffness of the hand system depends on the stiffness of different hand components, such as actuators and transmission, as well as the stiffness of the links and joints of the structure itself. Displacements occurring in a mechanical system, in response to external forces, due to low stiffness are called compliant displacements. These displacements can have a negative effect on grasping performance of artificial hands if not controlled properly. Therefore, stiffness analysis is used to determine stiffness models of a system which can be used in compliance control algorithms. It is important to note that, at the design stages, attempts to increase the stiffness of a system often lead to an increase in the weight of the mechanism as well. This not only increases manufacturing costs but also have negative implications on the usability of an artificial hand, especially if the hand is to be used as a prosthetic hand.

3.2 Examples of existing artificial hands

Early pioneering hands In the 1980s, two "milestone" robot hands were introduced, the Stanford/Jet Propulsion Laboratory (JPL) hand and the Utah/Massachusetts Institute of Technology (MIT) hand (Figure 3.2). "These two robot hands still represent a milestone and a term of comparison for the design of new devices" (Melchiorri and Kaneko, 2008).

Stanford/JPL hand had three digits representing the thumb and upper fingers. The hand was designed to have the minimum number of joints that would satisfy mathematical grasping conditions assuring control of all object twists, wrenches and internal forces. The hand was intended to perform dexterous manipulation by grasping the object using the fingertips.

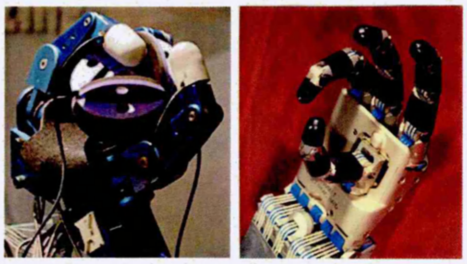


Figure 3.2: Left) Stanford/JPL Hand. Right) Utan/MIT Hand

The Utah/MIT hand was designed to have static and dynamic performance similar to the human hand. It had three fingers and a thumb with 4DoF each. The hand was initially actuated by thirty-six remote electric motors arranged in antagonist pairs. Motion was transmitted using belts and not tendons, with tension actively controlled using tension sensors. The actuation system was later replaced by pneumatic actuators and tendon and pulley transmission system.

Robonaut hands Robonaut hand is the size of a gloved astronaut's hand to fit tools used by astronauts (Ambrose et al., 2000). It is integrated with a forearm and has 20DoF plus 2DoF in the wrist. The wrist is fully actuated, the hand is underactuated using twelve actuators.

The upper fingers and thumb are responsible for *dexterous manipulation*. The lower fingers and palm are responsible for *grasping*. Each upper finger 4DoF are actuated by three actuators. The thump's 3DoF are all independently actuated. Each lower finger has three joints allowing flexion only and actuated by a single actuator. The palm has an active DoF performing the cupping motion. The forearm houses fourteen electric motors. Motion is transmitted to the joints through flexshafts and leadscrews. The hand is equipped with motor and joint position sensors. The "leadscrew assemblies as well as the wrist ball joint links are instrumented as load cells to provide force feedback". No details are given regarding the presence of tactile sensors.

A second version is developed with aims that include more grasping-based applications (Bridgwater et al., 2012). The modifications include adding an active DoF to the thumb, using tendon transmission and omitting the palm DoF. The overall size of the hand is reduced to approximate a human hand without an astronaut glove.

DLR hands The German Aerospace Center (DLR) hand is a four-digit modular robotic hand of much bigger size than the human hand (Butterfass et al., 1998). It has a total of 16DoF actuated by twelve actuators placed in the palm and fingers and an exoskeletal structure. The hand uses Force Sensing Resistor (FSR) for tactile sensing, a stereo camera in the palm, strain gauge based joint torque sensors, and a 6-axis force/torque sensor at the wrist.

The second generation, the DLR Hand II (Butterfass et al., 2001), has an endoskeletal structure and miniature 6-axis force/torque sensors at the fingertips instead of the FSR. The palm is fitted with a DoF to rearrange the fingers for either power grasping or fine manipulation.

DLR and the Harbin Institute of Technology (HIT) developed the third generation, the multisensory DLR/HIT dexterous hand (Liu et al., 2008a). Modifications include smoother contact surfaces but most sensory capabilities remain the same. The hand is manufactured by SCHUNK and commercially distributed under the name SCHUNK Anthropomorphic Hand (SAH).

In the next generation, DLR/HIT hand II (Liu et al., 2008b), the fifth digit is added, the overall size is reduced, and a 2-axis accelerometer is placed in the palm to allow measuring the hand orientation independently from the robotic arm it is attached to.

Grebenstein (2012) developed the Awiwi robot hand for the DLR Hand Arm System. The hand was designed to have dynamic performance similar to the human hand and was verified to be able to achieve the motions of Kapandji (1992) test (see Chapter 4) and the grasps of Cutkosky (1989) and Feix et al. (2009) taxonomies.

Figure 3.3: From left: Robonaut 1, Robonaut 2, DLR I, DLR II, SAH, and Awiwi hand

The Shadow dexterous hand The Shadow Dexterous Robot Hand (Shadow Robot Company, 2013) is an anthropomorphic robot hand designed to replicate most of the human counterpart's motion capabilities. The integrated hand has five digits and twenty-four joints. Fingers' DIP joints are coupled to the PIP joints, all other joints are independently actuated including two joints for the wrist. The hand can be either actuated using motors or air muscles. Interaction sensors are either single point pressure sensors at fingertips or the BioTac sensor.

InMoov robot hand The InMoov anthropomorphic hand is part of an international collaborative hobby project (Langevin, 2012). It has five digits with three joints per digit plus two joints in the palm to produce the cupping motion. The hand is actuated using five hobby Radio-Controlled (RC) servo motors, one per finger.

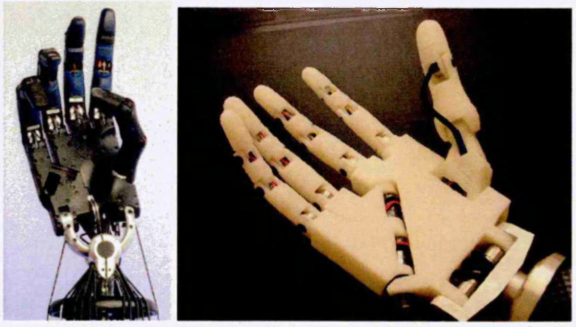


Figure 3.4: Left) Shadow Robot Hand. Right) InMoov Hand

Sophisticated three fingered grippers Some very dexterous robot hands appear less anthropomorphic than the earlier reviewed hands (Figure 3.5). The Barrett Hand is a three-finger gripper with tactile array sensors on the fingertips and the palm (Barrett Technology, 2010). Each finger has two joints actuated by one motor and the palm has a motor to reconfigure two of the fingers allowing them to be opposite or adjacent to the third finger. The adaptive robot gripper from Robotiq has three fingers with adaptive finger mechanisms (Robotiq, 2012a). The fingers can move sideways (adduction/abduction) and can perform pinching at the fingertips. The Laboratory of Robotics and Mechatronics (LARM) hand IV has three underactuated adaptive fingers, which uses 4-bar linkage mechanisms (Carbone and Ceccarelli, 2008). A recent design modification allows the LARM hand IV to reconfigure two of the fingers to change orientation thus improving the distribution of grasping forces on cylindrical surfaces and even achieve some within-hand manipulation (Luo, 2013). SCHUNK Dexterous Hand (SDH) has three fingers, which can be rearranged for a circular or parallel grasp, and tactile array sensors (SCHUNK).

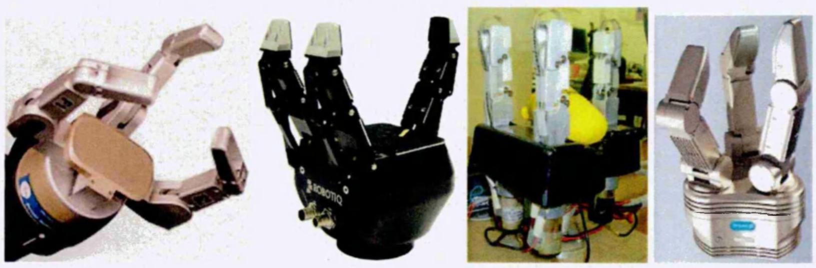


Figure 3.5: From left: Barrett Hand, Robotiq adaptive gripper, LARM hand, and SCHUNK Dexterous Hand

Other anthropomorphic hands Hoshino and Kawabuchi (2006) describe a hand designed to perform grasping and sign language gestures. It has five digits, each finger is actuated by one motor while the 4DoF thumb is actuated by three motors. Abduction of all fingers is controlled by one motor. They also describe a hand designed to perform fingertip pinching grasps. It has a large number of DoFs "exceeding" the human hand. An axial rotation DoF is added to the thumb to achieve opposition. Distal joints of all digits are controlled independently to achieve fine torque control.

Nara Institute of Science and Technology (NAIST) hand has four digits and vision-based fingertip tactile sensors (Ueda et al., 2010). It aims to achieve in-hand manipulation. Nakamoto et al. (2006) built a large anthropomorphic hand to study stiffness control and object recognition using tactile array sensors. It has five digits each with three joints and 4DoF actuated by three actuators.

The MechaTE five-digit robot hand is developed for entertainment applications and "does not have a substantial gripping force". The hand has no sensors and uses five RC servo motors to actuate fourteen joints in the fingers through an adjustable elastic transmission.

Saito et al. (2009) analysed human hand functionalities and proposed a classification of twenty-two prehensile and forty-one non-prehensile "modes". They developed two five-digit prosthetic hands. One device, powered by a single motor, is suitable for two to three-year-old children. The other device, with 17DoF actuated by fourteen micro motors embedded in the palm, is claimed to be able to reproduce 77% of the prehension modes. The device uses thirteen ON-OFF tactile sensors to control hand posture and grasps but sensor output is not fed back to the user.

Comparison between reviewed hands Appendix E presents a set of comparison tables showing the specifications, main mechanical and sensory properties, and functionalities and applications of the above-reviewed hands.

3.3 Applications of artificial hands

There are two main classes of artificial hands' application observed in the literature: *robotics* and *prosthetics*. In *robotics* applications, the artificial hand is normally attached to a robot arm and controlled by a robotics control system. In *prosthetics* application, the hand is attached to a human user's amputated arm. The user controls the device through some kind of a user interface.

The distinction between the two classes of application is very important due to the very different requirements of each class. Some requirements affect the physical aspects of the device, such as weight and communication bandwidth. Other requirements affect the functional aspects of the device, since the type of tasks the hand should be able to do largely depend on the application.

Robotic hands

Most anthropomorphic robotic hands are developed or used for the purpose of studying hand functions, such as grasping, in controlled lab environments. Some devices are implemented in real-life applications, such as the Robonaut robot developed for space applications. This kind of applications may have higher reliability constraints. However their work nature remains relatively non-repetitive, therefore the types and locations of potential failures are hard to predict.

Design criteria are usually defined by performance requirements and the type of robot used with the hand, ie. the host robot. If the hand is to be installed on a 6DoF robot arm, it is usually preferred to design a modular hand. However, to reduce cost and increase motion range and hand forces, it is common to integrate the hand with a forearm housing the actuators.

Devices that are intended to study hand functions are designed to operate in a controlled lab environment. This relaxes constraints on power the source, storage and consumption. Weight is constrained by the host robot's payload capacity.

Prosthetic hands

Prosthetic hands can be viewed as a type of robotic hands with more demanding requirements. To meet the demand of patients with varying levels of transradial amputation, it is common to design *modular* hands with all necessary components (including power storage and the high-level *controller*) embedded in the hand. This imposes limitations on the actuators' number and size, and subsequently: motion capabilities, power and speed. This is a particular problem since "power output" and "speed" are important specifications from a prosthetics user's point of view.

Weight is also an important factor. Prosthetic hands need not only to be within the user's payload capacity, they must be light enough not to cause pain and fatigue or feel "uncomfortable". Considering the power and speed requirements and the limits on size and weight, power efficiency and storage are especially challenging constraints.

With regard to size, Saito et al. (2009) points out the problem of *size fit*. An example of the problem is manifested in Japan where the population have anthropometric dimensions considerably different from European populations. Japanese male patients using German prosthetic hands select devices intended for smaller female hands. Subsequently, Japanese female users select devices intended for children, which are not functionally adapted to suit adult requirements.

Communication bandwidth is an important factor limiting the capabilities of advanced prosthetic hands. Currently, the most common approach to interface between a device and its user is using Electromyography (EMG) to command the hand and vibrotactile stimulation to receive sensory data. EMG is a non-invasive method to detect very limited signals from muscle motion, which impose limitations on the type of motions the hand can perform. Vibrotactile stimulation uses small vibration motors pressed against the skin; however, this solution is very constrained due to the limited spatial resolving capacity of the hairy skin on the arm.

Research is undergoing to develop high-bandwidth neural interfaces, achieved through implants. Such interfaces will allow users to control more complex mechanical systems. It also has the potential to allow users to receive information from sensors. For example, one research was able to interface a FSR sensor installed on a prosthetic hand's fingertips with the user's nerves, allowing the user to perceive "touch" and "texture" of surfaces (Tan et al., 2014). However, until such solutions are safe and robust enough for public use, the interface bandwidth is a critical restriction on prosthetic artificial hands.

3.4 Discussion

The main purpose of this chapter is to establish an understanding of anthropomorphic artificial hands' construction and uses. This section discusses the literature covered in this chapter in light of the information on the human hand construction and uses reviewed in Chapter 2. The discussion is presented in three parts. The first part discusses the concept of anthropomorphism. The second part discusses the hardware components of artificial hands. Finally, the third part defines the borders between the hand, arm, and controller.

3.4.1 Anthropomorphism

Anthropomorphism is hard to define and there are considerable differences in meaning among sources using the term. Biagiotti et al. (2004) and Melchiorri and Kaneko (2008) define it as "the capability of a robotic end-effector to mimic the human hand" with regard to "external perceivable properties" such as size and shape. Liarokapis et al. (2013) relates it to the hand's motion capability and compare artificial hands' workspace to that of the human hand. Hammond III et al. (2012) imply that it is a function of the configuration of the digits, i.e hand posture.

Given the different uses of the term, it is important to define *anthropomorphism* for use in this thesis. This section discusses some observations on *anthropomorphism* to formulate the definition. The section is presented in three subsections. The first subsection discusses some general observation on *anthropomorphism*, including factors relating to the perception of *anthropomorphism*. The second and third subsections discusses *anthropomorphism* from the *physical* and *functional* views respectively. This is relevant to the statement of this thesis since *physical anthropomorphism* determines which hands can be used with the method developed in this thesis, while *functional anthropomorphism* is involved in how the method evaluates a hand's performance.

It is important to point out that this thesis does not aim to present a new definition of *anthropomorphism*. This section only discusses different definitions and concepts presented in the literature to formulate the definition used in the framework presented in this thesis.

General observations on anthropomorphism

Dimensions and anthropometric references As indicated in Chapter 2, there is no standard anthropometric data that is correct for all populations. Hands of different human individuals varies considerably in bone dimensions, proportions, joint position, and RoM with negligible effect on manual abilities (Grebenstein et al. (2010), Alexander and Viktor (2010)). Also, depending on different populations, certain dimensions and proportions may be accepted as "normal". Human or artificial hands that do not comply to these "normal" references may be dismissed as "abnormalities"; therefore, determining what constitutes an "anthropomorphic" dimensions is to some extent subject to the observer's culture and personal judgement. In an effort to develop a method suitable for as many artificial hands as possible, this thesis does not use a defined set of anthropometric data as a reference for developing evaluation method. Instead, the thesis relies on the common features, which appears in several resources studying adult humans from both genders, to define *physical* aspects of *anthropomorphism*.

Proximity to other primates This thesis is interested in artificial hands that appear similar to, but not necessarily indistinguishable from, human hands. As a result, the features identified in this section are not sufficient to distinguish between human hands and hands of some close non-human primates, such as apes.

Perception of anthropomorphism Melchiorri and Kaneko (2008) definition of *anthropomorphism* points out a variable that is not part of the hand: the *observer's perception* of the attributes contributing to *anthropomorphism*. Klatzky et al. (1985) indicate that humans "attend more to material" properties during haptic interaction, while they "emphasise the geometric properties" when vision is used (Chapter 2). This points out that *observer's perception* depends on the nature of interaction: *visual* or *haptic*. Therefore, a distinction can be made between *visual* and *haptic* perception of *anthropomorphism*. This thesis focuses hereinafter on the *visual* aspects.

Physical anthropomorphism

The *physical* view involves the *anthropomorphism* of the hardware of an artificial hand, regardless of how it perform its functionalities. This is relevant to this thesis because it determines which hands can be used with the evaluation method developed in this thesis. From this view, *anthropomorphism* would involve the artificial hand having similar construction and motion and sensory capabilities to the human hand.

Some developers attempt to reproduce the human hand's skeleton shape and arrangement, all the way down to bone geometry. Other developers present arguments against this approach and instead study the motion capabilities of the human hand then develop artificial structures with similar capabilities but not necessarily similar construction (Grebenstein et al., 2010).

Given this thesis focus on external visually perceived *anthropomorphism*, reproducing the internal bone structure of the hand is not considered to contribute to *anthropomorphism*. Sensory capabilities are important for the functional performance of hands, which is considered in this thesis; however, they cannot be visually perceived and therefore are not considered to contribute to *anthropomorphism*. Also, this thesis does not take into consideration the aesthetics of *anthropomorphism*, including varying dimensions and surface properties, or omitting digits and joints.

Other factors that contribute to the *anthropomorphic* construction and capabilities of artificial hands are discussed below.

Number of digits The human hand surface anatomy (Figure 2.1) suggests that for an artificial hand to be anthropomorphic it should contain a palm and five digits: one thumb with high mobility at the radial side of the palm and four fingers at the top of the palm. However, it is evident from the literature that hands with less number of digits can be considered anthropomorphic. It is very common to describe artificial hands with four digits (thumb and three fingers) as anthropomorphic. In fact, many researchers, such as Grebenstein et al. (2010), explicitly state the condition of having four or five digits to be considered anthropomorphic. Therefore, this thesis defines an anthropomorphic hand to have four or five digits.

Number of joints It is common with prosthetic hands to fix or omit the DIP joints of the fingers. This is done to reduce the kinematic complexity and development cost. When omitting the joints, the distal link of the finger is usually designed to have a length similar to the middle and distal phalanges combined. This usually does not affect the *anthropomorphic* appearance of the device, it is clear from the literature that such devices are widely considered *anthropomorphic*. Therefore, it is concluded that an anthropomorphic hand must have two to three joints per digit.

Motion capabilities There is no standard reference for the RoM of human hand joints. However, the literature mostly agrees on the joints' DoF and allowed direction of motion, which are described in Chapter 2. Therefore, this thesis assumes that an anthropomorphic hand must have digits with joints capable of flexion, i.e closing and opening the fingers. An anthropomorphic hand may have sideways motion, i.e abduction, only in the first joint of each digit resembling a finger. This does not apply to the digit resembling the thumb, which can have up to 6DoF.

Surface Biagiotti et al. (2004) indices (Chapter 4) assign equal values to the effect of surface *smoothness*, *extension*, and *softness* on *anthropomorphism*. Given this thesis focus on visual aspects, *smoothness* and *softness* factors are not considered. It is also important to point out that, while the human hand's surface covers the joints, this is not the case in the majority of robot hands. However, this thesis does not define any criteria for surface extension of anthropomorphic hands.

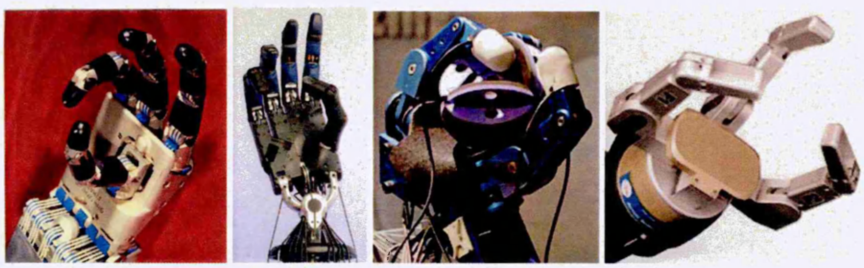


Figure 3.6: Examples of hands viewed as anthropomorphic or not anthropomorphic

Examples of anthropomorphic hands Figure 3.6 shows some examples of hands that are viewed, in this thesis, as *anthropomorphic* and hands that are not viewed as such. Given the above definitions of what constitutes an *anthropomorphic* hand from the *physical* view, the Utah/MIT hand and the hands shown in Figures 3.3 and 3.4, such as the Shadow Hand, are considered *anthropomorphic*. On the other hand, the Stanford/JPL hand and the hands shown in Figure 3.5, such as the Barret Hand, are not considered *anthropomorphic*.

Functional anthropomorphism

From the *functional* view, *anthropomorphism* relates to how a functionality is being performed. This is relevant to the evaluation method developed in this thesis because it is concerned with evaluating whether hands that are considered *anthropomorphic* form the *physical* view are performing their functionalities in a manner that is also *anthropomorphic* from the *functional* view.

Many of the tasks described in Chapter 2 can be performed using either an *anthropomorphism* or a *non-anthropomorphic* posture. This is best illustrated by Hammond III et al. (2012) grasping example (Figure 3.7).

In addition to hand posture, this thesis considers two other factors to contribute to *functional anthropomorphism* when there is a contact between the hand and an object: location of contacts on the hand and the object's pose with respect to the hand.

This thesis uses the illustrations and descriptions of the different functionalities of the human hand (Section 2.3) to determine the hand posture, location of contacts, and object pose for each task. This is discussed in more detail in Chapter 5.

Figure 3.7: A robotic hand grasping a mug using: left) anthropomorphic, and right) non-anthropomorphic finger configuration (Hammond III et al., 2012)

3.4.2 Hand components

Reviewing the literature shows that it is common to separately develop sensory the solutions for artificial hands. Also, some literature focuses on hand capabilities while the actuation is carried out by separate unit and not always discussed. Additionally, surface properties are rarely emphasised despite their role in grasping. Therefore, this section discusses artificial hands' components in four categories:

- Structure: factors affecting motion, including aspects that do not fit in other categories
- Surface: the geometric and physical aspects of the structure's surface

- Sensors: *state* and *interaction* sensors, including integrated and modular solutions
- Actuation: aspects of *actuators* and *transmission* of motion and forces

Structure

Any hand has a root link, i.e the palm, and a set of digits attached to the palm. In addition to the kinematics of the structure of the palm and digits, there are two other important general structural aspects of hands: *modularity* and *skeletal structure.*

General integration and modularity Two classes of devices can be identified in the literature: *modular hands* and hands that are part of an *integrated arm-hand system.* A *Modular Hand (MH)* is a hand that contains within the palm or digits all the actuators, sensors and low-level control components required to operate the hand. A hand is considered an *Integrated Hand (IH)* if any of the actuators, sensors or low-level controllers cannot be housed within the palm or digits, whether they are housed in a unit attached to the wrist resembling a "forearm" or remotely located in a separate unit. Integrated hands cannot fully function if separated at the wrist.

Skeletal structure Two skeletal types found in nature are employed in artificial hands: *endoskeletons* and *exoskeletons.* A hand is considered to have an *exoskeleton* if the rigid structure houses some or all of the other components, such as actuators, transmission or sensors. It is considered to have an *endoskeleton* if the rigid structure does not house any components.

Surface

The structure's surface geometry and physical properties affect the hand's appearance and operation. Biagiotti et al. (2004) proposes that surface "smoothness", "extension" and softness together account for twenty percent of an artificial hand's "*anthropomorphism*". Surface geometry affects the possible hand motion when a collision with objects is wanted or avoided. Surface physical properties, i.e friction and compliance, affects the hand's ability to apply forces on objects. Artificial hands normally consist of separate links each with its own exclusive surface.

Sensors

State sensors State sensors acquire information about *position, displacement, speed, acceleration* and *effort* of *joints, actuators* and *transmission* components. Not all information are required at the same time, a subset is sufficient to fully estimate the state of the system.

It worth noting that acceleration sensors were not used in any of the reviewed hands except limited use to estimate absolute orientation by sensing the gravitational acceleration vector. Transmission position or effort sensors are used to estimate joint state from actuators' state. In the presence of a rigid relation between actuators and joints, i.e using rigid transmission, joint and actuator states can be directly derived from one another.

Interaction sensors Interaction sensors observed in the literature acquire information about the occurrence, location, and force of contact, pressure distribution at contact, temperature and vibration of the object in contact.

Actuation

Actuators Any powered mechanical system requires one or more actuators to induce the motion. Actuators convert a form of energy into a form of motion.

Actuators can be categorised according to input form of energy and output form of motion. The forms of energy input used with actuators of reviewed artificial hands are: *electric energy* and *hydraulic* or *pneumatic pressure*, and the forms of motion output are: *rotary* and *linear* motion.

All actuators require feedback control in order to guarantee a certain desired motion is achieved. This is usually carried out by a dedicated low-level controller to offload the necessary calculations from the high-level controller. Some self-contained actuator units come with the necessary low-level controller integrated with the actuator. Such systems are usually referred to as "modular actuator units". This is most common with electric actuators.

Transmission Motion and force generated by actuators must be *transmitted* to the joints through mechanical transmission. Transmission can also "couple" the motion of multiple joints. Such mechanisms may modify the motion's *displacement, speed* or *force*.

Transmission stiffness affects displacement and force of transmitted motion. Transmission can be categorised into three main categories according to stiffness: *rigid, flexible* and *elastic*. *Rigid transmission* is not flexible in any direction, for example a rigid metal linkage. *Flexible transmission* is flexible in directions other than that of the intended direction of transmitted motion, for example "low-elasticity" tendons. *Elastic transmission* is a subclass of flexible transmission which is flexible in the intended direction of transmitted motion, for example springs and elastic tendons.

Transmission can convert between rotary and linear motion. Transmission with mechanical advantage can alter displacement, speed and force. Some flexible and elastic transmission only transmit motion in one direction due to the directional flexibility or the construction of the linkage. For example, tendons allow only "pulling" motion, and flexible shafts made of twisted steel wires allow rotation in one direction only. Finally, flexible transmission requires designated routeing. This can be fixed - defined by ducts, grooves and/or pulleys - or flexible routeing using tubes and sheaths. A very common configuration of flexible sheath routeing of tendons is known as tendon-outer-tube transmission.

Components of the human hand

For modelling and simulation purposes, human hand components are described here using the same categorisation:

- Structure: The human hand is integrated with the arm and has an endoskeletal structure.

- Surface: The human hand is covered with a single continuous flexible surface covering all its links and joints.
- State sensors: The human hand contains "actuator position", "transmission effort", "joint position" and "joint effort" state sensors.
- Interaction sensors: The skin detects occurrence, pressure distribution, shape, and temperature of contact.
- Actuators: The human hand is actuated by muscles, most of which are remotely located in the forearm. Muscles can only apply a "pulling" force; therefore, the human hand is actuated by antagonist muscles.
- Transmission: Forces from remote muscles are transmitted through a complex network of tendons. The muscles antagonist arrangement is not in *pair configuration* due to the tendon network interconnectivity.

3.4.3 Interfacing with artificial hands

A *controller* uses the hand to execute tasks. This introduces the question: *what is the hand's responsibilities?* This thesis defines an interface between the hand and controller that defines the limits of each entity's role. This interface is utilised in task descriptions in Chapter 5 and simulation in Chapter 6 as it defines the inputs and outputs of the descriptions and simulation processes.

Therefore, the hand is viewed as an input/output device. It is a sensor that can input data and it is an articulate mechanical system that can output motion and forces.

Commanding motion In this interface, the hand accepts commands as a set of discrete "robot arms", where each digit acts as an individual "robot arm". There are four command domains and three spaces where these commands can be issued. The domains are *position, displacement, speed* and *effort*. The spaces are *actuator, joint,* and *tip*.

Reading sensors For *interaction sensors,* there are two approaches. A 2D "flat" approach provides the readings in an array that only explains sensed quantity at sensor position on the hand's "flat" surface. A 3D "point cloud" approach uses n-dimensional point clouds to encode the sensed quantity as well as the spatial location where it was sensed.

State sensors data are provided in three matrices for *joints, actuators,* and *transmission.* Each matrix contains six rows and as many columns as the total number of components' DoFs in the hand. The first row identifies the component, the following five rows specify the component's *position, displacement, velocity, acceleration* and *effort* in the component's local frame.

Chapter closure

This chapter reviewed key theory related to artificial hands and notable solutions and discussed the literature in light of the information on the human hand presented in the previous chapter. It showed that *anthropomorphism* is a complex concept and can be decomposed into several components. It also pointed out that some aspects of *perceptual anthropomorphism* may be *aesthetic,* which are not considered in this thesis. It also discussed the components of artificial hands and observed that a hand can be modelled as an input/output device. Finally, this chapter defined the *anthropomorphic* reference to be used in this thesis.

The information on the *construction, capabilities,* and *functionalities* of human and artificial hands, as well as the definition of *anthropomorphism,* are utilised to review different methods of evaluating hands and identify their strengths and shortcomings in the next chapter.

4

Existing Evaluation Methods And Tools

Based on the definition of anthropomorphic artificial hands in the previous chapter, this chapter reviews key existing evaluation methods and computational simulation tools to identify their sufficiency to evaluate different aspects of a hand. This chapter points out the strengths and shortcomings of each method and proposes an approach that addresses these shortcomings.

Introduction

Several existing methods evaluate artificial hands using different measures. The most common type of measures evaluates a hand's functional performance as a grasping device. Alternatively, a hand is evaluated in terms of its motion capabilities regardless of its functional performance. Hands are rarely evaluated from an apprehension perspective, i.e as a sensing device, nor are they commonly evaluated as a non-prehensile tool or a visual expression device.

Many of these methods use dedicated computational simulation tools. Additionally, several other tools have been developed to analyse hands without the explicit aim of evaluation.

This chapter reviews key existing evaluation methods in an effort to define a comprehensive single evaluation method or a set of mutually compatible methods. It also reviews some computational tools that can potentially be used for evaluation purposes.

Section 4.1 discusses key existing evaluation methods and point out their strengths and shortcomings. Section 4.2 summarises the lessons learnt from existing methods and outline a concept method that combines their strengths and overcomes their shortcomings.

4.1 Existing evaluation methods

There are several methods used to evaluate artificial hands, some more developed than others. This section reviews the key methods found in the literature.

4.1.1 Medical tests

Kapandji clinical evaluation of the thumb's opposition

Grebenstein (2012) used the medical tests described by Kapandji (1992) to evaluate a robot hand's design. Kapandji (1992) describes a ten step test to evaluate thumb's opposition movement (Figure 4.1) and a four step test to evaluate retropostion movement (Figure 4.2). These tests are performed without instruments using "the hand itself as the reference systems".

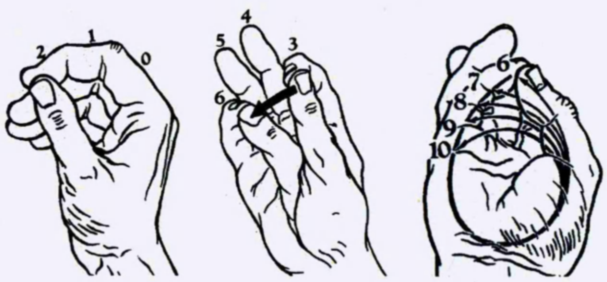


Figure 4.1: Kapandji Opposition Test (Kapandji, 1992)

Opposition test This test comprises several steps. All steps refer to using the tip of the thumb to touch a location on the hand or other fingers. The test score is the highest step reached provided all steps are performed in order.

- Part one :: "terminolateral pinch", "longitudinal rotation does not occur" in this part
  - **Step 0** Touching the lateral side of the first phalanx of the index finger
  - **Step 1** Touching the lateral side of the second phalanx of the index finger
  - **Step 1** Touching the lateral side of the third phalanx of the index finger
- Part two :: "tip-to-tip pinch"
  - **Step 3** Touching the tip of the index finger, this is the "minimal opposition" position
  - **Step 4** Touching the tip of the middle finger
  - **Step 5** Touching the tip of the ring finger
  - **Step 6** Touching the tip of the small finger, this is "extreme opposition arch" position
- Part three :: running the tip of the thumb down the small finger
  - **Step 7** Crossing the distal interphalangeal joint crease of the small finger
  - **Step 8** Crossing the proximal interphalangeal joint crease of the small finger
  - **Step 9** Touching the proximal crease at the base of the small finger
  - **Step 10** Touching the distal palmar crease above the MCP joint of the small finger

Retropostion test In this test, both hands are placed on a flat surface. The hand to be tested is placed flat with its palm down, with the thumb fully radially abducted. The opposite hand is held upright on its ulnar side, close to the tip of the thumb. The thumb to be tested is then moved up as high as possible.

The uppermost point reached, measured in terms of the other hand's MCP joint, is noted. The test scores are: stage one, reaching the MCP joint of the little finger, stage two, reaching the MCP joint of the ring finger, stage three, reaching the MCP joint of the middle finger, and stage four, reaching the MCP joint of the index finger. IF the thumb cannot move up by itself, the retropostion is denoted as stage 0.

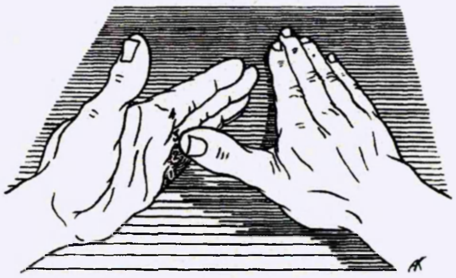


Figure 4.2: Kapandji Retropostion Test (Kapandji, 1992)

Other medical tests Kapandji (1992) refers to two other medical methods to evaluate the thumb's motion: the *anatomists' method* and the *surgeons' method* (Figure 4.3). Each method uses the two angles shown in the figure as a performance measure.

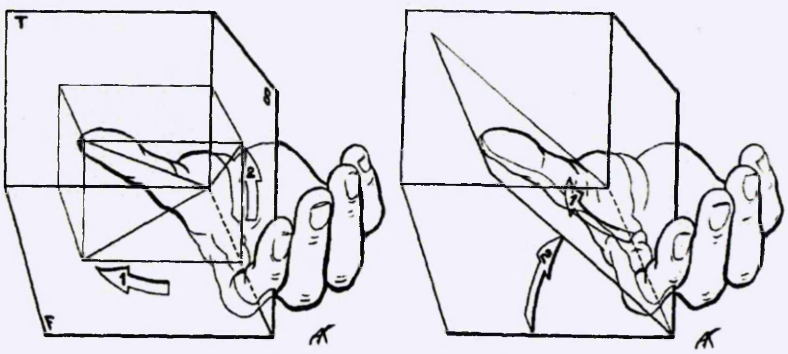


Figure 4.3: Left: the anatomists' method, Right: the surgeons' method (Kapandji, 1992)

4.1.2 Biagiotti et al. Weighted Indices

Biagiotti et al. (2004) proposed a method to evaluate artificial hands by comparison to the human hand. The method identifies three areas for evaluation and uses a weighted sum of components to obtain an index that reflects a hand's performance in each area.

The three proposed indices are "level of anthropomorphism" evaluating the hand's general appearance, "potential dexterity related to mechanical structure" evaluating its mechanical performance as a grasping and manipulation device, and "potential dexterity related to sensory devices" evaluating its sensing capabilities. Coefficients - weights - of components for each index sums to 1, resulting in an index value that ranges between 0 and 1.

Anthropomorphism index

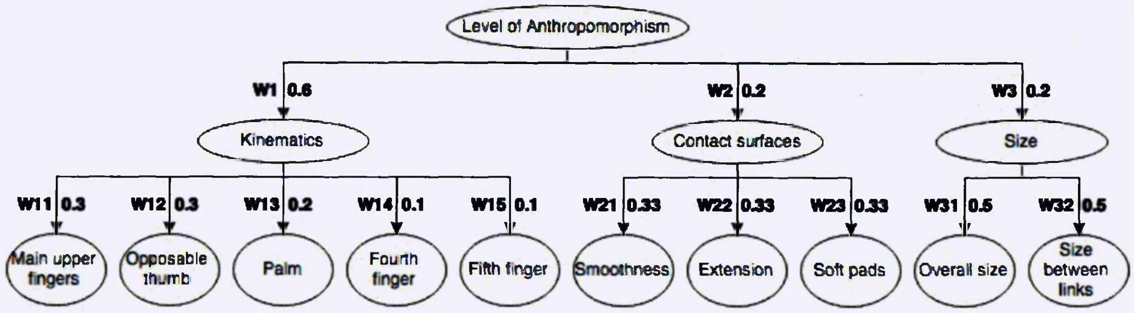


Figure 4.4: Weighted components of the anthropomorphism index (Biagiotti et al., 2004)

Figure 4.4 shows the components of the *anthropomorphism index* a_x and the weights suggested by Biagiotti et al. (2004) to calculate it. Note that sub-components are weighted relative to the weighted value of their parent component. The human hand has $a_x = 1$.

Biagiotti et al. (2004) describe three components of the index: kinematics, contact surfaces and size. Kinematics component "considers the presence of the main morphological elements". The value of each element is measured "according to the number of articulations inside each finger in comparison with the human case".

Biagiotti et al. (2004) defines extension and smoothness of contact surfaces as "the capability to locate contacts with objects all over the surface of the available links", and soft pads as the "availability of external compliant pads". The last component relates to the overall size of the hand and internal size ratios, i.e the difference in length of different digits and segments.

Dexterity

Biagiotti et al. (2004) define dexterity as "the capability of the end-effector, operated by a suitable robotic system, to autonomously perform tasks with a certain level of complexity". This acknowledges the role of *control* in the hand's dexterity. To avoid involving control systems, they consider *potential dexterity*, i.e the maximum *dexterity* the hand can achieve given a suitable control system. The *potential dexterity* is therefore completely based on "intrinsic" hardware components. *Potential dexterity* is divided into two areas: the mechanical structure and the sensory abilities.

Potential dexterity related to mechanical structure Biagiotti et al. (2004) note that methods of evaluating the potential dexterity of kinematic structures, such as the manipulability ellipsoid, "require the knowledge of some mechanical details and parameters which are often unavailable". Therefore they propose to "roughly quantify" potential dexterity based on "functional capabilities allowed by the features of [the] mechanical structure, such as number of degrees of freedom, smoothness of the contact surfaces, etc". A hand can be classified into two groups: *hands with capabilities limited to grasping* - including underactuated hands with complex kinematic configuration - and *hands that are capable of some kind of internal manipulation.* Furthermore, each group is divided into two categories depending on whether the functionality is limited to *fingertip* operation or extended to *all active elements of the hand.*

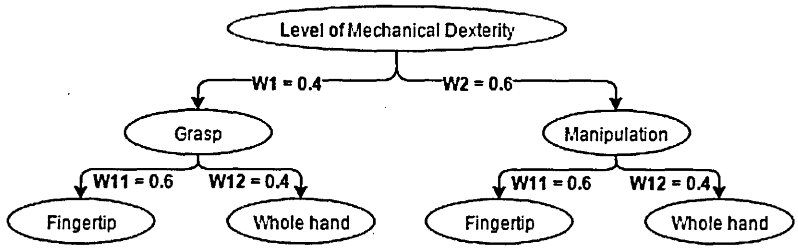


Figure 4.5: Weighted components of the mechanical dexterity index (Biagiotti et al., 2004)

Potential dexterity related to sensory devices The proposed index aims to evaluate the hand's sensory capabilities. This includes joint and motor position *state sensors.* As for *interaction sensors,* Biagiotti et al. (2004) considers the category to include *"force/torque sensors collocated within the kinematic chain"*, as well as two other sensor types: *"tactile sensors directly placed on external surface"* and *"Intrinsic Tactile (IT)"* sensors. They also identify a third sensor category that is not found in the human counterpart: *additional sensors.* This includes acceleration sensors, proximity sensors, and cameras. Interaction sensors are considered most important to achieve dexterity. The human hand has σ_x less than 1 due to lack of *additional sensors.*

Discussion of the method

This method is the most comprehensive among the reviewed methods, it compares hands in three areas: *anthropomorphism, mechanical* and *sensory potential dexterity.* It is an abstract method in the sense that it requires minimal information and no complex computation, making it suitable for fast evaluation and comparison of many hands. The method possesses a good potential, and the paper puts forward many concepts that are extensively utilised in this thesis. However, it suffers from some shortcomings, each index is separately reviewed below.

Anthropomorphism index The index is the most developed index in the method; however, it suffers from some drawbacks. First, the suitability of the components to evaluate anthropomorphism is in question, so are the proposed weights. Biagiotti et al. (2004) do not explain why they selected these components or the associated weights. Additionally, they do not explain how to measure a component or its quality. They give no details regarding the effect of different joints. It may be that they meant all joints have equal value. However, given that many prosthetic hands choose to omit some joints, such a statement needs supporting evidence.

Considering the surface properties, it is not clear how to determine how "extended" or "smooth" the surface is, nor why "compliant pads" will have an effect on the appearance of the artificial hand since it impossible to visually determine surface compliance. As for the "overall size" and "size ratio", these two components indeed have a very visual nature. However there is no explanation on how to evaluate them, nor to what reference are they compared.

Dexterity indices Biagiotti et al. (2004) notes that other evaluation methods require knowledge of "often unavailable" details and propose to "roughly quantify" *potential dexterity* based on "features of [the] mechanical structure". However, this statement and the proposed indices are self-contradictory since knowledge of mechanical details is required to determine whether or not a hand has manipulation capabilities. Additionally, the indices restrict hand functionalities to grasping and manipulations and ignores active sensing and non-prehensile functionalities. Furthermore, the manipulation component is divided into "fingertip" and "whole hand" parts. However, as already observed in Chapters 2 and 3, *dexterous manipulation* is performed using *precision grasps* with the fingertips. Therefore there can be no "whole hand" manipulation.

As for the sensory index, there is no analysis or discussion of the importance of each sensor type which would be a logical step preceding assigning weights. As with the index for anthropomorphism, Biagiotti et al. (2004) do not provide any details on how to measure the components nor the reasons behind the selection of the weights.

4.1.3 Liarokapis et al. Workspace Analysis

Liarokapis et al. (2013) proposed a method to "quantify anthropomorphism" of a robot hand based on the intersection of its workspace with that of a reference human hand model. They used a parametric 25 DoF human hand model with a 5DoF thumb, 4DoF upper fingers, and 6DoF lower fingers. They differentiate between the workspace of the fingers' phalanges and the "workspace" of the fingers' base frames, which they claim is "of outmost importance for specific grasp types".

Their method requires the definition of correspondences between the artificial hand and the human counterpart. To facilitate such process, they define a finger to have two or three joints and three to four DoF respectively. In the case of an artificial finger with higher DoF, the extra DoF are considered to "contribute to the positioning of its base frame" and are included in the separate analysis of the base frame workspace. Accordingly, two DoF of each of the reference model thumb and lower fingers are considered in the base frame analysis.

The method proposes to "map human to robot fingers with an order of significance starting from thumb and index, to middle, ring and pinky". As for the phalanges, the mapping system favours the distal, then the proximal, and finally the middle phalanx. In the case of mapping a

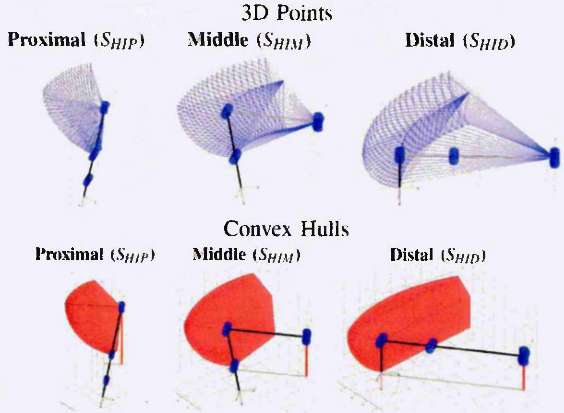


Figure 4.6: Computing workspace convex hulls from 3D points set (Liarokapis et al., 2013)

digit with more than "three phalanges", the method proposes to keep some joints fixed to zero in order to form three virtual phalanges per finger. The choice of which joints to fix depends on which combination of joints gives the highest anthropomorphism score. Note that the method has previously proposed to assign excess DoF to the finger base mobility, it is not clear from the paper when is either approaches used.

Liarokapis et al. (2013) quantify workspace using convex hulls (Figure 4.6) and perform a "one-to-one comparison" between the workspaces of each phalanx and the corresponding human counterpart. To generate a phalanx workspace, forward kinematics (of a DH parameters model) is solved while "exploring" the joint space of all DoF that "contribute" to the phalanx workspace. The joint space is discretized using a step of R/n, where n is usually 20 and R is range of motion.

The volumes of intersection and union between workspaces of each robot finger phalanx and the corresponding human phalanx are computed. The "anthropomorphism" score is the ratio of the intersection volume to the union volume. To avoid "penalizing" robot hands that have more joint range than the human hand due to the denominator being the union of both workspaces, the joint limits are "changed in order to be equal with the human limits".

Total "score of *anthropomorphism*" is computed as a weighted sum of individual scores of each finger's phalanges. Liarokapis et al. (2013) propose that these weights "can be set *subjectively* according to the specifications of each study". They are not defined but rather left to the user to set them as suits each study. The sum of weights should always be one.

Discussion of the method

This method defines anthropomorphism as a function of the hand's dexterity, and not appearance. It is, in fact, evaluating artificial hand's dexterity and not anthropomorphism. It is possible to define appearance as a function of possible motion range; however, it does not necessarily depend on the size of the workspace but rather the ability to take certain postures. This is something that is not evaluated by this method. Although Liarokapis et al. (2013) claims that it is possible to take into account any couplings or synergies, the summation nature of convex hulls used to quantify the workspace does not allow to exclude unreachable regions in the workspace. Therefore, this method does not guarantee that a certain configuration that lies inside the workspace and results in an anthropomorphic posture is actually permitted by the hand's structure.

Also, the method evaluates anthropomorphism as a function of the union of the workspaces of both human and artificial hands. This is certainly confusing, it makes sense that to evaluate anthropomorphism - defined as ascribing human attributes to a non-human artefact - should be evaluated exclusively with respect to a human reference, and not a reference that combines human and non-human attributes. Liarokapis et al. (2013) themselves note that if the artificial hand has a larger workspace than the human hand model, possibly caused by joints with a higher range of motion, this would lead to the "more dextereous" artificial hand having an incorrect lower score due to including the extra workspace in the union. Their solution is to clip the range of motion of the artificial hand to be equal to that of the human hand, which raises the question: why not simply use the human hand's workspace on its own as the reference in the first place?

It is worth pointing out that the method does not analyse the workspace of each digit as a robotic manipulator, but rather analysis each workspace of each phalanx individually. Therefore this method does not indicate the overall size of the hand's workspace. Also, the method assumes no change of orientation occurs in the fingers, which is not always true as in the case with hand models that takes into account the inclination of interphalangeal joints.

With regard to hand functionality, it is clear from the paper that the main *functionality* of an artificial hand in Liarokapis et al. (2013) opinion is grasping and manipulation. Workspace analysis only describes the motion capability of each digit on its own and not the functionality of the hand altogether. Even if the workspaces of all digits are compared with respect to each other, it does not, for example, reflect on the grasping performance of the system. The analysis does not indicate whether the fingertips, phalanges or palm can be used to apply force closure conditions on an object. This also means that the measure is not indicative to the hand's functional anthropomorphism, since there is no way to know if the intersection region is "useful" or not, or to define a measure of relative value between different regions in the workspace. Finally, no guidance is given to how to select the appropriate weights.

4.1.4 Feix et al. Fingertip Trajectory Analysis

Feix et al. (2013) proposed a method that uses empirical data collected from experiments with five subjects performing thirty-one of the thirty-three grasps of Feix et al. (2009) taxonomy. Two grasps, the "Distal Type" and the "Tripod Variation", "were omitted due to their very special nature". The method uses this data to create the human hand's "action manifold", which is defined as "all the postures (or a chosen subset) that a hand can reach". The high dimensionality data is mapped onto a two dimension space, which is used to represent the action manifold. This "latent space" is used to quantify "the anthropomorphic motion capability" of an artificial hand by projecting "all" its fingertip poses into the same space and measuring the overlap (Figure 4.7).

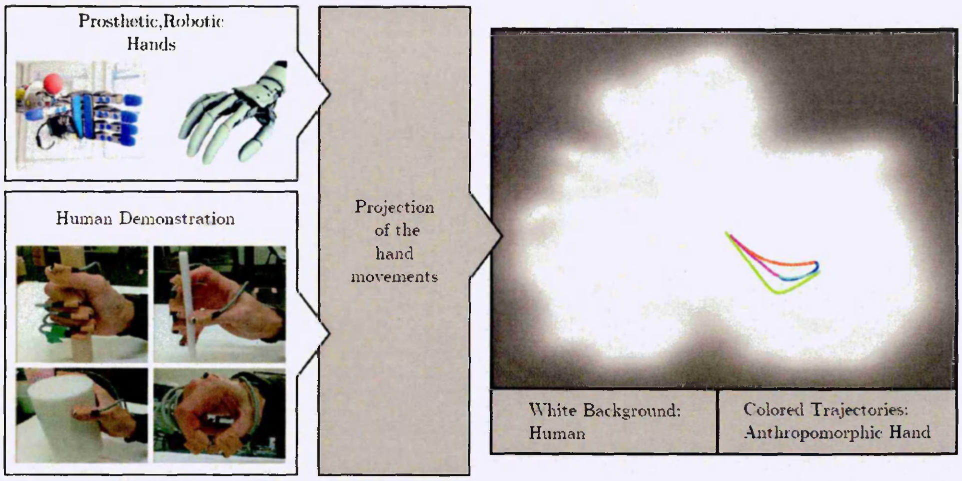


Figure 4.7: Overview of Fiex fingertip trajectory analysis system (Feix et al., 2013)

Feix et al. (2013) used a data acquisition system with six magnetic sensors to record the position and orientation of the five fingertips and the palm of the subjects while performing the grasps. The subjects were asked to place their hands in a flat posture before reaching for the object and grasping it using the designated grasp type. The subject would lift the object, replace it, then return to the flat hand posture. The data is stored with respect to the coordinates of the palm sensor frame to omit global hand movements. The dataset contains 4650 samples, each sample consists of five 12D vectors encoding the pose of each fingertip at a point along the trajectory.

Feix et al. (2013) use twelve dimensions to encode each fingertip pose, three for position in Cartesian space and nine elements of a rotational matrix for fingertip orientation. Feix et al. (2013) justify using the nine elements of a rotational matrix instead of three elements of Euler angles or the four elements of quaternions to represent orientation to avoid the singularity in Euler angles and because the euclidean distance between the elements of the quaternion does not represent proximity in orientation.

The data is then used to create the low-dimensional space using Gaussian Process Latent Variable Models (GP-LVM). Feix et al. (2013) evaluated fifty GP-LVM models and compared it to other dimensionality reduction methods and demonstrated that it is more efficient for accurate 2D representation of the higher-dimensions fingertip space of the hand. The human dataset shows that "subjects generate a similar trajectory" for the same grasp type, making it possible to define a "mean grasp trajectory".

To evaluate an artificial hand, the hand configuration space is sampled and forward kinematics is solved for each digit at each sample. The fingertip poses are then projected into the latent space. The overlap is measured by "discretizing the latent space into a regular grid and counting how many cells are populated" by the artificial hand's data. The method uses back-constrained GP-LVM to facilitate the mapping from the latent space back to the higher-dimension configuration space.

An "anthropomorphism index" is used to quantify the overlap between the artificial hand data and the human data, which represents the artificial hand's performance. The index is calculated as a percentage ratio of overlap area to the area occupied by the human data. Feix et al. (2013) report an "anthropomorphism index" 0.25% for the Otto Bock SensorHand, 2.8% for the Otto Bock Michelangelo Hand, and 5.2% (9.2% with random sampling) for FRH-4 Hand.

The method is implemented in MATLAB using the FGPLVM toolbox and version nine of Peter Corke Robotics Toolbox. The implementation is released as an open source toolbox.

Discussion of the method

The method may not be suitable for accurate prediction of an artificial hand's grasping capabilities for a number of reasons. The method uses only fingertips poses to encode the hand's posture. This assumes that the artificial hand being analysed has the same kinematic structure as the human hand, which is not always the case. This is problematic in two cases. First regarding grasps that only involve fingertips, i.e precision grasps: many artificial hands, especially prosthetic hands, do not include the distal joint. There is a high chance the hand will produce very different fingertip orientations than the reference dataset. Therefore the result will not be indicative of the hand's grasping capabilities or performance.

Secondly, this is more problematic with grasps that involve contact between the palm or other parts of the digits and the object. If the hand has a different kinematic structure, the fingertip poses will not be an accurate indication of the overall hand posture similarity.

The method does not take into account the geometry or physical properties of the hand's surface, nor does it evaluate the direction of forces generated by the hand digits.

The reference dataset includes trajectories from and to a "flat hand" posture. This means that the largest part of the dataset refers to intermediate postures that are not involved in the grasp itself. Therefore, a hand that is optimised for grasping - can only achieve grasp postures - could have the same evaluation score as a hand that can achieve many intermediate postures but not many grasp postures.

Finally, using the method as it is provided does not indicate which grasp types are attainable, which limits its application for optimisation towards specific grasps. Feix et al. (2013) propose to generate a special action manifold for such cases.

4.1.5 Roa et al. Graspability Map

Roa et al. (2011) proposed a method to generate a "map" of positions and orientations that a given hand base "can adopt to achieve a force closure precision grasp" on a given object. Roa et al. (2011) propose to use the map as a method to "compare the grasp capabilities of different mechanical hands with respect to some benchmark objects".

The method requires as input a point cloud representation of the object's surface, each point is described by a position vector measured with respect to the object's centre of mass and a surface normal pointing towards the centre of mass. The method also requires a model of the hand describing its kinematic structure and surface for collision detection.

In a preliminary step, the hand's kinematic configuration is analysed to determine the configuration subset "which potentially allow a force closure grasp". In this step, the force closure conditions are evaluated using "the normals to the fingertips", a "predefined coefficient of friction" and a virtual centre of mass "located at the centroid of the considered fingertip positions". This step produces a set of "reachable points for the fingertips of a mechanical hand which potentially lead to a force closure precision grasp".

This set is then used, along with the object model and a friction coefficient "that estimates the friction between the fingertips and the object" to generate the map. The method begins by defining a set of potential poses for the hand base frame around the object. Each pose is checked for collision with the hand while it is assuming the "configuration of maximum aperture". If a collision is present, the pose is discarded; otherwise, the intersection between the point clouds representing the object and the force closure workspace of each finger is calculated. The resulting sets are then analysed to evaluated the difference between the direction of fingertip force and the direction of the normal associated with the object surface point. If the points associated with at least two fingers point in the same direction as the normals to the object's surface, then force closure grasp conditions are evaluated, otherwise the pose is discarded.

The map represents the number of possible poses for the hand's base frame at each point is the space around the object in which a configuration exists that leads to a force closure grasp. Neither the hand configuration nor the grasp quality at that pose are represented. A variant of the map can include the grasp quality. The hand configurations that lead to force closure are not saved.

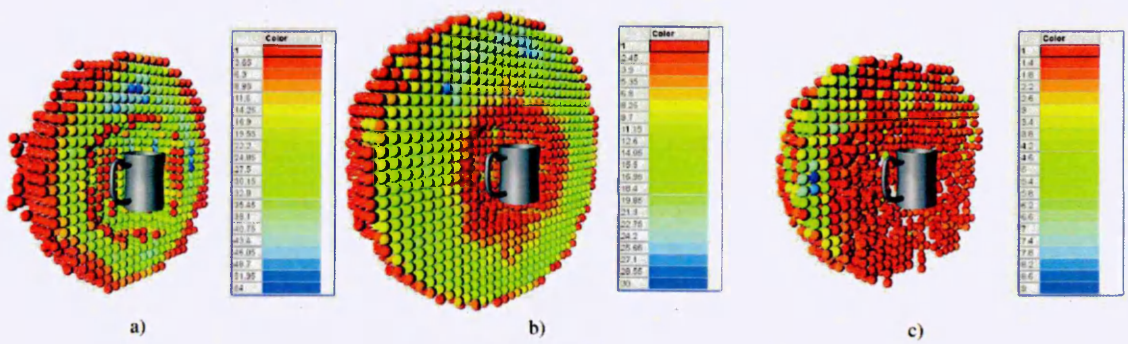


Figure 4.8: Graspability map for a cup and a) Barrett hand b) DLR hand II c) DLR-HIT hand II (Roa et al., 2011)

Discussion of the method

This method is completely concerned with the ability of an artificial hand to grasp an object. Unlike the above methods thou, this method is centred around the object more than the hand.

Although the method can be used to compare hands' grasping performance using one or more reference objects, the map is mostly concerned with the locations from which the hand can grasp the object more than the grasp quality or posture. While a variant of the map can include grasp quality, the hand configuration for any successful grasp is not stored, and therefore cannot be analysed for anthropomorphic resemblance.

This method checks for precision force closure conditions only, it cannot evaluate power grasps or the involvement of other parts of the fingers or the palm in the grasp. Furthermore, the method only considers forces generated by the fingertips and not reaction forces such as in grasps with side opposition. Nevertheless, this method remains the most accurate existing method to evaluate a hand's grasping capabilities, but it does not evaluate any aspect of anthropomorphism.

4.1.6 Malvezzi et al. SynGrasp Toolbox

SynGrasp Toolbox (Malvezzi et al., 2013) is a collection of MATLAB functions developed for the analysis of grasping performance of natural and artificial hands. The toolbox is not specific to anthropomorphic hands and can be used with non-anthropomorphic robotic grippers. The toolbox contains four groups of functions: Hand modelling, Grasp definition, Grasp analysis, and Graphics.

The Hand modelling group contains functions that allow defining the kinematic structure of a hand by defining a set of "fingers". Each finger is defined using the Denavit-Hartenberg parameters for the joints of the finger, a homogeneous transform matrix for the finger base frame, and a vector q containing values of joint variables. An array of these fingers is used to define a hand. Another function takes as an input a vector q representing a configuration and returns the hand in the new posture. Rigid and compliant kinematic coupling, along with "the synergistic organisation of hand joints" can be defined by a "synergy matrix associated to each hand". This matrix "can be manually set or dynamically calculated and can be used for the actuation either of rigid or soft synergies". The toolbox provide a set of hand models including "a kinematic and dynamic model, inspired by the human hand, that does not closely copy the properties of one specific human hand" but models the human hand in a similar way to robot hands. The model takes into account the "the synergistic organisation of the sensorimotor system" and implements a synergy matrix for the human hand from the literature.

The Grasp definition functions allow for defining contact points on the bases or ends of the links of each finger. The functions also allow for defining the selection matrix, the grasp and Jacobian matrices, joint and contact stiffness matrices and a synergy stiffness matrix. A virtual object is defined either using the contact points with their geometric centroid as the centre of mass or using the elementary geometric shapes: cylinder, box or sphere.

The Grasp analysis group enables a quasi-static analysis of the grasp quality along with other evaluation measures. "The toolbox allows to perform kinematic and force manipulability analysis, taking into account the joint coupling induced by the underactuation and hand compliance".

The Graphics group enables a simple visualisation of the hand and object. The links of the hand fingers are plotted as cylinders and the palm is plotted as an arbitrary shape connecting the bases of each finger. Figure 4.9 shows an example of the visualisation of the kinematic manipulability

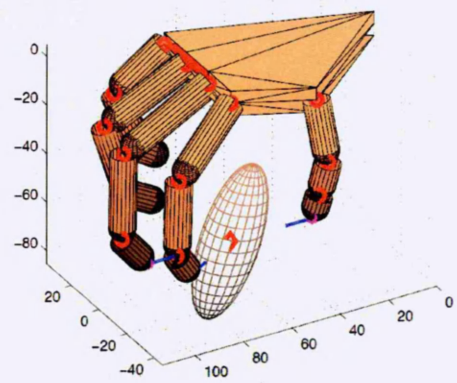


Figure 4.9: SynGrasp Toolbox analysis of a 20 DoFs anthropomorphic hand kinematic manipulability ellipsoid (Malvezzi et al., 2013)

analysis of a 20 DoF human hand model.

Discussion of the tool

This is a useful tool for grasp analysis. It allows modelling many aspects of the hand, including surface properties, soft and hard synergies, and joints' stiffness. The tool allows analysis of the kinematic manipulability of the hand and grasp quality

However, the toolbox does not allow for modelling of the geometry of the hand's surface, but rather plot the digits as cylinders and the palm as an irregular polyhedron connecting the bases of the digits. This has two negative effects, one regarding the accuracy of the contact points localisation and the other relates to the very poor visualisation.

The toolbox does not allow modelling of objects with irregular geometry, it provides the option to either use a basic geometric shape (box, cylinder or sphere) or to define an arbitrary polyhedron object using predefined contact points and their centroid as the centre of mass. Such shapes are very unrealistic and inherently assume a near perfect fingertip positioning w.r.t the centre of mass. It also limits the possible locations of a contact to either the base or tip of each link.

This toolbox can be used as a base for the implementation of any new methods developed in this thesis. Since the toolbox is released with an open source and contributions are welcomed and encouraged by the original authors.

4.2 Discussion

This section discusses the strengths and shortcomings of above methods and propose some concepts of evaluation.

4.2.1 Lessons from existing methods

What is wrong with existing methods?

Lack of comprehensiveness Existing methods only focus on either motion capabilities or grasping performance. Also, the developers of these methods did not rely on a comprehensive understanding of different the components, capabilities, and functionalities of human and artificial hands. In fact, most methods limit hand capabilities to motion capabilities only and hand functionalities to grasping only. This does not allow the user of the method to determine which hand components and capabilities are affecting the output and which components and capabilities were not considered during the evaluation process.

Methods that aim to evaluate grasping performance either evaluate hand postures or analyse grasp forces, but not both. They are in fact either evaluating a hand's anthropomorphic postures or its grasping performance, but not its anthropomorphic grasping performance. Also, the methods are not mutually compatible, for example the Graspability Map cannot be combined with Feix et al. (2013) Fingertip Trajectory Analysis.

Flawed encoding Methods that use fingertip poses to judge posture, especially those involving power grasps, are fundamentally flawed. They assume that the hand being evaluated have the exact same kinematic structure as the human hand, which is not always the case especially with prosthetic hands due to the omission of some joints.

Abstract representation of results Several methods use a simple percentage value to represent the evaluation results. This approach provides limited information on the performance of the hand being evaluated, such as what grasps it can actually do.

Evaluation at a late stage Some "methods" test the ability of a prototype to perform the required tasks, such as reproducing certain gestures or grasps. These tests are performed after the prototype has been constructed, which results in a costly and slow development process.

What can be learnt from existing methods?

Levels of analysis: abstract and extended evaluation Two types of analysis can be observed: an abstract approach and a detailed one. The first mainly relies on general *specifications* of a hand, such as number of actuators and joints, and does not consider factors such as the actuators' force capabilities or the joints' range of motion. This approach is useful for quick comparison of several hands. The second approach involves analysis of a detailed model describing properties such as links' dimensions and joints' range of motion. This approach is necessary for an accurate prediction of the hand's potential functional performance.

Anthropomorphic references Despite having problems with the approach, some methods utilise useful references. In particular, methods that evaluate motion capabilities, such as methods that implement medical tests and Liarokapis et al. (2013) Workspace Analysis, use the human hand motion range as a reference. Methods that evaluate grasping performance, such as Feix et al. (2013) Fingertip Trajectory Analysis, use taxonomies of anthropomorphic grasps. The use of anthropomorphic references allows for predicting human-like performance, thus excluding non-anthropomorphic performance such as optimised grasping for industrial applications.

Action manifold The concept of defining a *functional reference* of a hand in terms of a set of all possible tasks is useful as it allows for separate definitions of the *physical* and *functional anthropomorphic references* to evaluate artificial hands.

Functional criteria Some methods, such as the Graspability Map, utilises functional criteria, such as force closure conditions, to judge functional performance. These criteria are more accurate in determining the functional performance of a hand in comparison with methods that only rely on motion range or anthropomorphic postures.

Evaluation by simulation Some methods perform a computer simulation to evaluate a hand's design prior to prototyping it. This allows for evaluation during early stages in the development process with less cost than methods that use prototypes to perform the evaluation.

4.2.2 Evaluation concepts

Existing methods are not sufficient to comprehensively evaluate a hand. Therefore, this section proposes some ideas for a new method that combines the strengths of existing ones and provides alternative approaches to account for their shortcomings.

It has been observed that some methods evaluate the *anthropomorphism* of a hand's postures without investigating performance while others focus on *functional* performance regardless of its *anthropomorphism*. Therefore, it is possible to evaluate *anthropomorphic performance*: i.e the ability of a hand to *perform* a task in an *anthropomorphic* manner. This thesis categorises hand *components* and *capabilities* into *structure*, *surface*, *sensory*, and *actuation* components. The evaluation should consider each component's role when possible.

For a comprehensive evaluation of a hand's *anthropomorphic functional* performance, this thesis proposes to evaluate the hand's performance in each of the three *functionalities* identified in Chapter 2. The tasks of these *functionalities* are used to define an *action manifold* for the *anthropomorphic artificial hand*.

However, this approach is not useful if a user wants to determine if a hand is capable of performing a task not included in those *functionalities*. In this case, this thesis proposes to combine the methods used to evaluate each *functionality* in one method that takes as input a task description along with the hand model and produces as output the hand performance in this task only.

This thesis refers to the first approach as *functionality-based evaluation*, and refers to the second approach as *task-based functional evaluation*. Chapter 5 lists the tasks of the *action manifold* and analyses them to determine how to simulate each task and how to quantify a hand's performance in the task.

The two *functional* evaluation approaches above are simulation based. Several evaluation methods have their own dedicated implementations which perform all required simulation and analysis. These tools are developed only for those methods, they cannot be used for our methods. However, there are other simulation tools that are developed for other hand related purposes, such as the SynGrasp Toolbox. These have some potential to be used in the proposed method; however, it may still be necessary to implement dedicated tools. Chapter 6 discusses and implements the simulation tools.

Chapter closure

This chapter reviewed some existing methods used to evaluate human and artificial hands. It noted that existing methods suffer from a number of drawbacks. It proposed that these drawbacks can be overcome by a more comprehensive understanding of the functionalities performed by the human hand and the roles of different hand parts in each functionality.

Therefore, the following chapter discusses hand functionalities in more details to identify the roles of different parts, determine how to simulate their tasks, and how to evaluate a hand's performance in each task.

5

Task Modelling And Analysis

THE *ACTION MANIFOLD* OF A HAND is supposed to include all the tasks that the hand can do. This chapter outlines the evaluation framework by defining this *action manifold*, which is used as a *functional* reference to evaluate artificial hands' performance, and analysing the manifold tasks to determine how to simulate them. Finally, a syntax is defined to describe hand tasks and *anthropomorphic* postures.

INTRODUCTION

The previous chapter proposed to evaluate an artificial hand by testing, in simulation, its ability to perform the tasks that can be performed by its human counterpart. In order to perform this evaluation, a *reference* that defines what *are* the tasks that the human hand can perform is needed.

As discussed in Chapter 4, Feix et al. (2013) define the *action manifold* of the human hand as the set of "all the postures (or a chosen subset) that a hand can reach", which they used as a *reference* to evaluate the artificial hands. The *action manifold* they defined limits the tasks that the human hand can do to grasping tasks, and describes each grasp only as a "posture".

To address this limitation, this thesis extends this concept to include tasks that carry out other human hand *functionalities* and to the roles of different hand parts in each task. Therefore, this thesis defines the *action manifold* as *the set of all the tasks, or a chosen subset, that a hand can do*.

For evaluation purposes, a well defined *action manifold* is required to be used as a *functional reference*. This thesis calls this the *action manifold of the anthropomorphic hand*, which is - hypothetically - *the set of all the tasks that an ideal anthropomorphic hand can do*.

However, given the versatility and large number of tasks that can be performed by the human hand, and thus would be expected that an *ideal anthropomorphic* hand can do, defining such set is not easy. To the extent of the knowledge of the author of this thesis, there is no comprehensive list of all the tasks that an ideal *anthropomorphic* artificial hand should be able to do. Therefore, this chapter studies the primitive tasks of the hand *functionalities* identified in Chapter 2 to select the set of tasks that comprises the *action manifold of the anthropomorphic hand*.

In order for the evaluation of an artificial hand to be inclusive of the roles of different hand parts in each task, these roles must be clearly understood. Therefore, the selected tasks are analysed to determine the hand capabilities and components required to perform them. Based on this analysis, the steps to be performed to simulate the tasks are determined.

Several simulation programs are implemented in the next chapter to perform the evaluation on a number of hand models. Most of these programs are designed specifically for the tasks in the *action manifold of the anthropomorphic hand*. However, this introduces a limitation for users who wish to evaluate a hand's ability to perform only a particular task or modify the *action manifold*. To address this limitation, the simulation and evaluation programs can be combined into one single program that does not include any reference tasks but requires, as input, models of the tasks to be simulated in addition to the model of the hand being evaluated. Therefore, this chapter presents a task description syntax which can be used to describe single tasks, the tasks in the *action manifold*, modify the *action manifold*, or define a new one. Hand modelling is discussed in the next chapter.

In Section 5.1, the tasks that comprises the *action manifold* are selected and analysed to determine the hand capabilities and components required to perform each task and how to simulate it. Section 5.2 discusses the components sufficient for a unified and comprehensive task description syntax, including a syntax to describe *anthropomorphic* postures.

5.1 Anthropomorphic hand action manifold

This thesis proposes to use the tasks of the human hand *functionalities* to compile an *anthropomorphic hand action manifold*. However, some *functionalities* contain infinite number of possible tasks. Therefore, this section selects from the tasks reported in the literature a group of tasks that represent each *functionality*. Finally, this section analyses the selected tasks to determine the hand capabilities and components required to perform each task in order to simulate it.

5.1.1 Selecting tasks to comprise the action manifold

There are eight Exploratory Procedures (EP) in the *active sensing functionality*. Two of them, *Function* and *Part Motion Test*, require prior knowledge and are generally ignored in the literature. These two are also not *sensing* tasks from the hand's perspective, but *grasping* tasks, while the sensing part involves global motion and visual feedback. Also, one of the remaining six EPs, the *Unsupported Holding EP*, is only a *grasping* task from the hand's perspective, while the *sensing* part is mainly carried out by *effort state sensors* in the arm. Therefore, the remaining five EPs are used as the *action manifold* tasks of the *active sensing functionality*.

There are thirty-three grasps in the *grasping functionality*, two of which - Distal Type and Tripod Variation - are not considered in this thesis as they are *skillful tasks*, which brings the total number down to thirty-one grasps, including twelve precision grasps. The *within-hand manipulation functionality* can be performed using any of the twelve *precision grasps*. Therefore, these tasks are used as the *action manifold* tasks of the *prehensile functionalities*.

The *non-prehensile skills* group is much more diverse. *Bi-manual music skills functionality* and *piano playing* from the *keyboard skills functionality* are not included in the *action manifold* because they are *skillful tasks*. For the *gesturing functionality*, the ten counting gestures and the seventeen "basic handshapes" signs of BSL are used as the *action manifold* tasks. For *pointing and aiming functionality*, the *hand task* component is only the *pointing gesture*. For the *keyboard skills functionality*, the tasks of *typing on a computer keyboard* and *tapping on a Morse code transmitter* are used.

This leads to a total of seventy-eight tasks for the *action manifold*. Below, each group is discussed to determine how to simulate the tasks. Section 5.2 presents a syntax to describe tasks, for the description of all *action manifold* tasks see Appendix B.

The *action manifold* tasks are single-handed *primitive* tasks. Bi-manual and simultaneous within-hand tasks, and a possible way to describe *skillful tasks*, are discussed in Section 5.2.

5.1.2 Analysing the tasks in the action manifold

It is necessary to identify the motion and sensory capabilities required to perform a task - and the interaction between the hand and any involved objects - in order to simulate the task and evaluate a hand's ability to perform it. This section analyses the tasks of the *action manifold* to identify these capabilities, the next section discusses how to simulate the tasks based on this analysis.

The motion and sensory capabilities of a hand result from its physical construction. Chapter 3 categorised hand components into four categories: *structure*, *surface*, *sensors*, and *actuation*. The *structure* and *actuation* give rise to the hand's motion capabilities, and *sensors* give rise to the hand's sensory capabilities. *Surface* geometry and physical properties, such as friction and compliance, affects the hand's interaction with external objects. This thesis discusses the components giving rise to capabilities required for the performance of the tasks.

The tasks of the *action manifold* are categorised into five groups based on the task aims observed in Chapter 2, which are *information exchange*, *grasping*, *within-hand manipulation*, *visual expression*, and *force exchange*. Each category is discussed separately.

Active Sensing functionality (Information Exchange)

Motion capabilities These tasks require the hand to assume postures that appear anthropomorphic and position the sensitive parts of the hand's surface in a pose suitable to make contact with objects. There are no timing or force requirements, the tasks can be successfully performed at any speed or using any forces. As for postures, graphic illustrations show Lateral Motion EP being performed using the extended upper fingers, Pressure and Contour Following EPs being performed using the extended index finger, and Static Contact EP being performed using a flat open hand posture. There is no specific posture for Enclosure EP.

Sensory capabilities Lateral Motion and Static Contact EPs require the ability to sense surface texture and temperature respectively, both of which are exclusively surface properties that can be detected using interaction sensing. Lateral Motion EP requires force data to estimate surface texture, this is implied in Tan et al. (2014) work on interfacing an FSR sensor with a prosthetic hand user's nerves (see Chapter 3) which allowed the user to perceive texture. This is also verified by an experiment designed by the author of this thesis and conducted by a student undertaking a master's degree under the supervision of the author (see Appendix C). The remaining three EPs require both interaction and state sensors to both detect surface information and relate the information to each other or to the hand's origin frame at the wrist. Pressure EP aims to estimate object's hardness by comparing the force used to compress the object's surface with the resulting displacement. This requires interaction sensors to detect the force at contact as well as position state sensing to estimate the displacement. Contour Following EP aims to track the edge of the object to estimate its geometry. This requires the ability to detect the edge and the ability to tract its position relative to the hand's origin frame. Enclosure EP requires the ability to detect contact at different locations on the hand's surface and relate the positions of those contacts to each other to obtain an estimation of the object's geometry and volume.

Interaction with external objects All EPs need to make contact with surfaces or edges of objects. Lateral Motion, Pressure, and Contour Following EPs make contact at the fingertips. Contact may occur anywhere on the hand's palmar surface in Static Contact and Enclosure EPs. Lateral Motion and Contour Following EPs involve motion at contact that may be affected by the surface friction; however, it is a global motion which is not considered in this thesis.

Hand components Components required to achieve the above capabilities are:

- **Structure** The structure arrangement and dimensions affects the hand's ability to assume anthropomorphic postures and position the interaction sensors.
- **Surface** The hand must make contact with objects at specified locations on the hand.
- **Sensors** The tasks require force, force array, and temperature interaction sensors as well as joint position state sensors. Sensor locations are determined by contact locations.
- **Actuation** The kinematic coupling of the transmission system affects the possible configurations which the structure can achieve.

Prehensile functionalities: Grasping

Motion capabilities Grasping tasks aim to position the hand links in a posture that will restrain the object by satisfying force or form closure conditions. The hand should apply appropriate grasp forces. The postures should also appear anthropomorphic.

Sensory capabilities The tasks require the ability to monitor locations of contact with objects as well as the forces exchanged at the contact points. The former can be accomplished using force array interaction sensors and position state sensors. The latter can be accomplished using either force interaction sensors or joint effort state sensors.

Interaction with external object Feix et al. (2009) taxonomy represents all possible graspable objects using primitive geometric shapes (Figure 2.12). The hand makes contact with the objects at several locations, usually fingertips for precision grasps and all surface for power grasps, to apply the grasp forces. For description of each object and associated contact locations see Appendix B. Surface friction (and compliance) affects the exchange of forces at contact.

Hand components Components required to achieve the above capabilities are:

- **Structure** The structure arrangement and dimensions affects the hand's ability to assume anthropomorphic postures, and position the links and apply forces to restrain the object.
- **Surface** Surface friction and compliance affects transmission of forces through contact points. The hand must make contact with objects at specified locations on the hand.
- **Sensors** The tasks require joint position state sensors and force interaction sensors or joint effort state sensors. Sensor locations are determined by contact locations.
- **Actuation** The actuators provide the grasp forces. The transmission system properties affect transmission of forces and the kinematic coupling affects the possible configurations which the structure can achieve.

Prehensile functionalities: Within-hand Manipulation

Motion capabilities Within-hand manipulation tasks aims to move the hand links so as to change the object's pose with respect to the hand origin frame without loosing force closure. These tasks restrain the object using only forces and grasp the object using the fingertips. The tasks can be performed successfully at any speed, therefore the tasks are quasi-static.

Sensory capabilities These tasks share the same sensory requirements as grasping tasks in addition to the ability to monitor the positions of hand links to control the hand motion.

Interaction with external object This functionality can be performed using any of the twelve precision grasps of Feix et al. (2009) taxonomy. The hand makes contact with the objects at the fingertips. Surface friction (and compliance) affects the exchange of forces at contact.

Hand components Components required to achieve the above capabilities are:

- **Structure** Same as Grasping *functionality* plus the ability to move the segments while maintaining force closure grasp.
- **Surface** Same as Grasping *functionality*.
- **Sensors** Same as Grasping *functionality*.
- **Actuation** Same as Grasping *functionality* plus the ability to move the structure while maintaining force closure grasp.

Non-Prehensile functionalities: Gesturing (Visual Expression)

Motion capabilities The only functional motion required in gesturing functionality, and pointing and aiming functionality, is the ability to assume anthropomorphic postures. The gestures can usually be performed at any velocity, and there is no force requirements given the absence of contact.

Sensory capabilities The tasks require the ability to monitor joint positions to ensure the required posture is achieved. There are no interaction sensing requirements due to absence of contact.

Interaction with external objects There is generally no interaction with external object. The only two exception to this is if both hands come in contact during two-handed signs and if the hand makes contact with an object while pointing at it, in both cases no force or information exchange is required.

Hand components Components required to achieve the above capabilities are:

- **Structure** The structure arrangement affects the hand's ability to assume anthropomorphic postures.
- **Surface** Surfaces are not involved in these tasks.
- **Sensors** Joint position state sensors are required to monitor posture.
- **Actuation** The transmission system kinematic coupling affects the possible configurations which the structure can achieve.

Non-Prehensile functionalities: Keyboard skills (Force Exchange)

Motion capabilities The task of "typing on a computer keyboard" requires the ability to move the fingers to press single keys (with appropriate force) without pressing adjacent keys. The task has no velocity requirements. The task of "tapping on a Morse code transmitter" requires the ability to press and release a key after a specific duration, with appropriate force. The postures used during the tasks should also appear anthropomorphic.

Sensory capabilities These tasks require state sensors to control posture and forces. The task of "tapping on a Morse code transmitter" also require interaction sensors to detect contact in order to control timing.

Interaction with external objects The tasks involve force exchange with keys of the keyboard or Morse code transmitter. A keyboard is a grid of keys with particular dimensions and key travel, the grid resolution is defined as 19.05 mm (0.75 inches) in both directions and the key travel is 3.81 mm (0.15 inches). The keys may have activation force. Keys of a Morse code transmitter has the same properties.

Hand components Components required to achieve the above capabilities are:

- **Structure** The structure arrangement affects the hand's ability to assume anthropomorphic postures and position the links to deliver the forces needed to press the keys.
- **Surface** Surface friction and compliance affect force exchange between the hand and object. The hand must make contact with objects at specified locations.
- **Sensors** Joint position and effort state sensors are required to perform the tasks. Force interaction sensors is required at the contact location to detect contact, especially for tasks involving timing.
- **Actuation** The actuators provide the forces required to induce the motion in the structure as well as the forces required to press the keys. The transmission system properties affect transmission of forces and the kinematic coupling affects the possible configurations which the structure can achieve.

5.1.3 Stepwise analysis of the tasks in the action manifold

Based on the analysis of the hand capabilities and components required to perform each task, and the objects involved in the task, this section proposes a way to simulate each task. This analysis also enables determining how to model tasks and hands to be used in the simulation environment, task modelling is discussed in Section 5.2, hand modelling is discussed in Chapter 6 on the implementation of the simulation environment.

Active Sensing functionality

To perform the tasks of this *functionality*, the hand must be able to make contact with the object at the specified locations while assuming an anthropomorphic posture. The hand should also contain all the necessary sensors. Therefore, to simulate such tasks, the hand model is used to perform the required postures and make contact with an object model at the specified locations. This involves testing the hand posture for anthropomorphism and testing the hand's surface for correct contact with the object. Separately, the test checks if the hand contains the required sensors.

Prehensile functionalities: Grasping

To perform the tasks of this *functionality*, the hand must be able to make contact with the object at the specified locations and restrain the object either by applying grasping forces only or by also achieving form closure. The hand should assume an anthropomorphic posture during the grasp. To simulate this task,the same approach as with the simulation of *active sensing* tasks above is followed with the addition of testing for force and form closure conditions at every iteration.

Prehensile functionalities: Within-hand Manipulation

To perform the tasks of this *functionality*, the hand must first grasp the object using a precision (force closure) grasp then move the hand digits to move the object with respect to the hand (Jones and Lederman, 2006). Therefore, to simulate this task, the test first grasps the object using the steps for grasping above (without testing for form closure). Then, once a precision grasp is achieved, it examines the hand's ability to move the digits in order to move the object. Alternatively, the test checks for all possible configurations of the hand and object that leads to a successful grasp, then determines if two different configurations are continuous; i.e, there exist a successful grasp at every configuration between the two. If so, then the hand can move the object from its pose in one configuration to the other without loosing force closure grasp.

Non-Prehensile functionalities: Gesturing

The tasks of this *functionality* only requires the ability to assume anthropomorphic postures. Therefore, to simulate this task, the hand's configuration space is scanned and a test checks if each configuration leads to an anthropomorphic posture. Separately, the test checks if the hand contains the sensors necessary to monitor the posture.

Non-Prehensile functionalities: Keyboard skills

One task of this *functionality*, "typing on a computer keyboard", requires the ability to make contact with a specified location of an object without making contact with any other location. The task also requires the ability to assume anthropomorphic postures and to deliver an appropriate force at the contact. This task can be simulated by modelling the object (a keyboard) and testing whether the hand can assume the required postures and press the keys without touching other keys. The other task can be similarly simulated except that instead of the spatial constraints (not pressing other keys) it has temporal constraints. The digits must be able to press and release the key in the specified duration. This last part mainly involves the actuation systems ability to move the digits fast enough to perform the task.

5.2 A SYNTAX TO DESCRIBE TASKS

A fixed simulation-based evaluation system that is based on pre-defined tasks (the *action manifold*) may not be suitable for certain cases, such as if a user wishes to evaluate a hand's ability to perform a particular task that is not included in the pre-defined tasks. For this reason, a syntax is developed to describe hand tasks based on the task analysis above. This description is used as input to a simulation method that combines all the individual tests proposed for each of the five categories in Section 5.1.3. One part of this syntax, the syntax to describe *anthropomorphic postures,* is also used as input to a Fuzzy logic system (see Chapter 6) that test for postural anthropomorphism in all the above five individual tests.

Ideally, a comprehensive task description should include all information required to simulate or perform the task as well as to determine the hand capabilities required by the task. Generally, this could be a human-readable verbal description or a computer data structure. This section discusses the description of simple and complex tasks, postures and objects involved in the task, and the task characteristics. This section aims to describe tasks in both human-readable and data structure formats; however, the priority is for data structures as they are necessary for simulation. This section discusses the components required in a description and how can they be represented in a human-readable format, data structure representations are discussed in Chapter 6 on the implementation of the simulation and evalution program.

5.2.1 DESCRIBING SIMPLE TASKS

Most basic task information can be inferred from the characteristics proposed by Dollar (2014). For example, occurrence of contact indicates that an object is involved in the task, and prehension indicates that the object should be grasped. However, these characteristics on their own do not provide any information about the *anthropomorphism* of the task, the involved objects, or any data acquisition or *force exchange* occurring during the task. Therefore, to describe simple tasks, Dollar (2014) characteristics are used at the *header* of a task description (with few additions and modifications, see Section 5.2.5) and more details of the involved postures, objects, and *information* and *force exchange* are added in the *body* of the description.

ANTHROPOMORPHIC POSTURES Tasks can be accomplished using an *anthropomorphic* or a *non-anthropomorphic* posture. Therefore, a task description should include any postures associated with the task. However, the majority of reviewed literature - including literature mainly concerned with hand postures during grasping - does not explicitly (verbally) describe hand postures. Instead it provides graphic illustrations of the postures. Therefore, a syntax to describe hand postures must be defined, and the reference postures must be infered from the provided graphic illustrations. This point is discussed in more detail in Section 5.2.3.

Task objects A task description should include any objects involved in the task and its relations with the hand. An object description should be as informative as necessary, including geometry, mass, and surface friction. Relations between the hand and the object, such as locations of contacts on the hand and object pose with respect to a hand-fixed frame, determine some of the task requirements and affect the *anthropomorphism* of the task performance. This point is discussed in Section 5.2.4.

Information exchange The above description elements are mainly concerned with the motor *output* role of the hand, but not its sensor *input* role. Since several tasks require acquiring information about the external environment, it is necessary to include in the task description the type of the required information. This is very important for evaluation as some hands many contain the motion capabilities required for *active sensing* tasks but not the sensory capabilities. Given the sensor capabilities of human and artificial hands, *interaction sensors* requirements can be *force*, *force array*, or *temperature* data. *State sensors* data can be *position*, *velocity*, or *effort* of the joints.

Force exchange Some tasks of the human hand *functionalities* involve applying forces on the external object without prehension. This is usually performed by the fingertips. Such forces are usually applied through global motion carried out by the host arm; however, in some cases the forces my be generated through a with-in hand motion. Therefore, task descriptions should include any necessary non-prehensile *force exchange* described as a contact wrench in a hand frame defined in a similar manner as *object frame relations* (see Section 5.2.4).

5.2.2 Describing complex tasks

Complex tasks, such as "time-separated sequences", "simultaneous bi-manual", and " simultaneous within-hand" tasks, cannot be described using the above approach. Therefore, this thesis utilises Dollar (2014) proposal to describe them as a "sum of (their) discrete sub-components".

Motion sequence A "time-separated sequence" implies motion; however, it does not indicate if the motion is slow enough to ignore the effect of inertial forces (quasi-static) or if those forces will affect the task performance. Some tasks may have timing constraints, such as the task of *tapping on a Morse-code transmitter*, affecting motion velocity and acceleration. Therefore, it is important to include a detailed description of motion as well as temporal constraints in the task description.

This thesis describes motion sequence tasks where timing is not a crucial element - a *time invariant sequence* - using a sequence of task descriptions for each step, which is referred to as *instances*. These *instances* form a series of eigenpostures which the hand must follow to execute the task. The transition between the instances is assumed trivial, if transition is nontrivial it must be described as a separate *instance*. Timing parameters are added to describe a *time constrained sequence*.

Sequence identifier in the task description header indicates the order of the description in a motion sequence, with the value *zero* indicating that this task is not part of a sequence. Timing parameters can be described in terms of time required to change from previous hand state to new hand state, which is referred to as *rise time*, and the duration in which the hand state should be maintained or the task should be performed, which is referred to as *hold time*. These values are in seconds, and the value *zero* indicates that there is no timing constraints.

Bi-manual tasks A bi-manual task is described as two or more *instances*, at least one *instance* per hand. A hand identifier flag is included in the description to indicate if it is part of a bi-manual task description. Bi-manual tasks are usually mirrored between users who prefer to use their left hand (left-handed) and users who prefer to use their right hand (right-handed). Therefore, this thesis adopts the approach of describing BSL signs by describing bi-manual tasks in terms of "prime" and "secondary" hands, where the "prime" hand is the user's preferred hand, i.e left for left-handed users. Therefore, the flag can take the values "P" or "S" to indicate description of the prim or secondary hand respectively. The flag is set to zero for single-handed tasks.

If both hands come in contact with each other during the task, this thesis describes the relations between them as a hand-object relation. Therefore, each hand is described as the task object for the other hand.

Within-hand task requirements Simple descriptions are not sufficient to indicate if a task can be performed simultaneously with another task in the same hand, i.e inter-task compatibility. To determine two tasks compatibility with each other, the descriptions must include some parameters that allow the detection of any conflict.

The example of "thumb-typing on smartphone" task suggests a possible solution. In this example the palm and a set of digits - the fingers - are performing the first task; supporting the smartphone, while the digit unused by this task - the thumb - is utilised by the second task; typing on the screen. The first task requires the palm and four digits, leaving one digit unused. In this case, any task that only requires the unused digit can be performed simultaneously with the first task. Therefore, palmar and digital requirements are included in the form of six Boolean variables representing, in order, the palm, thumb, index, middle, ring, and small finger.

Compound and skillful tasks Some tasks may include other tasks, for example *non-prehensile aiming* task can be performed using a *grasped* object (stylus) and playing percussion musical instruments may require *grasping* the drumsticks. To avoid complication, this thesis only describes the part of the task that directly involve the hand. For the above two examples, this is a *grasping* task to hold the stylus or drumsticks, regardless of what they are used for. A similar approach can be used to describe *skillful tasks*, provided that the task can be broken down into *primitive "sub-componenets"*.

5.2.3 Describing anthropomorphic postures

Most reviewed literature does not verbally describe hand postures, instead it provides graphic illustrations of the postures. While a graphic illustration is useful to describe the posture to a human observer, it cannot be directly used as input to a computer algorithm or simulation program. Therefore, this thesis needs to establish a syntax to describe hand postures and infer reference postures for each task from the provided graphic illustrations.

The only literature that includes verbal descriptions of postures is the literature on *gestures* and *signs*. However, there is usually a graphical illustration accompanying the description, which relaxes the requirements on the definiteness of the verbal description. The verbal descriptions provided in this literature are analysed to determine how to describe postures in a clear and defined way without the graphic illustrations.

Analysis of BSL descriptions

The analyses begins by analysing descriptions of BSL "basic handshapes" signs (Table 5.1). These are single hand postures that are most used in BSL. These postures are sometimes used during the description of other signs. The first observation is that the descriptions take the following form:

- hand/hand part(s) is/are at [*state*]

State can be definitive, as in "hand is *closed*", or a *relation* with another hand part, as in "thumb is *across* the fingers". It can also include a location as in "bent at the *palm knuckles*", magnitude approximation as in "*tightly* closed", or shapes as in "curved in a *'C' shape*".

It is noted that specific words (Table 5.3) are used to describe the state. Identifying when each word is used is done by comparing the descriptions with the provided illustrations (Table 5.2).

Another observation is that the hand is described as "tightly closed" when all joints of all fingers are flexed, making the fingers "curled" into the palm. But it is described only as "closed" when the first and second joints of each finger are flexed but the last joint remains extended. All descriptions starting with "the hand" always include a separate description of the state of the thumb, which indicates that the term "hand" is mainly a reference to the fingers. Some of these descriptions include a separate description of one or more of the fingers.

Another observation is that the finger abduction is described as a relation - separation - between fingers, not an independent state of individual fingers. The word "extended" is used exclusively to describe the extension of the MCP joints, while the word "straight" is used with the interphalangeal joints.

The thumb is usually described in terms of its relation to the fingers. Finally, it is observed that magnitude of any state is described using *approximate* values, as in *slightly* and *tightly*.

Handshape	Description
Fist	The hand is [tightly closed] and the thumb is [across the fingers]
Bunched Hand	The finger ends and thumb are [bunched together]
Closed Hand	The hand is [closed] and the thumb is [against the index finger]
Flat Hand	The fingers are [straight and together]
Open Hand	The fingers and thumb are [straight and spread apart]
Clawed Hand	The fingers are [extended and bent and spread apart]
Bent Hand	The fingers are [straight and together and bent at the palm knuckles]
'C' Hand	Hand is [closed] with index finger and thumb [extended and curved in a 'C' shape]
'O' Hand	The tip of the index finger touches the tip of the thumb to form an 'O' shape
'L' Hand	The hand is [closed] with the index finger and thumb [extended in 'L' shape]
'M' Hand	The index, middle and ring fingers are [extended, straight and held together]
'N' Hand	The index and middle fingers are [extended, straight and held together]
Irish 'T' Hand	The hand is [closed] with the index finger [bent round the top of the thumb]
'V' Hand	The index and middle fingers are [extended and spread apart]
'Y' Hand	The hand is [closed] with the little finger and thumb [extended]
Full 'C' Hand	The thumb is [curved] and the fingers are [held together and curved in a 'C' shape]
Full 'O' Hand	The tips of fingers and thumb are [held together to form an 'O' shape]

Table 5.1: Description of basic BSL handshapes (Smith, 2009)

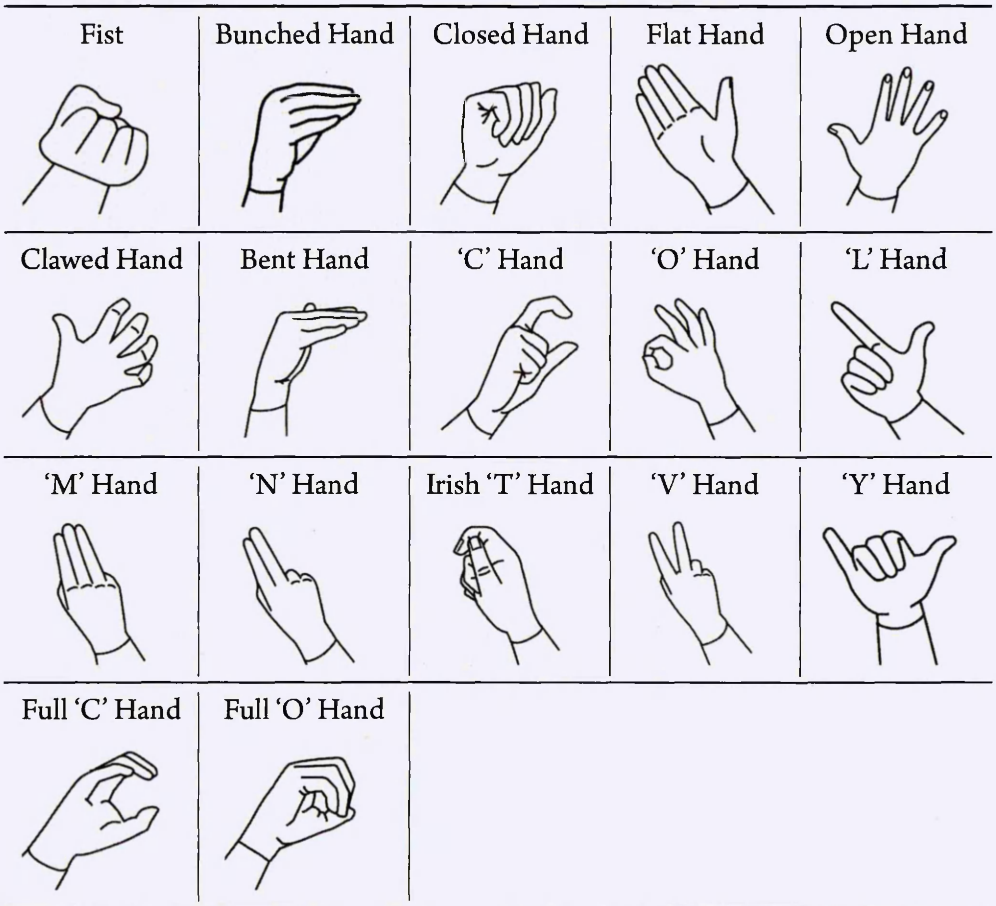


Table 5.2: Images of basic BSL handshapes signs (Smith, 2009)

Hand part	Definitive state	Relative state	Location	Magnitude	Shape
Hand	Closed			Tightly	
Digits Finger ends Top of (digit) Tip of (digit)	Extended Straight Bent Curved	Across Bunched Together Spread apart Bent round Touches	(palm) knuckle		'O' shape 'C' shape 'L' shape

Table 5.3: Words used in descriptions of BSL signs

Describing postures

The syntax is defined by comparing the words above with the human hand motion capabilities. The posture of a finger is described as the state of three motions; abduction, flexion of the MCP joint, and flexion of interphalangeal joints. Abduction can only be described as a relation between pairs of fingers, therefore state of abduction can be "crossing", "together", or "separated". Flexion at the MCP joint is described using the words "extended" and "bent at first-knuckle". The words "straight", "curved", or "curled" are used to describe flexion at both the PIP and DIP joints, where "curled" refers to both joints being fully flexed. Flexion at only one of the two joints is described using "bent at second-knuckle/third-knuckle". The word "slightly" is used with "bent" to describe the magnitude of the motion.

Describing the thumb's posture is more complex due to its high mobility. The terms "in opposition" and "in retroposition" are used to describe the opposition state. This thesis adopts the approach of some resources to use "abducted" and "adducted" to describe palmar abduction. Radial abduction is described using "far" from or "adjacent" to the palm. Note that this state is only applicable when the thumb is *in retropostion*. Flexion at MCP and IP joints is described the same way as the fingers. Finally, a description of the thumb tip's contact relation with the fingers can be added, as in "touching the back of the fingers".

This standard posture description syntax takes the form

- The *hand* is in *state*. The *finger(s)* is/are in *state*. The *thumb* is in *state*.

There are four possible states for the hand; *closed, tightly closed, open*, and *flat*. The fingers could be any or all of the four fingers, including using the terms *upper* and *lower* fingers. Their states are any of the words mentioned above, described in the order; abduction state, MCP flexion state, and interphalangeal joints state. The state of the thumb is described in the order; opposition, palmar abduction, radial abduction, MCP flexion, IP flexion, and contact relations with other fingers. Any digit state not described is assumed to be the default indicated by the state of the hand, if no hand state is described then *open* state is assumed. Table 5.4 lists the possible states.

The description of the above *'M' Hand* posture using the description syntax would be; *The hand is flat. The small finger is bent at first knuckle and bent at second knuckle. The thumb is in opposition,*

Hand part	State
Hand	(Tightly) Closed | Open | Flat
Fingers	Crossing | Together | Separated Extended | (Slightly) Bent at first knuckle Straight | Curved | Curled | (Slightly) Bent at second/third knuckle
Thumb	In opposition | In retropostion Abducted | Adducted Far from palm | Adjacent to palm Curved | Extended/Straight | (Slightly) Bent at first/second knuckle

Table 5.4: Posture description possible states

abducted, curved, and touches the back of the small finger. The new descriptions of all BSL basic handshapes used in the *action manifold* is provided in Table B.10.

5.2.4 Describing objects

A task description should include, when necessary, a description of any involved objects as well as the contact and spatial relations between the hand and the object.

Object

An object description should indicate at least the geometry of the object. If needed, the description can also include the mass, inertia matrix, and surface compliance and friction.

However, a verbal description is not an efficient representation for simulation purposes, especially for complex geometric objects, where a data structure would be more efficient to fully describe the object. This point is revisited in Chapter 6.

Contact relations

To describe location of contact, the hand is divided into regions of palm and proximal and distal digits' segments. The middle phalanx, if present in the artificial hand, is considered as part of the proximal segment. This results in eleven locations on the hand where contact with an object can occur. Figure 5.1 shows an example of possible contact locations on the InMoov robot hand.

The full relation is described as an array of eleven integers, each describing the state of contact at a location. The first integer represents the palm. Each two subsequent integers represent the proximal and distal segments of a digit; starting at the thumb, followed by the index finger, and so on. There are four possible states of contact on each location; 0) the segment should not be in contact, 1) the segment may be in contact, 2) at least one segment within the digit should be in

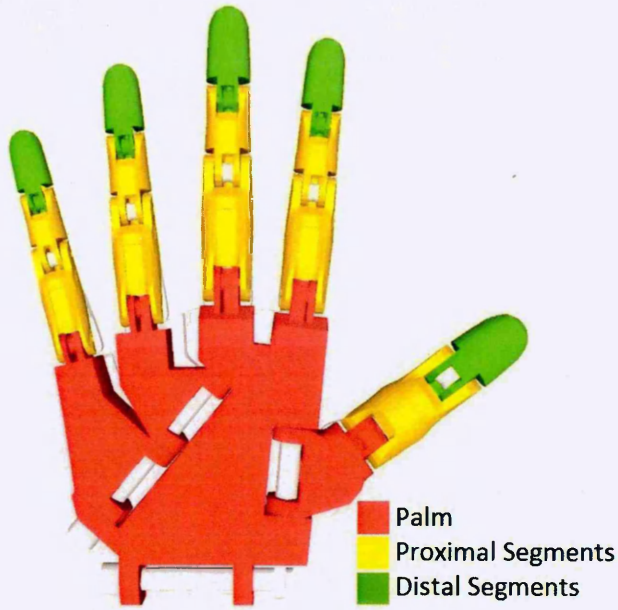


Figure 5.1: Contact locations on the InMoov robot hand (built at Sheffield Hallam University based on the model provided by Langevin (2012))

contact, and 3) this segment should be in contact. For example, to describe contact occurring on the fingertips of all digits, the relation is written as: [0 - 0 3 - 0 3 - 0 3 - 0 3 - 0 3].

Pose

In order to simulate a task, the task description should indicate where the object should be located with respect to the hand. Object pose is ideally defined between a frame fixed at the object's Centre of Mass (CoM) and a frame fixed at the hand. The hand frame is chosen to be either the wrist, a joint frame, or a tip frame, possibly translated to the surface. However, given the differences in dimensions between different hands, it may be easier to define the pose as to lie in a *workspace* of the palm or digits, or within a *range* defined by locations on the hand. Here, a simple way to describe the relation as a *frame*, *workspace*, or *range* is presented.

Frame *Frame* relations are defined relative to the wrist, joint, or tip frames. The wrist frame is denoted by uppercase 'O' (origin), joint and tip frames are denoted by uppercase 'D' (digit) followed by the digit number and a lowercase suffix 'p', 'm', 'd', or 't' to indicate *proximal, middle, distal* joint, or the digit *tip* respectively. A lowercase prefix 'f' is used to indicate the description is of a *frame*. Finally, the frame can be translated along its z-axis to the palmar (frontal) surface, denoted by the suffix '_f', or the dorsal (back) surface, denoted by '_b', or it can be translated along its y-axis to the radial surface, denoted by '_r', or the ulnar surface, denoted by '_u'. For example, to describe a frame at the palmar surface of the index distal joint, it is written as "fD2d_f". Figure 5.2 shows an example of frame locations on the InMoov robot hand for the wrist and first two digits as well as the translation of the index distal joint frame to the four possible surfaces. The description of the *frame* is followed by six numerical values describing the object's CoM pose relative to the

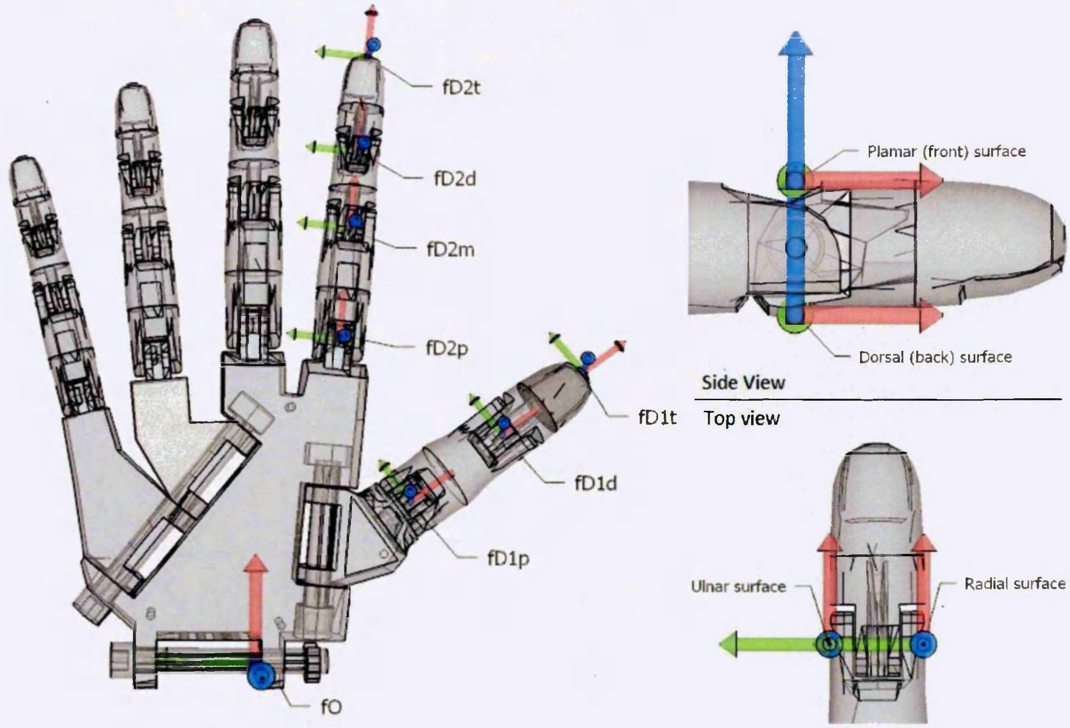


Figure 5.2: Example frame on the InMoov robot hand (model source: Langevin (2012))

frame in terms of translation in mm along the X, Y, and Z axes and rotation in degrees about the three axes.

Workspace A *workspace* relation is described by indicating that the object frame lies in the *palm* workspace, denoted by 'P', or the workspace of a digit segment, denoted by 'D' followed by the digit number and segment identifier 'p', 'm' or 'd'. The prefix 'ws' is used to indicate a description of a *workspace*. The palm workspace is defined by the width and length of the palm and assigned a height equal to the length of the longest digit. It can be divided into proximal and distal halves, denoted by suffix 'p' and 'd' respectively, and radial and ulnar halves, denoted by 'r' and 'u' respectively. A *workspace* relation may be followed by a *range* relation for the allowed object orientating within the workspace. Finally, the symbol '$\cap$' is used to indicate that the frame lies in the intersection of two or more workspaces. For example, to describe that the object CoM lies in the intersection of the palm's distal and radial workspaces, it is written as "ws[$P_d \cap P_r$]".

Range A *range* is described using reference points on the hand model. These can be the location of the origin (denoted by 'O'), a joint or tip (denoted by 'D' followed by digit number, segment identifier, and translation to surface), the extension of a segment model in 3D space (denoted by 'P' for "palm" or 'D' followed by digit number and segment identifier and an indication of the direction of extension), or the length of a digit (denoted by 'D' followed by digit number and the suffix '_l'). To describe the direction of extension, the suffix '_p' or '_d' is used to indicate "proximal" or "distal" ends respectively, '_f' or '_b' to indicate "palmar" (frontal) or "dorsal" (back) ends respectively, or '_r' or '_u' to indicate "radial" and "ulnar" ends respectively. The prefix 'r' is used to indicate a description of a *range*. The description of the relation consists of the minimum and maximum values for hand points for each of the six pose values plus the minimum and maximum numerical values derived from the dimensions of the object. The minimum and maximum values, if required, are separated by the character '~'.

For example, to describe the pose relation for the object associated with "precision sphere grasp" as a *range*, it is written as: [rO~ P_d, rP_r~ P_u, rP_f+43~ rD3_l, rO, rO, rO].

5.2.5 Task characteristics

Dollar (2014) described five tasks characteristics which are useful for task description and analysis. They can be used to determine required analysis methods and parameters.

Occurrence of contact indicates that the model and subsequent analysis of the task should include a contact interface model. It also indicates that the task may involve interaction sensing. Occurrence of prehension further indicates that restraint analysis is required. Occurrence of motion indicates that further analysis may be required if the task has any temporal constraints. The indication of whether the motion is global or within hand determines whether the analysis applies to the host arm or the hand itself. Occurrence of motion at contact indicates that surface properties at contact need to be included in the analysis.

Redefined characteristics

Some of Dollar (2014) definitions of characteristics relating to motion are misleading. Additionally, the five characteristics do not cover all the proposed parameters, such as presence of reference postures. Therefore, two of the original characteristics are redefined and three new ones are introduced.

Motion Dollar (2014) approach of describing motion begins by indicating if "*any part of the hand* moves relative to *body fixed frame*", including global and within-hand motion. The following characteristic defines *if* the motion is within the hand, which is only applicable when the earlier characteristic is true. However, this means the description of a task that includes within-hand motion only and a task that includes global and within-hand motion will be the same, with no way to determine the state of global motion. Therefore, "motion" characteristic is renamed and redefined to be exclusive for "global motion"; *there is "global motion" if the hand base frame moves relative to body fixed frame.* Subsequently, *within hand motion* is independent, allowing description of occurrence of global motion only, within-hand motion only, or both.

Motion at contact Dollar (2014) definition of "motion at contact" may be misleading. The term "motion at contact" implies that the two contacting surfaces are moving relative to each other, i.e slipping or rolling. However Dollar (2014) defines motion at contact as a motion between the object's reference frame and contact point frame(s). This definition therefore applies to situations such as compressing compliant objects as in Pressure EP, where contact point frame(s) move relative to object frame without the occurrence of slipping or rolling. This further complicate things if the relations between the object's reference frame and the object's surface points frames are not fixed, for example when handling soft fabrics. "Motion at contact" is redefined to be: *there is motion at contact if the contact points change position on either surfaces with time*

New characteristics

This thesis proposes three new characteristics to be included in a task description *header*. Three Boolean flags denoted by 'R', 'D', and 'F' indicate the presence of associated postures, *information exchange*, and force constraints respectively, with the force constraints described in the body of the task description as contact wrenches.

Chapter closure

This chapter presents an outline of a framework to evaluate artificial hands by defining the tasks the hands should be able to perform and how to simulate these tasks. The chapter selected seventy-eight tasks that comprise the *action manifold of the anthropomorphic hand*, which is the set of all tasks that a hypothetical ideal *anthropomorphic* hand can do. This *action manifold* is the *functional reference* to evaluate *anthropomorphic* artificial hands in the proposed framework.

The tasks were analysed to determine the hand capabilities and components required to perform the them. The roles of *structure, surface, sensory,* and *actuation* components and motion and sensory capabilities of artificial hands in the performance of the tasks were determined. Also, the objects involved in the tasks, and how the hand will interact with them, were determined. This chapter also proposed the steps required to be performed in simulation to perform the tasks.

Based on the analysis of the tasks, this chapter proposed a syntax to describe manual tasks, including a syntax to describe *anthropomorphic* postures. This syntax can be used to describe any hand task, which can then be used as input to a simulation and evaluation program to evaluate a hand's ability to perform the task. The syntax can also be used to describe the tasks in the *action manifold*, modify the *action manifold*, or define a new one. It is used to describe the tasks in the *action manifold of the anthropomorphic hand* in Appendix B.

The next chapter implements the simulation steps proposed in Section 5.1 to evaluate anthropomorphic posture and grasping capabilities and discusses how to use the simulation results as an indication of a hand's performance.

6
Hand Evaluation

THIS CHAPTER DESCRIBES THE IMPLEMENTATION OF PROCESSES TO QUANTIFY FUNCTIONAL PERFORMANCE of an anthropomorphic hand by simulating the tasks in the *action* manifold or individual tasks described using the task description syntax.

INTRODUCTION

Chapter 4 suggested two approaches to *functional* performance evaluation. In *functionality-based evaluation*, a predefined set of tasks representing all hand *functionalities*, called the *action manifold of the anthropomorphic hand*, are simulated and the artificial hand's ability to perform these tasks is evaluated based on the simulation results and the presence of specific hand components required for successful performance of the tasks. The evaluation processes described here, and task modelling syntax described in Chapter 5, are designed to be able to account for tasks of any functionality.

Section 6.1 proposes a process that uses Fuzzy logic to evaluate postures. Section 6.2 proposes a process to evaluate *anthropomorphic grasping* performance.

The simulation processes, and other parts of the evaluation method, require a computer model of the hand being evaluated. The particular components of that model depends on the requirements of each process. The modelling requirements of each process are discussed in its section. For the MATLAB implementation code of the processes discussed in this chapter please see Appendix D.

6.1 Posture evaluation

The posture evaluation process (Figure 6.1) investigates a hand's ability to assume *anthropomorphic postures*. Assuming that the hand surface is uniform and parallel to the kinematic structure, the evaluation is performed exclusively in the kinematic domain.

Reference postures are defined using the *anthropomorphic posture description syntax* proposed in Chapter 5. The hand configuration space is scanned and each configuration is evaluated to determine if it leads to a reference posture. Additionally, the process is used during other evaluation processes to test configurations selected through each process routine. At any given configuration the process compares the current and the reference postures. Fuzzy logic is used to perform the comparison in Sections 6.1.2 and 6.1.3.

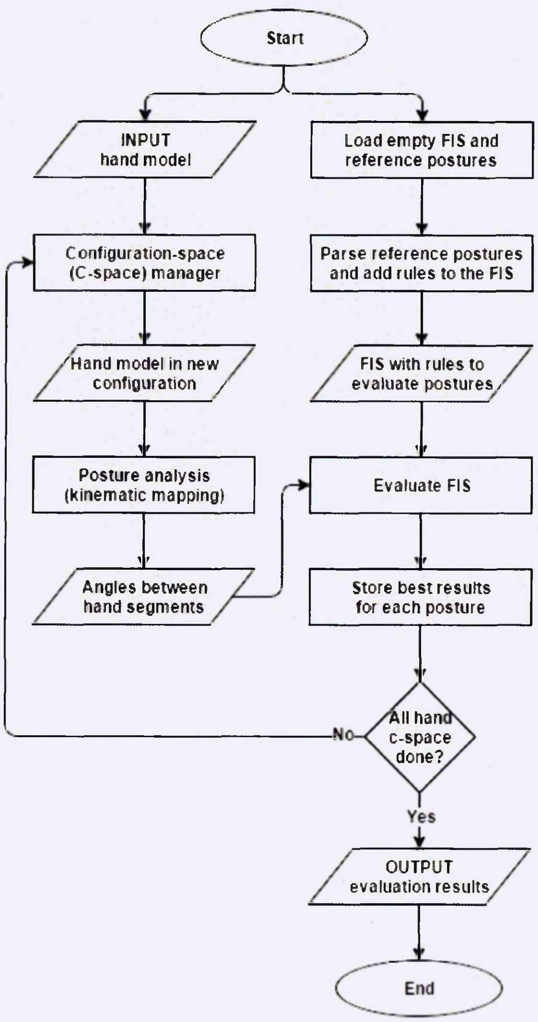


Figure 6.1: Flowchart of posture evaluation process

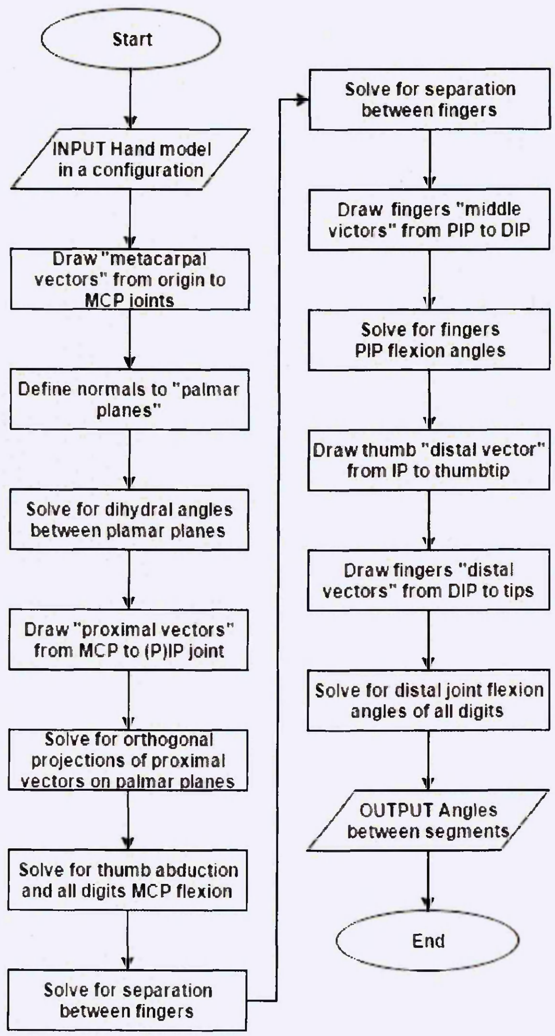


Figure 6.2: Flowchart of posture analysis process

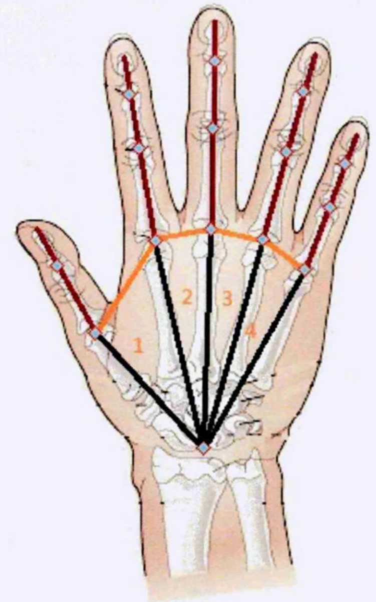


Figure 6.3: Bio-inspired abstract kinematic mapping for posture representation (background hand image source American Society for Surgery of the Hand)

6.1.1 Representation of artificial hand posture

Given that the *anthropomorphic* postures are defined with respect to the human hand, the artificial hand's posture needs to be encoded in a compatible format. The joint angles of a hand kinematic model cannot be used directly to encode posture because different hands have different kinematic structures. A kinematic mapping, based on the human hand, is used to address this issue (6.3). This mapping requires definitions of correspondences between the joints of the human hand and those of the kinematic model to be included in the model.

The mapping is inspired by the human hand bone arrangement. Any hand is represented by five serial link chains, the first chain is made of three links and the subsequent chains are made of four links each. All links originate from the hand origin frame at the wrist. This point is ideally placed directly in line with the longitudinal axis of the middle finger. The mapping can be applied to models of the human hand (Figure 6.4) or artificial hands (Figure 6.5).

Correspondences between digits and joints of the human hand and those of the kinematic model to be mapped must be defined in the model. These are defined with an order of significance starting from the thumb to the small finger and from the proximal to the distal joints. For digits with more than three joints - two for the thumb - all excess joints are assigned to the palm itself.

Vectors representing the metacarpal links (black vectors in Figures 6.3 to 6.5) are drawn from the hand origin frame to the MCP joint's first DoF. Auxiliary lines (yellow vectors) connect the MCP joints of adjacent digits forming a triangle with the metacarpal links. Subsequent links (red vectors) are drawn from the first DoF of the link's joint to that of the following link's joint. The final link is drawn from the last joint to the tip of the digit.

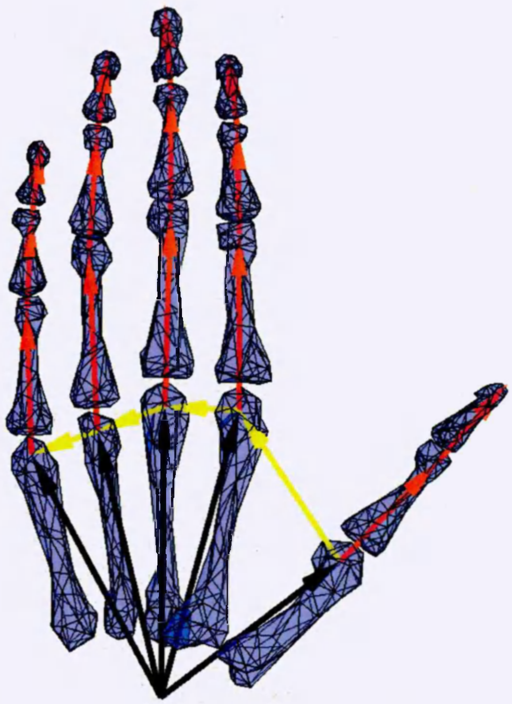


Figure 6.4: Kinematic mapping applied to a model of the human hand (Appendix A)

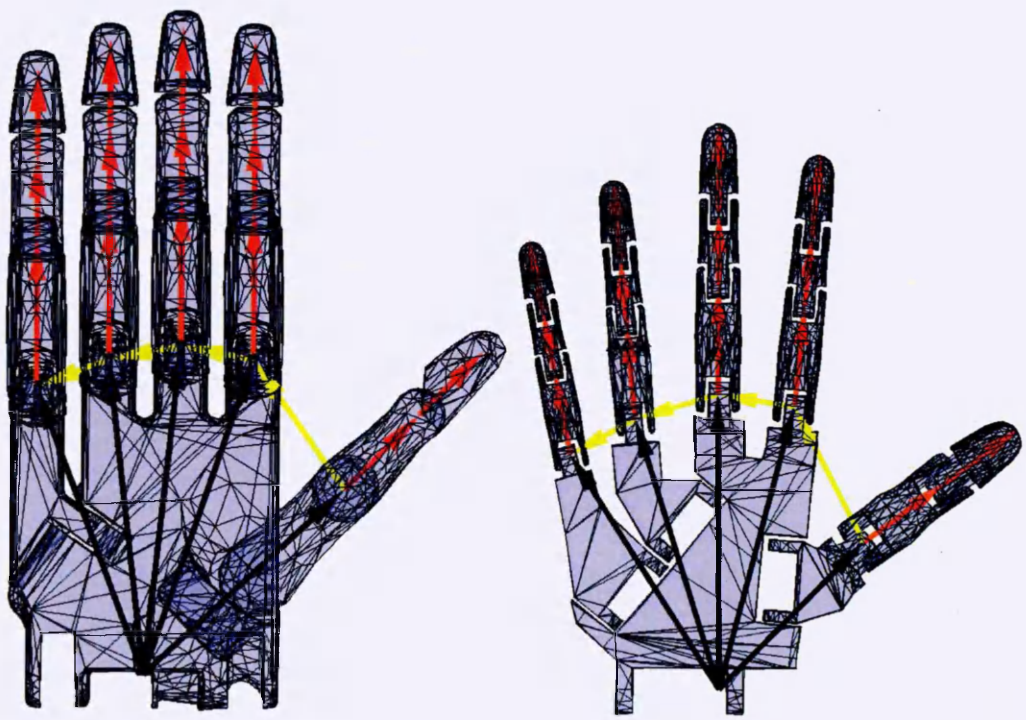


Figure 6.5: Kinematic mapping applied to models of: left) the Shadow robot hand, and right) InMoov robot hand

The palm is represented by the four triangles formed by the metacarpal links and the auxiliary lines. These triangles are used as reference planes to determine the state of the palm and digits, hereinafter called *palmar planes*. The second *palmar plane* - between upper fingers' metacarpals - is the main reference plane for the hand.

A plane is defined using a point and a normal unit vector. The point can be the hand origin or the location of an MCP joint associated with the plane. The normal is the cross product of the vectors of the two metacarpal links forming the plane, calculate so that its direction lies in the palmar (positive z-axis) direction.

Measuring and encoding postures

The palm The externally observable *palm arching* is a result of the motion of the lower fingers' metacarpals. The dihedral angles between the main reference plane and the third *palmar plane* and between the third and fourth *palmar planes* can be used to encode these motions if needed. These angles are to some extent analogues to the motion of the IMC joints. Figure 6.6 shows an example of measuring these angles by measuring the angles between the normals to *palmar planes* in the Shadow and the InMoov robot hands. The other DoF normally attributed to the CMC joints, abduction, can also be represented by the angle between the two metacarpal vectors of each *palmar plane*. Note that palm arching is not included in *anthropomorphic posture descriptions*. These four values are reserved for future use and not used in the current process.

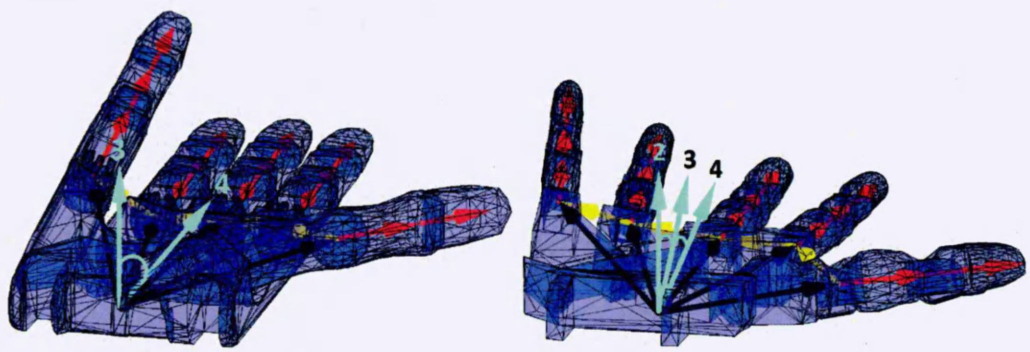


Figure 6.6: Measuring dihedral angles between palmar planes of models of: left) the Shadow robot hand, and right) InMoov robot hand

The fingers Absolute measurements of MCP abduction are not required since humans observe them as *separation* between pairs of adjacent fingers. Therefore, abduction is measured between the orthonormal projections of the first phalangeal vectors of the pair of fingers on their local reference plane. The local reference plane is the main reference plane for the upper fingers, the third *palmar plane* for the Ring finger, and the fourth *palmar plane* for the Small finger. Figure 6.7 shows an example of measuring abduction between the upper fingers of a model of the Shadow robot hand. Flexion at the MCP is also observed with respect to the palm. MCP flexion is measured as the angle between the first phalangeal vector and its projection on the local reference plane. Flexion of subsequent joints, the interphalangeal joints, is simply measured between the vectors of the phalanges before and after the joint. Figure 6.8 shows an example of measuring MCP flexion (φ_1) and DIP flexion (φ_2) of a model of the InMoov robot hand.

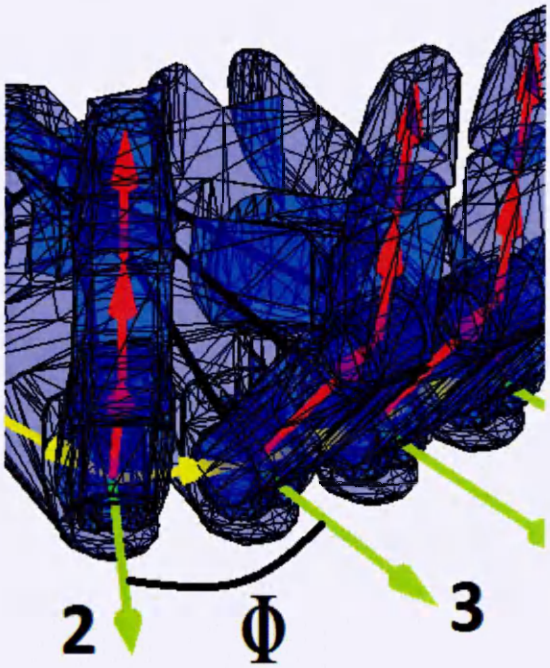


Figure 6.7: Example of measuring finger abduction of the Shadow hand

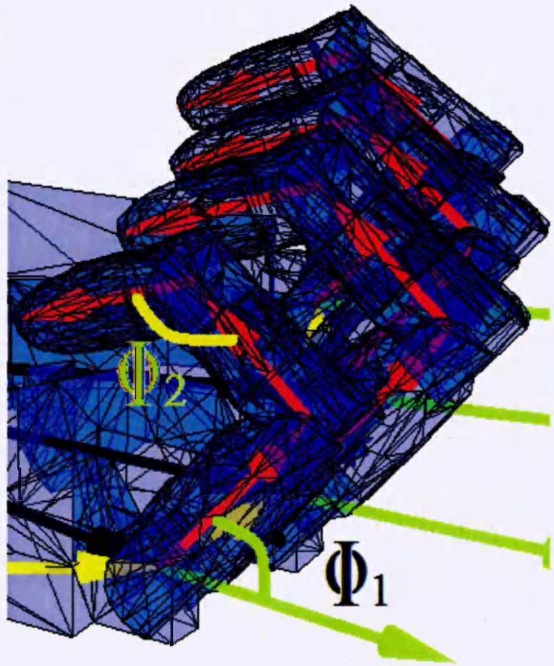


Figure 6.8: Example of measuring finger flexion of the InMoov hand

The thumb The dihedral angle between (the normals to) the thumb's *palmar plane* and the *main reference plane* is used to encode state of thumb *opposition* (Figure **??**). The angle between thumb and index metacarpals can be used as a measure of the thumb metacarpal's abduction; however, this is only reserved for future use and not utilised in the current system. Radial abduction angle is measured between the orthonormal projections of the auxiliary line (between the thumb and index) and the thumb's proximal vector on the *main reference plane* (φ_2 in Figurefig::MappingThumbAbduction). The auxiliary line is chosen because it is an approximate representation of the flexible web between the thumb and the palm, which is more externally observable than the index finger due to its proximity to the thumb. Palmar abduction angle is measured between the thumb's proximal vector and its projection on the *main reference plane* (φ_1 in Figurefig::MappingThumbAbduction). The thumb's MCP flexion is measured between the proximal phalangeal vector and its projection on the thumb's *palmar plane*, similar to the fingers' MCP joints. Finally, the IP flexion is measured between the vectors of the two phalanges.

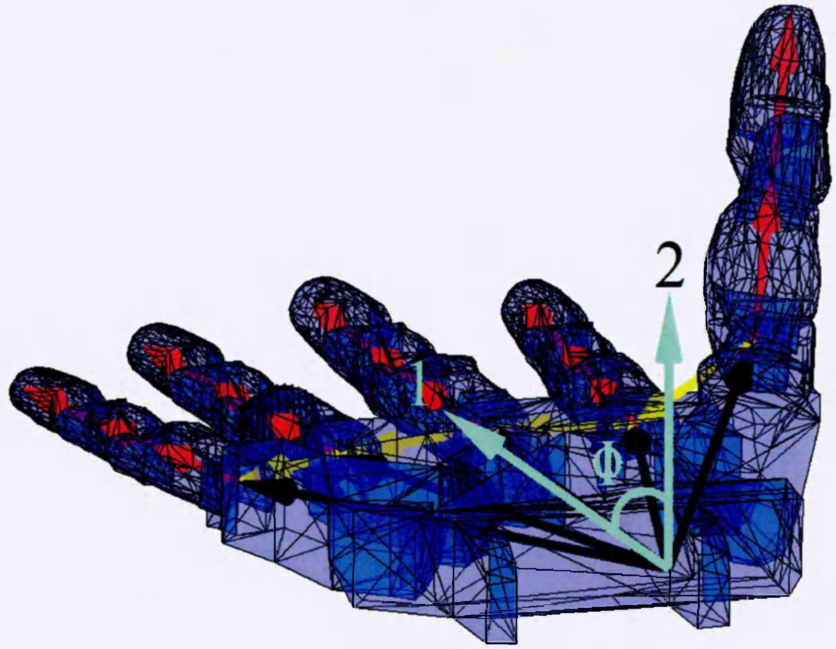


Figure 6.9: Measuring thumb opposition of a model of the InMoov robot hand

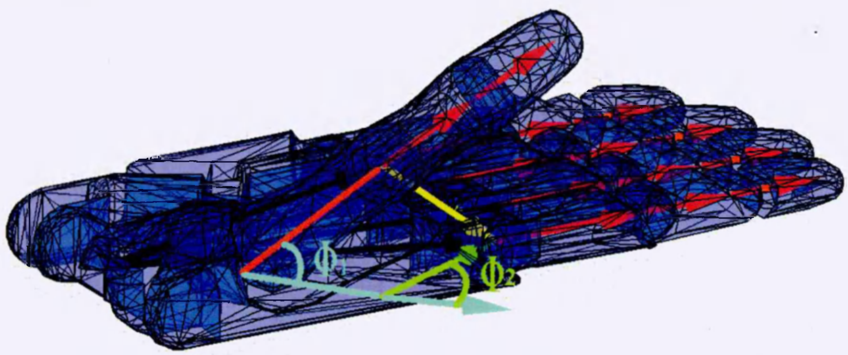


Figure 6.10: Measuring thumb abduction of a model of the Shadow robot hand

6.1.2 Input member functions

Inspired by the uncertainty in human perception of postures, fuzzy logic is used to perform the comparison between a reference posture and the hand posture at a configuration. Reference postures are described using verbal states, while postures at configuration are measured in numerical values. In a Fuzzy Inference System, the input member functions serves to attribute verbal states to the input numerical values.

There are three flexion angles for each finger and a total of three separation angles between all four fingers. Each flexion angle can be attributed one of three states: *extended/straight, slightly bent*, or *bent*. Separation angles can be attributed: *crossing, together*, or *separated*. To determine the numerical values associated with each state, the zero value is attributed to the *home state* (extended, straight, and together) and the remaining motion range is divided equally on all states.

The thumb posture is encoded by five angles. *Opposition* can be attributed *in opposition* or *in*

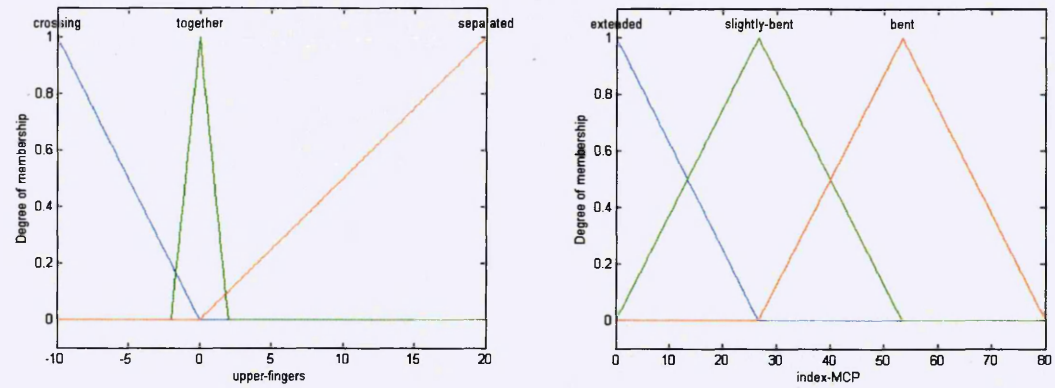


Figure 6.11: FIS input member function for; left) finger separation, right) finger flexion

retropostion state. *Palmar abduction* can be attributed *abducted* or *adducted* state. *Radial abduction* can be *far from* or *adjacent to palm. MCP flexion* and *IP flexion* angles can be attributed *extended/straight, slightly bent,* or *bent.*

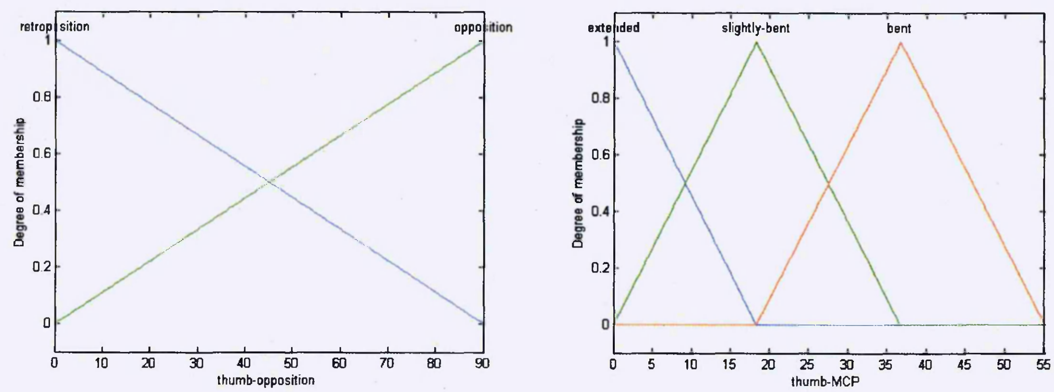


Figure 6.12: FIS input member function for; left) thumb opposition, right) thumb flexion

6.1.3 Parsing the reference postures

The verbal descriptions of the reference postures are used to generate the rules to be used in the Fuzzy Inference System. These rules are used to evaluate the hand posture at a configuration, which is encoded using the above mapping. The result is the evaluation score for the posture.

One output variable is defined for each posture. Two membership functions are defined for the output variable: anthropomorphic and non-anthropomorphic (Figure 6.13). A text parsing routine converts the posture descriptions to two fuzzy logic rules.

- The first rule states that if all the input values (angles of the kinematic mapping) match the posture description then output (posture) is anthropomorphic.

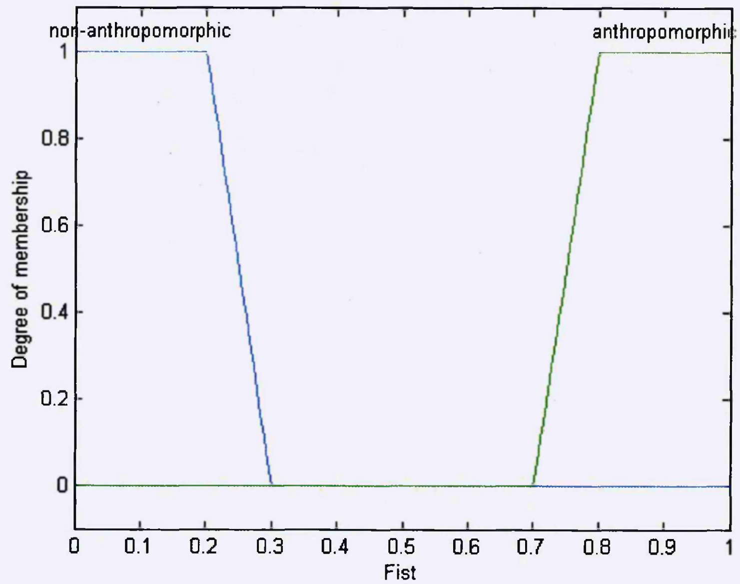


Figure 6.13: Membership functions of the output variable

- The second rule states that if all the input values do not match the posture description then output is non-anthropomorphic.

For example, for the posture *"fist"* with description *"The hand is tightly closed. The thumb is in opposition, abducted, curved, and touches the back of the fingers."*, the two rules will be;

- *If (upper-fingers is together) and (center-fingers is together) and (lower-fingers is together) and (index-MCP is bent) and (index-PIP is bent) and (index-DIP is bent) and (middle-MCP is bent) and (middle-PIP is bent) and (middle-DIP is bent) and (ring-MCP is bent) and (ring-PIP is bent) and (ring-DIP is bent) and (small-MCP is bent) and (small-PIP is bent) and (small-DIP is bent) and (thumb-opposition is opposition) and (thumb-palmar-abduction is abducted) and (thumb-MCP is slightly-bent) and (thumb-IP is slightly-bent) then (fist is anthropomorphic)*

- *If (upper-fingers is not together) and (center-fingers is not together) and (lower-fingers is not together) and (index-MCP is not bent) and (index-PIP is not bent) and (index-DIP is not bent) and (middle-MCP is not bent) and (middle-PIP is not bent) and (middle-DIP is not bent) and (ring-MCP is not bent) and (ring-PIP is not bent) and (ring-DIP is not bent) and (small-MCP is not bent) and (small-PIP is not bent) and (small-DIP is not bent) and (thumb-opposition is not opposition) and (thumb-palmar-abduction is not abducted) and (thumb-MCP is not slightly-bent) and (thumb-IP is not slightly-bent) then (fist is non-anthropomorphic)*

6.1.4 Experimental validation

The method is verified using a model of the human hand and the seventeen BSL basic handshapes. Stillfried et al. (2013) human hand model (Appendix A) was used to perform the test.

Posture	FIS output
Fist	0.8643
Bunched Hand	0.8723
Closed Hand	0.8601
Flat Hand	0.8606
Open Hand	0.8744
Clawed Hand	0.8744
Bent Hand	0.8674
C Hand	0.8674
O Hand	0.8550
L Hand	0.8719
M Hand	0.8552
N Hand	0.8743
Irish T Hand	0.8629
V Hand	0.8631
Y Hand	0.8550
Full C Hand	0.8698
Full O Hand	0.8617

Table 6.1: Fuzzy Inference System output for each posture

Due to the high number of possible hand configurations ($2.4832x10^{28}$ for the above human hand model at a sampling resolution of 5°), random sampling of the configuration space was used instead of uniform scanning of all possible configurations. The simulation was performed on MATLAB R2014a running on a commodity PC. Each simulation session was set to timeout after eight hours, in which about $1.2x10^{6}$ configurations are tested, if not all postures were found. The simulation was repeated thirteen times before all seventeen postures were found. No single simulation session found all postures, the simulation run for one-hundred-and-four hours in total.

As seen in Figure 6.13, a posture which matches the anthropomorphic reference posture description will output a value between 0.8 and 1. All seventeen postures were detected with output values between 0.8550 and 0.8743.

Table 6.1 shows the Fuzzy Inference System output for each posture. Tables 6.2 and 6.2 show the results of evaluating the input values of each posture through the two membership functions of the output variable (Figure 6.13), where the first row of each posture corresponds to the first rule and membership function, i.e anthropomorphic, and the second corresponds to the non-anthropomorphic rule and membership function. These results show that some postures were detected despite that some of the examined posture angles where close but not identical to the reference posture, which emphasises the advantage of using Fuzzy logic to approximate human perception (Section 6.1.2).

Tables 6.4 and 6.5 show the complete output for each posture when evaluated by the Fuzzy Inference System for each of the seventeen reference postures, where rows are hand postures and columns are FIS for reference postures. These results show that non of the postures was reported a value higher than 0.8 for any FIS output other than the matching reference postures, i.e no posture was detected by more than one FIS. Tables 6.6 and 6.7 present the configurations of the human hand model at each posture. Tables 6.8 to 6.10 show images of the postures performed by the hand model in MATLAB.

6.1.5 Critique

Limitations of the method

Currently, the approach to perform the mapping suffers from four problems that range from minor to serious. The minor problems relate to the proximal vectors projections at 90 degrees pitch, where the projection will be a point, making it hard to measure any angles between the projection and other vectors. Also, after this point, the projection will be in the opposite direction, causing a wrong separation and MCP flexion angles measurement. These two problems are considered minor as the hand models used in this thesis do not go up to 90 degree pitch at the MCP joints. Another minor problem is that any hyperextension will be incorrectly measured as flexion.

A more serious problem relates to the process's sensitivity to any small misplacement in joint positions in the hand model. It is common with different human hand models to place the joint locations in different points along their rotational axis due to the differences in anthropometric data and the irregularity of the biological joints' geometry, this is most common in models using DH parameters conventions.

One possible solution to these problems is to develop a process to generate a mapping matrix for each hand model which can then be used at any configuration to convert from the hands' joint space to the kinematic mapping used with the Fuzzy inference system.

Evaluation time

The validation process in Section 6.1.4 was performed over a duration of approximately one-hundred-and-four hours. One reason behind the long time is the method's sensitivity to small misplacement's of joint position, which may have led to many incorrect mapping between the human hand model and the kinematic mapping. However, the two main reasons are the very large number of possible configurations and the implementation code in MATLAB.

With regard to the configuration space, a possible solution is to develop a probabilistic search method which uses the results of the already scanned configurations and attempt to predict the

Fist	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	1.00	0.48	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	1.00	0.52	0.00
Bunched Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.17	0.00
Closed Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.67	0.31	0.94	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.69	0.06	0.00
Flat Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.89	1.00	0.33	1.00	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.67	0.00	0.00
Open Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00
Clawed Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00
Bent Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.62	0.96	0.85	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.04	0.15	0.00
C Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.95	1.00	1.00	0.62	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.05	0.00	1.00	0.38	0.00
O Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.72	0.88	1.00	1.00	1.00	1.00	1.00	1.00	0.75	0.65	1.00	0.07	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.35	1.00	0.93	0.00

Table 6.2: Configuration of the human hand model at the identified postures (continue)

L Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.82	1.00	0.88	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.12	0.00
M Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.76	1.00	1.00	0.76	1.00	0.11	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.24	0.00	0.00	0.24	1.00	0.89	0.00
N Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.08	0.00
Irish T Hand	1.00	0.70	1.00	1.00	1.00	1.00	1.00	0.42	1.00	1.00	0.51	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.58	0.00	0.00	0.49	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
V Hand	0.43	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	0.80	1.00
	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	1.00	0.20	0.00
Y Hand	1.00	1.00	1.00	1.00	0.98	1.00	1.00	0.84	1.00	1.00	0.72	1.00	1.00	1.00	1.00	0.04	1.00	1.00	1.00	1.00
	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.16	0.00	0.00	0.28	0.00	0.00	0.00	0.00	0.96	0.00	0.00	0.00	0.00
Full C Hand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.72	0.88	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.74	1.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.26	0.00
Full O Hand	0.95	1.00	1.00	1.00	0.79	1.00	0.74	0.87	1.00	1.00	0.81	1.00	1.00	0.95	1.00	0.70	0.60	1.00	0.37	1.00
	0.05	0.00	0.00	0.00	0.21	0.00	0.26	0.13	0.00	0.00	0.19	0.00	0.00	0.05	0.00	0.30	0.40	1.00	0.63	0.00

Table 6.3: Configuration of the human hand model at the identified postures (continue)

	Fist	Bunched Hand	Closed Hand	Flat Hand	Open Hand	Clawed Hand	Bent Hand	C Hand	O Hand
Fist	0.8643	0.5000	0.5000	0.5000	0.1290	0.5000	0.5000	0.5000	0.5000
Bunched Hand	0.5000	0.8723	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Closed Hand	0.5000	0.5000	0.8601	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Flat Hand	0.5000	0.5000	0.5000	0.8606	0.5000	0.5000	0.5000	0.5000	0.5000
Open Hand	0.1256	0.5000	0.5000	0.5000	0.8744	0.5000	0.5000	0.5000	0.5000
Clawed Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.8744	0.5000	0.5000	0.5000
Bent Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.8674	0.5000	0.5000
C Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.8674	0.5000
O Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.8550
L Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
M Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
N Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Irish T Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
V Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Y Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Full C Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Full O Hand	0.5000	0.5000	0.5000	0.5000	0.1383	0.1383	0.5000	0.5000	0.5000

Table 6.4: Complete output for each posture when evaluated by all Fuzzy Inference Systems

	L Hand	M Hand	N Hand	Irish T Hand	V Hand	Y Hand	Full C Hand	Full O Hand
Fist	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Bunched Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Closed Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Flat Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
Open Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.1256
Clawed Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.1256
Bent Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
C Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
O Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
L Hand	0.8719	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
M Hand	0.5000	0.8552	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
N Hand	0.5000	0.5000	0.8743	0.5000	0.5000	0.5000	0.5000	0.5000
Irish T Hand	0.5000	0.5000	0.5000	0.8629	0.5000	0.5000	0.5000	0.5000
V Hand	0.5000	0.5000	0.5000	0.5000	0.8631	0.5000	0.5000	0.5000
Y Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.8550	0.5000	0.5000
Full C Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.8698	0.5000
Full O Hand	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.8617

Table 6.5: Complete output for each posture when evaluated by all Fuzzy Inference Systems (continue)

	IMC3	CMC1a	CMC1b	IMC4	IMC5	MCP1a	MCP1b	IP1	MCP2a	MCP2b	PIP2	DIP2
Fist	15.4699	-53.2278	-29.0205	-4.8701	-0.4400	1.5691	16.6931	0.8349	-23.8442	0.1446	-77.9931	-61.0773
Bunched Hand	10.4781	-53.2278	-15.5240	-4.8701	-6.4263	26.5345	13.1241	41.2470	-24.8095	-15.3300	23.0000	18.0000
Closed Hand	15.4699	2.9532	-12.7114	-4.8701	-0.4400	1.5691	26.7788	34.3355	-23.8442	0.1446	-77.9931	6.7599
Flat Hand	-4.0000	9.7697	-21.9618	-4.0000	-15.0000	15.2641	14.9052	33.0000	49.0000	18.0000	23.0000	18.0000
Open Hand	-4.0000	2.0000	10.6563	-4.0000	-15.0000	37.0000	6.0000	33.0000	49.0000	49.9046	23.0000	18.0000
Clawed Hand	-4.0000	2.0000	10.6563	-4.0000	-15.0000	37.0000	6.0000	-28.6696	49.0000	49.9046	-47.6377	18.0000
Bent Hand	8.7629	15.4699	-12.9489	-0.5514	7.7349	37.8050	16.6862	33.0000	-21.9338	21.9655	23.0000	18.0000
C Hand	15.4698	-53.2278	-13.3731	-4.8701	7.7349	23.3144	45.7793	7.0809	51.3574	49.9046	-11.5814	-7.1528
O Hand	-4.3545	-26.9303	-12.7169	-4.8701	7.5356	20.3730	18.2042	6.1871	24.0328	-16.1258	-40.4131	-43.2597
L Hand	11.7646	-4.2532	10.2279	-4.8701	7.5356	48.1327	18.2042	37.0064	47.9969	49.9046	30.9970	8.1653
M Hand	-4.0000	-53.2278	-37.8163	-4.0000	-15.1834	-0.5579	45.7793	1.7183	53.7927	1.3350	23.0000	18.0000
N Hand	-4.0000	-53.2278	-30.5151	-1.4807	-6.3117	18.5872	31.5379	1.7183	53.7927	1.3350	23.0000	18.0000
Irish T Hand	15.4699	-11.7464	-37.3871	-4.8701	6.8227	42.6352	6.0000	33.0000	48.5151	46.8557	-57.7121	-61.0773
V Hand	-4.0000	-53.2278	-30.5151	-1.4807	-6.3117	9.3339	31.5379	1.7183	52.3493	36.1425	23.0000	18.0000
Y Hand	-0.2056	-14.7348	10.6570	-4.8701	-15.1834	37.8050	5.4063	33.0000	-29.0842	24.8410	-79.3024	18.0000
Full C Hand	-4.3545	-53.2278	-13.3731	-4.8701	7.5356	23.3144	45.7793	7.0809	52.3160	11.2182	-11.5814	-7.1528
Full O Hand	-4.3545	-33.5047	-5.2178	-3.7904	-2.2254	15.6713	-1.4176	8.4267	3.9696	22.4603	-20.9266	-19.7292

Table 6.6: Configuration of the human hand model at the identified postures

	MCP3a	MCP3b	PIP3	DIP3	MCP4a	MCP4b	PIP4	DIP4	MCP5a	MCP5b	PIP5	DIP5
Fist	-30.3676	0.9829	-66.9038	-69.0987	-51.3744	-2.9082	-60.8186	-55.2904	6.5536	-51.2585	-94.2588	-77.8723
Bunched Hand	-24.6160	-9.3454	33.0000	19.0000	-43.8682	-12.5911	36.0000	33.0000	-37.2423	-55.2737	0.0000	5.0000
Closed Hand	-30.3676	0.9829	-66.9038	6.8287	-51.3744	-2.9082	-60.8186	19.6321	6.5536	-51.2585	-94.2588	-5.8950
Flat Hand	42.0000	15.0000	33.0000	19.0000	24.0000	6.0000	36.0000	33.0000	6.0000	17.0000	0.0000	5.0000
Open Hand	42.0000	17.9510	33.0000	19.0000	23.9999	-13.7530	36.0000	33.0000	-23.9907	17.0000	0.0000	5.0000
Clawed Hand	42.0000	17.9510	-30.1337	19.0000	23.9999	-13.7530	-28.8101	33.0000	-23.9907	17.0000	-63.8241	4.9999
Bent Hand	-29.7403	15.0000	33.0000	19.0000	-47.2060	6.0000	36.0000	33.0000	-5.4250	-55.2737	1.0462	4.0987
C Hand	-24.6160	-5.2879	-64.4695	6.1816	-42.7556	-5.6194	-65.1946	18.8629	-5.4250	-55.2737	-95.1644	-4.9033
O Hand	48.1491	0.9829	-10.2224	-5.2075	25.1125	-5.6194	0.1509	4.2676	0.9988	27.0301	-35.0328	-22.0268
L Hand	-24.6160	-6.7634	-67.8180	3.8034	-48.3186	-9.4926	-66.9331	26.6358	0.9988	-58.6275	-98.8568	-1.3088
M Hand	50.1988	-13.4030	33.0000	19.0000	26.7750	-25.7552	36.0000	33.0000	2.4879	-36.8339	-101.5828	4.0987
N Hand	50.1988	-13.4030	33.0000	19.0000	-34.6855	-13.7485	-64.2297	33.0000	2.4879	-35.4955	-92.1662	4.0987
Irish T Hand	-27.2931	-7.3017	-73.2790	19.0000	-47.7300	-8.9048	-71.9640	32.9999	5.0479	-56.6121	-94.7880	5.0000
V Hand	50.1988	-10.8209	33.0000	19.0000	-34.6855	-13.7485	-64.2297	33.0000	2.4879	-35.4955	-92.1662	4.0987
Y Hand	-36.5168	-1.5992	-69.1190	19.0000	-53.8815	-6.7814	-69.9147	33.0000	6.0000	17.0000	0.0000	4.9999
Full C Hand	48.1491	0.9829	-10.2224	-5.2075	25.1125	-5.6194	0.1509	4.2676	0.9988	27.0301	-35.0328	-22.0268
Full O Hand	-0.6586	-1.5992	-8.7608	-20.8400	-13.2913	-6.7814	-8.5158	-0.5523	2.6677	-12.4294	-39.1937	-20.2034

Table 6.7: Configuration of the human hand model at the identified postures (continue)

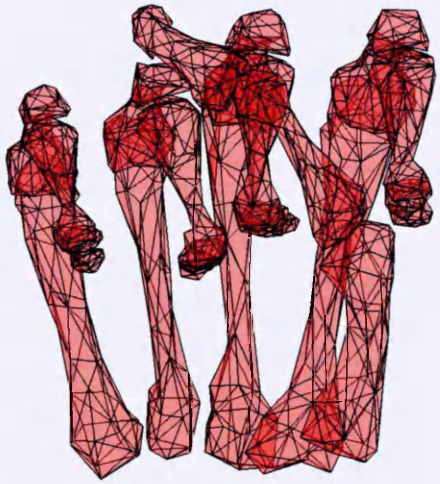
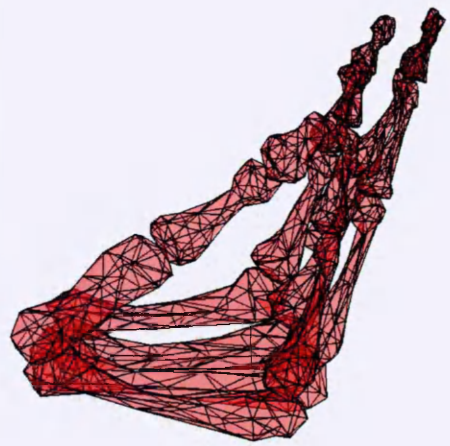
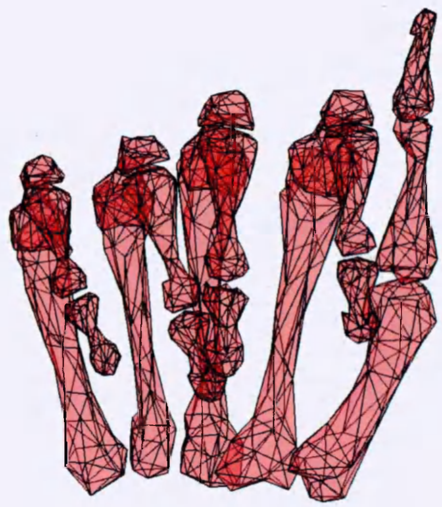
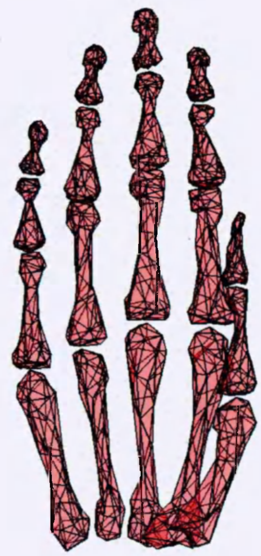
Fist	Bunched Hand
	
Closed Hand	Flat Hand
	
Open Hand	Clawed Hand
	

Table 6.8: Images of human hand model performing basic BSL handshapes signs

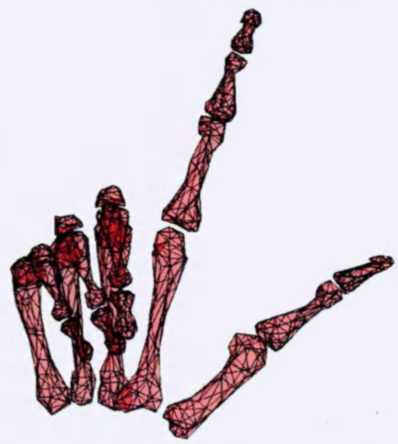
Bent Hand	'C' Hand
	
'O' Hand	'L' Hand
	
'M' Hand	'N' Hand
	

Table 6.9: Images of human hand model performing basic BSL handshapes signs (continue)

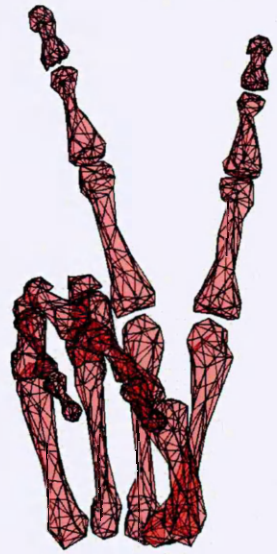
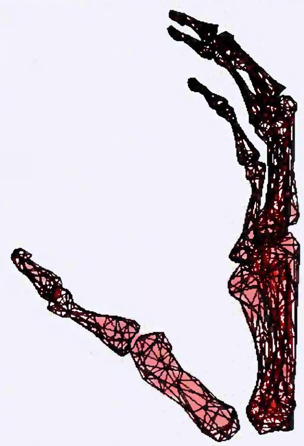
Irish 'T' Hand	'V' Hand
	
'Y' Hand	Full 'C' Hand
	
Full 'O' Hand	
	

Table 6.10: Images of human hand model performing basic BSL handshapes signs (continue)

configurations that have a higher probability to lead to successful results. As for the implementation code, the code could be optimised by using faster routines. Alternatively, the method can be reimplemented using a complied programming language. Complied programming languages, such as C++, are know to run faster than interpreted programming languages such as MATLAB.

6.2 Grasping evaluation

The grasping evaluation process (Figure 6.14) aims to determine the hand's ability to effectively grasp objects using an anthropomorphic grasp posture. This takes into account both the functional properties of the grasp as well as the anthropomorphic appearance, including posture, contact locations, and object pose with respect to the hand. This process takes into account the kinematic structure of the hand and its surface geometry.

The process begins by loading the object model associated with each grasp. Then the combined hand-object configuration space is scanned or randomly sampled. At every configuration, the process tests for collision and contact between the hand and object. Configurations leading to collision are discarded. If configuration leads to contact, the grasp quality and closure conditions are evaluated as well as the hand's posture and contact relations with the object. For each grasp, the combined hand-object configurations that result in the best score of quality and anthropomorphism are stored.

A configuration manager is used to scan hand and object configuration. This manger also allows for random sampling of the configuration space as well as manual selection of a configuration through a user interface (Figure 6.15).

To detect collision and contact, a hand model must include two meshes representing the core rigid structure and the surface respectively. The first mesh is used to detect collision with an object, while the second is used to detect contact. If the structure is the same as the surface, as in hands that utilise an exo-skeletal structure, or the surface is rigid, the collision mesh is a slightly smaller version of the contact surface mesh.

Five different quality metrics are used to evaluate a grasp: "distance to singular configuration", "grasp isotropy index", "hand manipulability ellipsoid", "minimum singular value of grasp matrix", and "uniformity of transform". These metrics are selected because they are used in several other simulation environments, such as Malvezzi et al. (2013) SynGrasp Toolbox, which facilitates comparison with those environments. Some quality metrics, such as "grasp isotropy index", take into account the force closure conditions; therefore, no separate test was included to verify closure conditions at this time.

A separate process was used to quantify the anthropomorphism of the grasp. The process included comparing the "opposition type", "thumb position", and "virtual fingers", described in Section 3.1.3, with the values reported in Feix et al. (2009) grasp taxonomy. The process also checks

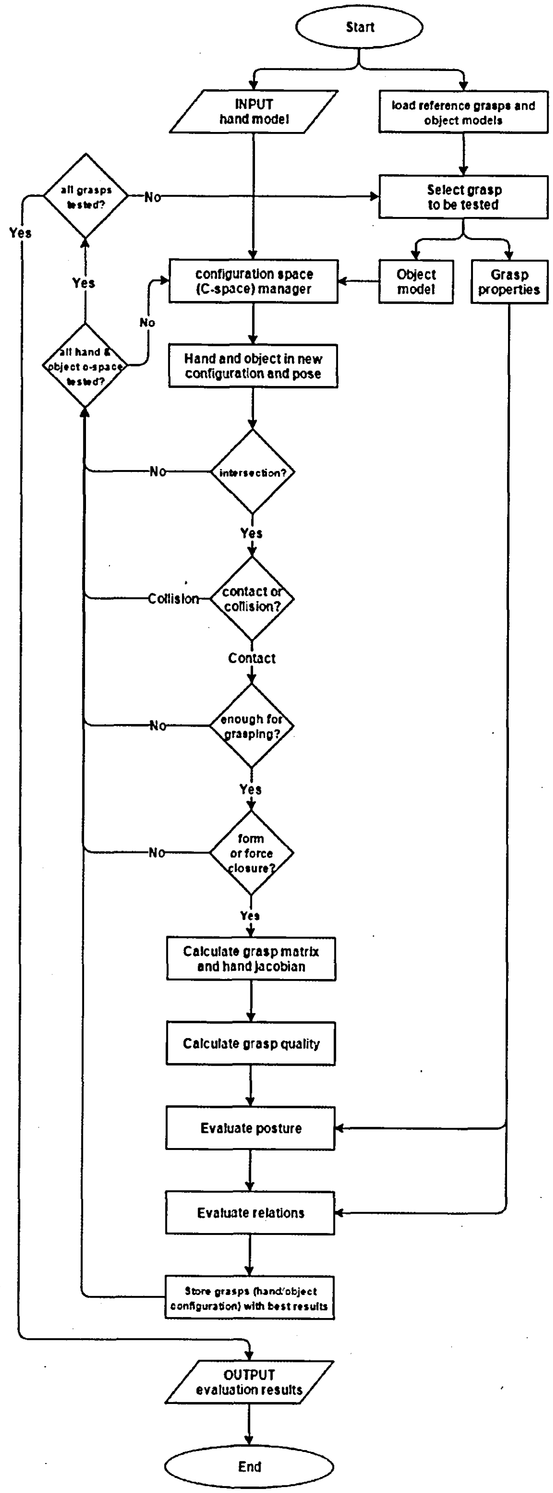


Figure 6.14: Flowchart of grasp evaluation process

the locations of contact on the hand. One anthropomorphism score is calculated as a weighted sum of the comparison score of each factor. The weights were chosen to emphasis contact locations (50% of the total score). Alternatively, postural anthropomorphism can be evaluated separately from contact relations (see Section 6.1).

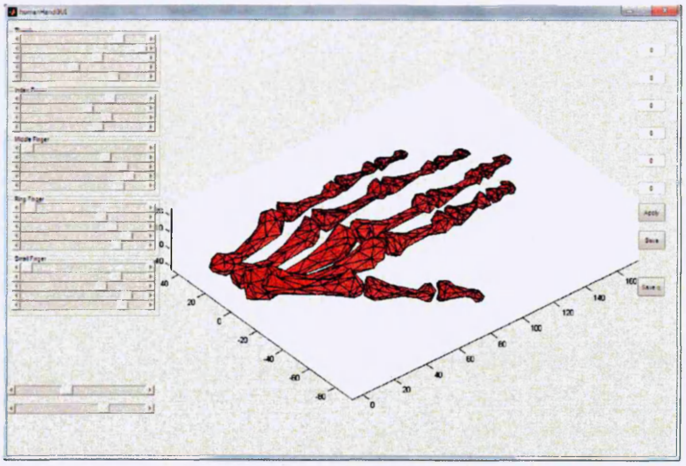


Figure 6.15: User interface to change the configuration of a hand model

6.2.1 Implementation and results

The InMoov hand is a low-cost 3D printed robotic hand originally developed as part of a hobby project. The hand is developed to perform very simple grasping operations and used mainly for entertainment purposes. However, several individuals have recently used the hand as a low-cost, do-it-yourself, prosthetic hand due to its relatively highly anthropomorphic appearance compared to prosthetic devices available at a similar cost. The advances in the field of consumer desktop 3D printers, and the increased social efforts to empower people with disabilities, makes such projects of low-cost 3D printed hands very useful advances towards making more aesthetically-appealing prosthetic hands available to larger number of users and at more affordable cost.

Therefore, the process was implemented in MATLAB and trialed using an InMoov robotic hand model. It was able to reproduce fourteen grasps; however, five were with poor anthropomorphism. The hand failed to perform the remaining seventeen grasps. Figures 6.16 to 6.43 show the successful grasps performed by the InMoov hand. The grasps of the InMoov hand are simulated and accompanied with pictures of a human hand performing the same grasps.

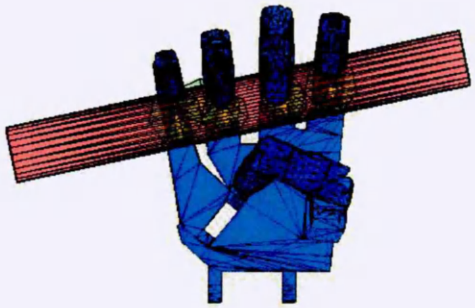


Figure 6.18: InMoov hand performing Small Diameter grasp in simulation

Figure 6.19: Human hand performing Small Diameter grasp

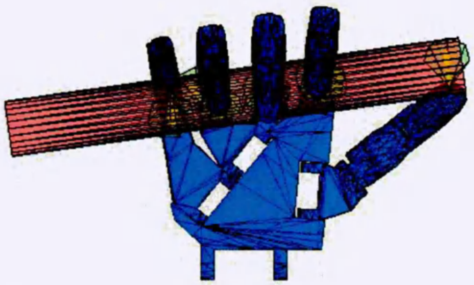


Figure 6.20: InMoov hand performing Medium Wrap grasp in simulation

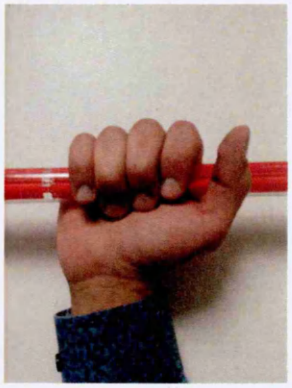


Figure 6.21: Human hand performing Medium Wrap grasp

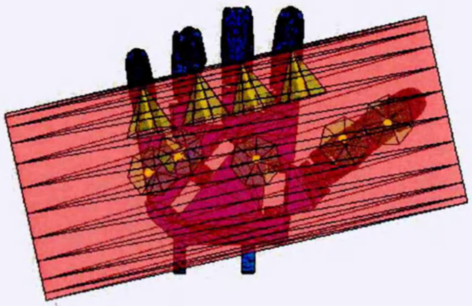


Figure 6.16: InMoov hand performing Large Diameter grasp in simulation

Figure 6.17: Human hand performing Large Diameter grasp

Figure 6.22: InMoov hand performing Adducted Thumb grasp in simulation

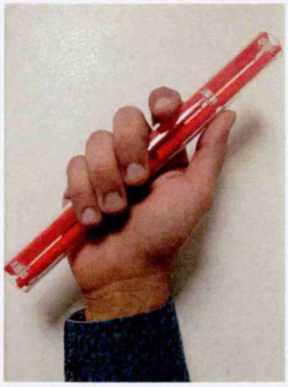


Figure 6.23: Human hand performing Adducted Thumb grasp

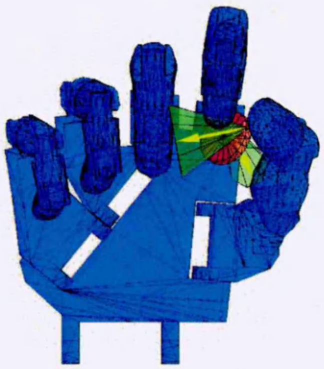


Figure 6.24: InMoov hand performing Palmar Pinch grasp in simulation

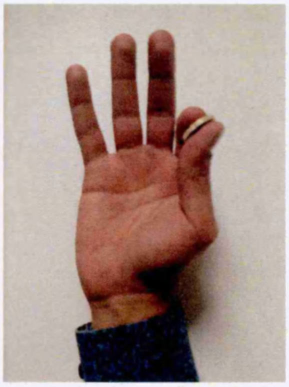


Figure 6.25: Human hand performing Palmar Pinch grasp

Figure 6.26: InMoov hand performing Power Sphere grasp in simulation

Figure 6.27: Human hand performing Power Sphere grasp

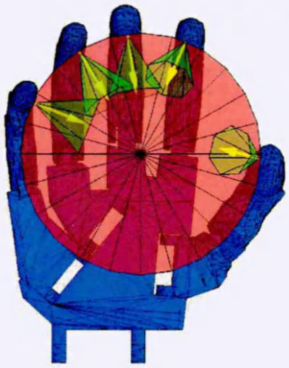


Figure 6.28: InMoov hand performing Precision Disk grasp in simulation

Figure 6.29: Human hand performing Precision Disk grasp

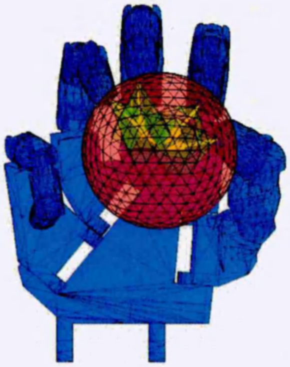


Figure 6.30: InMoov hand performing Precision Sphere grasp in simulation

Figure 6.31: Human hand performing Precision Sphere grasp

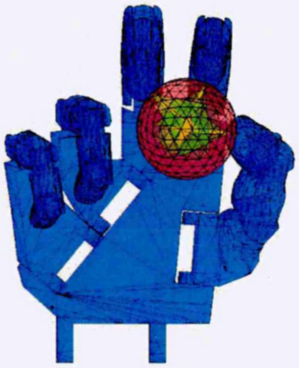


Figure 6.32: InMoov hand performing Tripod grasp in simulation

Figure 6.33: Human hand performing Tripod grasp

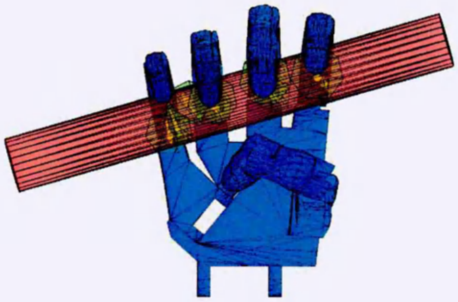


Figure 6.34: InMoov hand performing Fixed Hook grasp in simulation

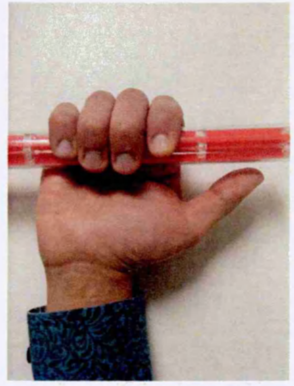


Figure 6.35: Human hand performing Fixed Hook grasp

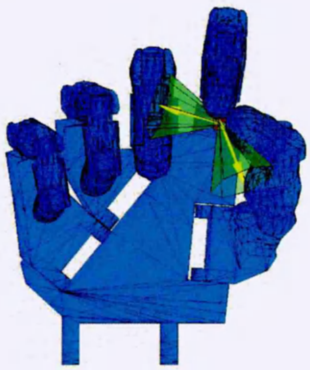


Figure 6.36: InMoov hand performing Tip Pinch grasp in simulation

Figure 6.37: Human hand performing Tip Pinch grasp

6.2.2 Critique

The hand configuration space is very large, scanning the entire space is time consuming, especially when it must be sampled at a fine resolution to allow valid contact on hands with rigid surfaces. This is even a bigger problem when the object itself has a large configuration space (range of possible poses).

Not using a separate step to verify closure conditions leads to situations where the ability of the hand to grasp objects cannot be determined. The current routine uses grasp quality metric to evaluate a grasp, which only outputs a "quality score", but not a "yes or no" result. Very low results are assumed to be an indication of the inability of the hand to perform the grasp; however, it is hard to define a sharp threshold between successful and failed grasps using the quality metrics alone. Also, the quality metrics currently used assume that the hand actuators can apply infinite forces; therefore, they do not permit the evaluation of the actuation capabilities of the hand.

Figure 6.38: InMoov hand performing Sphere 4 Finger grasp in simulation

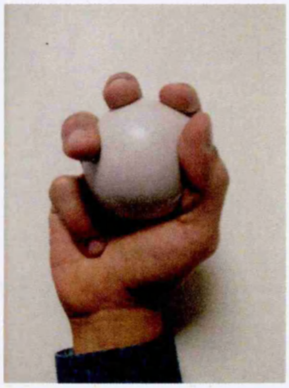


Figure 6.39: Human hand performing Sphere 4 Finger grasp

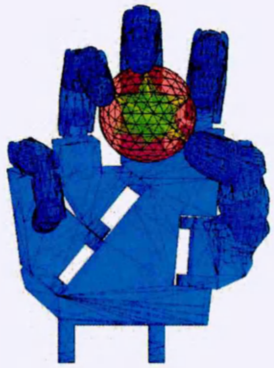


Figure 6.40: InMoov hand performing Quadpod grasp in simulation

Figure 6.41: Human hand performing Quadpod grasp

Figure 6.42: InMoov hand performing Sphere 3 Finger grasp in simulation

Figure 6.43: Human hand performing Sphere 3 Finger grasp

Chapter closure

This chapter discussed two methods of functional evaluation of anthropomorphic artificial hands. A method to evaluate anthropomorphic postures and a method to evaluate anthropomorphic grasping capabilities are proposed and applied on models of the human hand and the InMoov robot hand.

The first method was tested using a model of the human hand and the seventeen BSL basic handshapes. The method is shown to be able to detect when a hand configuration leads the hand to assume an anthropomorphic posture. The second method was tested using a model of the InMoov robot hand. It was able to detect several successful grasps.

7
Conclusion

THIS CHAPTER CONCLUDES THIS THESIS by discussing the results of the work presented in Chapters 5 and 6 and suggesting future work to be carried out to implement and further improve the methods and outlined framework presented in this thesis.

INTRODUCTION

This thesis studied the literature on human and artificial hands to determine how to evaluate the ability of artificial hands to perform the functionalities of the human hand. The thesis presents an outline of a framework to perform such evaluation by proposing a new approach to categorising tasks of hand functionalities and analysing the tasks to determine the hand capabilities involved in each task and how to simulate the tasks. The thesis also presents a syntax to describe hand tasks and anthropomorphic postures and two methods for evaluating anthropomorphic postures and grasping capabilities.

Section 7.1 discusses the outline of the framework presented in Chapter 5, including task analysis and syntax to describe hand tasks and anthropomorphic postures, and the methods to evaluate anthropomorphic postures and grasping capabilities presented in Chapter 6. Section 7.2 presents the conclusion of this discussion and the thesis. Section 7.3 suggests some future work towards improving the framework and implementing methods to evaluated other hand functionalities.

7.1 Discussion

This thesis explored anthropomorphic artificial hands and methods to evaluate them. The aims of this research was to outline a framework for comprehensive evaluation of the functional performance of artificial hands and implement a method to evaluate the anthropomorphic postures and grasping capabilities of artificial hands. These aims were approached by studying the human hand to determine how to evaluate artificial hands and by implementing part of the outlined framework using computer simulation. The sections below summarises the work done towards these aims.

7.1.1 Outline of evaluation framework

Evaluation concepts

It was observed that hands can be considered from a physical view, which is concerned with the construction and capabilities of the hand, and a functional view that is concerned with what tasks the hand can do. It was also noted that existing evaluation methods lack a comprehensive understanding of the human hand and its functionalities, which leads to developing methods that only consider few aspects of artificial hands and cannot be extended to produce a comprehensive evaluation of how an artificial hand approximates the human counterpart.

For this reason, this thesis focused on developing a comprehensive understanding of the human hand and it uses. It employed an approach that differentiates between the hand's physical construction and capabilities on one side and its functionalities on the other. This was followed by reviewing artificial solutions to determine how the construction, capabilities, and functionalities of the human hand can be replicated artificially.

This approach allowed a definition of what this thesis calls the *action manifold of the anthropomorphic hand*, which is - hypothetically - *the set of all the tasks that an ideal anthropomorphic hand can do*. This manifold defines what a hand is used for and how it is used. It categorised the tasks of the human hand into five groups the share similar goals. A further analysis of the tasks in this manifold determined what parts of the hand construction and which capabilities are involved in each task.

Based on this analysis, a stepwise analysis of each task's performance was defined. This stepwise analysis serves as the guide to how to simulate each task, and subsequently, determine if a hand is able to perform the task. This approach is thus able to evaluate an artificial hand's ability to perform any functionality.

The analysis, and the thesis approach of distinguishing physical and functional views, suggested that tasks can be performed in either an anthropomorphic or a non-anthropomorphic manner. This is determined by the posture which the hand assumes during task performance and, if interaction with objects occur, the relations between the hand and the object.

Additionally, the analysis indicated that, regardless of anthropomorphism, the success or failure of performing a task depends on a set of functional criteria, for example force conditions for grasping tasks. Therefore, a comprehensive functional evaluation must evaluate both the anthropomorphic appearance of the task performance as well as the functional criteria necessary for the successful performance of the tasks.

Action manifold of the anthropomorphic hand

Chapter 5 presents an approach to categories and list all the tasks that a hand can do. The approach is used to list a set of tasks that a hypothetical ideal anthropomorphic hand can do, which is called *the action manifold of the anthropomorphic hand.* This is done in order to define a reference to evaluate how close an artificial hand is to this hypothetical ideal hand.

The literature have indicated that some of the categories presented in Chapter 5, such as active-sensing and grasping, have been thoroughly studied and probably all the possible tasks of these categories have been identified. On the other hand, the literature indicates that other categories, particularly gesturing, contain a large number of tasks that varies between different communities and populations. Therefore, Chapter 5 selected a set of example tasks for these categories that are deemed sufficient to outline the framework but are not necessarily suitable for all communities. Therefore, artificial hands' developers must take into account the communities in which the device will be used and modify the action manifold accordingly.

Task and posture description syntax

For the above reason, i.e the ability the action manifold, Chapter 5 presents a syntax to describe tasks. The syntax is defined by analysing the tasks currently selected for the manifold and determining the aspects needed to describe them.

Additionally, it was found that existing methods lack any way to explicitly describe hand postures, which is necessary to evaluate the anthropomorphism of task performance. Therefore, a syntax was proposed to describe anthropomorphic postures.

7.1.2 Implementation of posture and grasp evaluation methods

Chapter 6 presented a partial implementation of the outlined framework which focused on evaluating the ability of an artificial hand to assume anthropomorphic postures as well as perform successful grasping tasks using anthropomorphic postures.

Posture evaluation A method was developed which used Fuzzy logic to compare a reference posture, described using the posture description syntax developed in Chapter 5, and the current posture of a model of an anthropomorphic hand. The method was tested using a human hand model and the postures of the seventeen BSL basic handshapes, it was able to successfully detect all postures.

Grasping evaluation A method was developed to test an artificial hand's ability to perform grasping tasks. The method tests for both, the functional properties of the grasp as in force conditions as well as the anthropomorphic appearance of the grasp. The method was applied on a model of an artificial hand and was able to detect several successful grasps.

7.2 Conclusions

In conclusion, the thesis aims have been met as following:

Outlining an evaluation framework which is comprised of the following:

- a new approach to categorising and listing tasks of hand functionalities in a functional reference called *the action manifold of the anthropomorphic hand*
- describing the tasks using a syntax that includes the aspects needed to simulate the tasks, including anthropomorphic postures
- a stepwise analysis of how to simulate the tasks and thus determine the hand's ability to perform the task

Two methods have been implemented to evaluate artificial hands ability to assume anthropomorphic postures and perform grasping in an anthropomorphic manner. The first method used Fuzzy logic to determine if a hand is capable of assuming reference postures described using the posture description syntax. The method was verified using a simulation environment and a model of the human hand. The second method involved evaluating the force conditions of grasps as well as the relations between the hand and the grasped object. The method was applied to a model of an artificial hand and was able to detect several successful grasps.

7.3 Future work

7.3.1 On evaluation of other functionalities

It was noted that hand tasks can be categorised according to aim into five categories; grasping, manipulation, sensing, non-prehensile manipulation, and visual expression. Chapter 6 proposed methods to evaluate gestures and grasping functionalities. This section presents some ideas on how the remaining functionalities can be evaluated.

Dexterous manipulation evaluation

Dexterous manipulation refers to the ability to move the object with respect the hand's base frame while maintaining a precision grasp. Therefore, this test is only applicable if the hand can perform precision grasps in the grasping test. Given the results of the grasping test, this thesis proposes to evaluate the manipulability of each successful precision grasp. Existing manipulability tests are sufficient for this stage of the test. However, an additional informative measure can be included, that is the range of possible motion of the object expressed in terms of relative transitions and rotations from the object's pose in the initial grasp.

Active sensing evaluation

Active sensing is performed by making contact between sensitive area on the hand's surface and the object or surface being investigated. To test this functionality, the six EP of Klatzky et al. (1985) can be used as reference tasks.

Some tasks require a static contact while others involve performing a motion. The motion is global motion performed by the arm. Therefore, it does not need to be included in the test.

To test a hand's ability to perform this functions, first it is important to determine if the hand contains the sensory devices required by each task. Then, the test needs to evaluate if the hand can position these sensory devices in a position that is suitable to perform the task, i.e make contact with an object or surface. To check this, the test would define the task "objects" to either be a flat surface or protruding edges, depending on each EP characteristics. The test would define a set of *clearance criteria* that are necessary for the sensing element to reach the surface or edge. This clearance criteria checks if other parts of the hand may collide with the surface or edge being explored.

Finally, the test would check if the task is performed in an "anthropomorphic" manner using two measures: the location of contact/sensing device, and the hand posture during task performance.

Non-prehensile manipulation

This functionality refers to tasks involving exerting forces on an object without grasping it, for example pressing keys on a keyboard. Although these tasks involve contact with objects, the does not need to take the object in consideration during the evaluation process.

These tasks are commonly performed in prosthetic hands using a "pointing" gesture and a global motion. It is possible to just evaluate if the hand can perform this gesture using the process described in Section 6.1. This would indicate if the hand is sufficient for basic pressing tasks. To further evaluate that hand's performance, another process is proposed.

Given the lack of prehension in these tasks, it can be concluded that any action by the hand on any object can be explained using a single "virtual finger". However, it is possible that different digits may exert forces on different objects simultaneously, such as pressing multiple keys at the same time. Furthermore, the force exchanged between the hand and the object depends on the contact model used. Finally, some tasks may require time sensitive operation. This means the time it takes to apply and remove the force should also be taken in consideration.

For evaluation of this functionality, this thesis proposes to use the task of typing on a computer keyboard as a reference task. A "keyboard" is defined as a flat surface with finite dimensions. The surface would be divided into a grid resembling the keys of a keyboard, the grid resolution would be defined according to the computer keyboard's common standards as 19.05 mm (0.75 inches). These standards also define a minimum key travel of 3.81 mm (0.15 inches).

To test the hand, the test would evaluate the hand's ability to "press" various keys. Most importantly, a digit should be able to press a single key without pressing adjacent keys. Secondly, individual digits should be able to "penetrate" the virtual keyboard plane by the minimum travel and be able to delver an appropriate force. Third, the test would evaluate the hand's ability to press multiple keys at the same time, and whether the relation between the key combinations is fixed, i.e can only press keys separated by certain distances, or relatively unrestricted. Finally, the test would investigate the time it takes the digit to press and release the key.

Task-based functional evaluation

The general functional approach relies on a set of predefined reference tasks to evaluate a hand's potential functional performance. This allows for a standard evaluation of a hand, but it does not allow a user to evaluate the potential performance of a hand to carry out an arbitrary task. To address this limitation, this thesis proposes to combine the tests of all functionalities in one process that does not contain any predefined reference tasks. This process would take as an input a hand model and a task model describing the task and any objects involved. The task modelling format must be sufficiently comprehensive to allow for describing tasks from any functionality. The task characteristics can be used to determine the task type and the required analysis. From there, the task model must contain the information required to perform the analysis. For example, a grasping task model must contain a model of the object to be grasped and any associated anthropomorphic postures.

7.3.2 Potential for design and optimisation

The evaluation processes proposed in this thesis have direct application in comparing performance of different iterations during a design or optimisation process. There are also less obvious ways the conceptual framework of the thesis can be used for design and optimisation.

Applications in design

Component database By performing the correlation analysis between hand components and hand functional performance, it would possible to obtain values associated with the functional contribution of each component. These values can be used as a guide to which components should be implemented to achieve a given target function.

Additionally, it would be possible to construct a database containing hardware components, each pre-analysed and assigned a "functional performance" value and a "compatibilty" value for every defined hand function and component respectively. Components would also be assigned cost value to favour economically, computationally and power efficient solutions. The database would be used to design a new hand through a selection process that aims to maximise performance and compatibility sum while minimising cost sum.

Applications in optimisation

Kinematic structure and coupling Data from functional evaluation would be processed using Principle Component Analysis to determine any potential for coupling joints (or omitting links) without loss in performance. Changes can be re-evaluated for verification.

Contact surface properties Contact surface friction and compliance affects most functions, especially prehensile functions. During functional analysis, alternative properties would be evaluated. A resulting "potential map" shows locations where changing the surface properties may improve some functions.

Interaction sensors location A map would be generated during functional analysis that shows the number of times each point on the surface came in contact with objects. Another map would show clearance for different locations on the surface of the hand. These maps would be used as a guide to placing the interaction sensors to maximise performance.

A

Hand Modelling

THIS APPENDIX describes the modelling of human and artificial hands for the simulation and evaluation environment developed in this research.

INTRODUCTION

All the processes proposed in this thesis requires as input a model of the hand to be evaluated. Modelling requirements are specified sparsely over several sections in the chapters of this thesis. This appendix collects all these requirements and presents them in an organised and stepwise format to allow users to model any hand they wish to simulate. A model of the human hand is used as an example to describe how to model a hand because human hands are more challenging to model than artificial hands due to geometric irregularities and variations in anthropometric data.

A.1 HUMAN HAND MODEL

For the purpose of verifying the simulation environment and evaluation processes, a model of the human hand is implemented. The kinematics and bones meshes of this model are based on the model provided by Stillfried et al. (2013) and its implementation in the OpenSIM environment. A generic skin model from the MakeHuman open source tool (Bastioni et al., 2015) was fitted to the hand kinematic model using some measurements from Alexander and Viktor (2010).

A.1.1 Kinematics

The first step in the modelling process is to model the kinematics of the structure of the hand. Kinematics are commonly modelled in robotic using Denavit–Hartenberg (DH) parameters; however, homogeneous transformation matrices are used in this thesis as they allow modelling the actual location of the joint, as opposite to the location of the joint axis only in DH parameters.

Stillfried et al. (2013) kinematic model (Figure A.1) contains nineteen segments (bones) connected by eighteen joints with 24DoF. This is one of the few models to rely on IMC joints instead of CMC joints for the lower fingers. Tables A.1 and A.2 show the model's the motion range and segments' dimensions respectively.

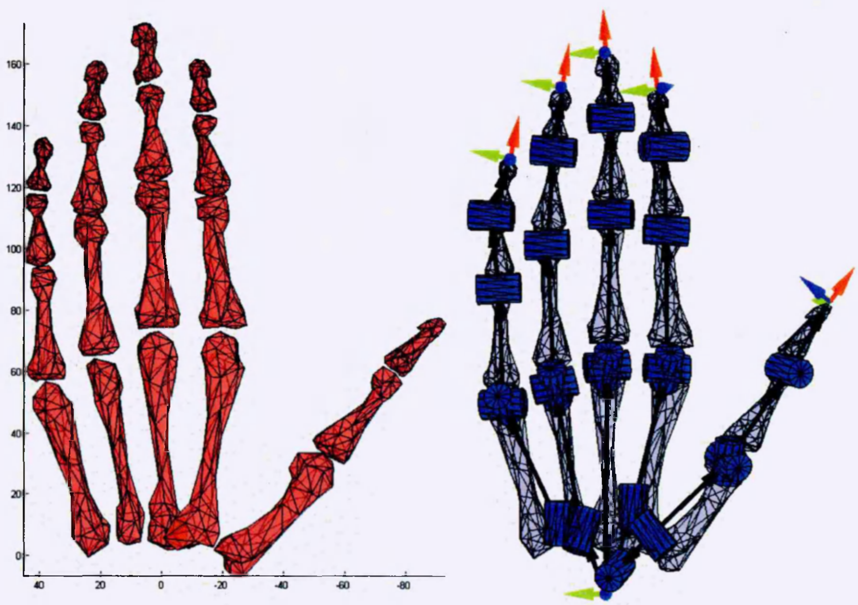


Figure A.1: Plot of human hand (bones) model implemented in MATLAB (with and without kinematic model plot)

The kinematic structure is modelled following a standard tree approach where joints and links, and the parent joint of each joint or link, are defined. First, the joints and links of the palm are defined. The very first joints (joints with no parent but the wrist) are assigned the parent joint value "zero" and defined with respect to the hand's origin frame at the wrist. The following joints are defined with respect to their parent joints.

Following that, the digits are modelled, starting with the thumb, then the index, and so on. Each digit requires the definition of a "base" and "tip" in addition to the joints and links. The base defines the parent joint from the joints of the palm, if the digit is not affected by any palm joints, the base is assigned the value "zero" and the first joint is defined with respect to the hand origin frame. The digit tip frame is defined with respect to the last joint in the digit.

A link parent always refers to a joint in its local group (palm or digit). Only palm links may have hand origin frame as parent.

For purposes of the currently mapping approach (Chapter 6), the kinematic model also includes a 3x5 matrix defining the DoF corresponding to each human hand finger joint. The first value for each digit is always one, while the second value is either 2 or 3, the third value can be 3 or 4, or it can be 0 to indicate absence of the DIP joint from this digit.

DoF	Range		Home	Range
	Min	Max	angle	total
CMC1a	-53.2278	15.4699	2.0000	68.6976
CMC1b	-38.6747	10.6570	10.6563	49.3317
MCP1a	-20.6838	71.8489	37.0000	92.5327
MCP1b	-22.4599	45.7793	6.0000	68.2393
IP1	-45.2637	57.4677	33.0000	102.7313
MCP2a	-31.5127	78.6671	49.0000	110.1798
MCP2b	-18.5065	49.9046	18.0000	68.4112
PIP2	-93.8505	30.9970	23.0000	124.8475
DIP2	-61.0773	64.6869	18.0000	125.7642
IMC3	-4.3545	15.4699	-4.0000	19.8243
MCP3a	-39.5914	78.2087	42.0000	117.8001
MCP3b	-20.6838	21.7151	15.0000	42.3989
PIP3	-81.3027	46.0085	33.0000	127.3112
DIP3	-69.0987	39.9925	19.0000	109.0912
IMC4	-4.8701	15.8136	-4.0000	20.6838
MCP4a	-60.2752	67.6090	24.0000	127.8842
MCP4b	-27.3874	17.1314	6.0000	44.5188
PIP4	-79.0109	51.6808	36.0000	130.6917
DIP4	-55.2904	56.5509	33.0000	111.8414
IMC5	-15.1834	7.7349	-15.0000	22.9183
MCP5a	-37.2423	17.4752	6.0000	54.7175
MCP5b	-84.3394	69.4998	17.0000	153.8392
PIP5	-105.7680	14.4958	0	120.2638
DIP5	-82.4486	21.1421	5.0000	103.5908

Table A.1: Motion range and home position of the human hand model joints in degrees (converted from radian values in Stillfried et al. (2013))

A.1.2 Collision mesh

A collision mesh is used to represent the rigid structure of the hand in order to detect collision with external objects during simulation. In case of the human hand, this would be the skeleton. Stillfried et al. (2013) implemented their model in the OpenSIM environment and included low-polygon 3D mesh models of the bones with the implementation (Figure A.1). The models are defined using different frame orientation from the one used in this thesis (Chapter 1). Therefore,

Digit	Bone	Length (mm)	Width (mm)	Thickness (mm)
Thumb	MC	49.4990	16.1400	13.9500
	PP	34.7730	14.3940	11.1790
	DP	23.7250	12.7490	8.0260
Index finger	MC	72.4490	17.8970	17.0980
	PP	44.4140	15.6380	11.8780
	MP	27.3910	11.9740	9.7600
	DP	17.5810	8.4310	6.3570
Middle finger	MC	71.1150	13.7860	14.8710
	PP	48.3840	14.2940	13.6010
	MP	31.6670	12.2850	9.1650
	DP	19.6450	9.6190	6.1070
Ring finger	MC	61.3800	11.1380	15.1400
	PP	46.1330	13.0270	11.9900
	MP	30.6110	11.9670	8.7100
	DP	19.3350	9.1980	5.6060
Small finger	MC	58.7840	13.0890	13.4660
	PP	37.4510	12.6730	10.3920
	MP	23.7400	10.0440	6.9320
	DP	17.3530	8.1640	4.9600

Table A.2: Stillfried et al. (2013) hand model segments (bone) dimensions

the entire model is reoriented using a transform matrix which was applied to all joints and links whose parent is the hand's origin frame.

In case of an artificial hand which has a rigid surface, as in hands employing an exo-skeletal structure, a the collision mesh is generated as a slightly smaller version of the mesh representing the structure's surface.

A.1.3 Contact mesh

A contact mesh is used to represent the outermost surface of a hand in order to detect contact with external objects during simulation. For this purpose, a generic skin model from the MakeHuman open source tool (Bastioni et al., 2015) is fitted to the hand using measurements from Alexander and Viktor (2010) (Table A.3).

The skin model comes as a single mesh which covers all the links of the hand (Figure A.2). This is problematic, as usually artificial hands are made of individual links each with its own separate surface. However, in the case of the human hand, all links share the same surface which may be affected by the motion of any link. Also, the generic model comes with dimensions and in a posture that do not fit the bone model of Stillfried et al. (2013). To correct this, van Nierop et al. (2007) approach in dividing the single mesh into separate segments is used (see Section 2.2).

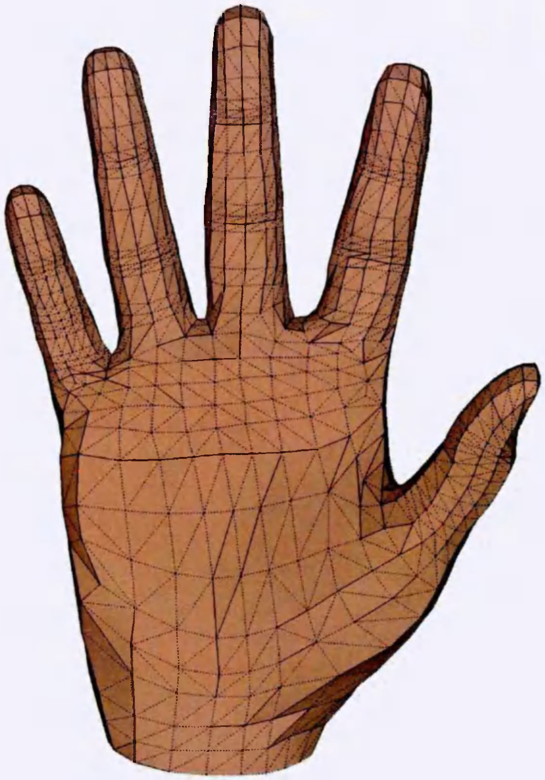


Figure A.2: MakeHuman skin model

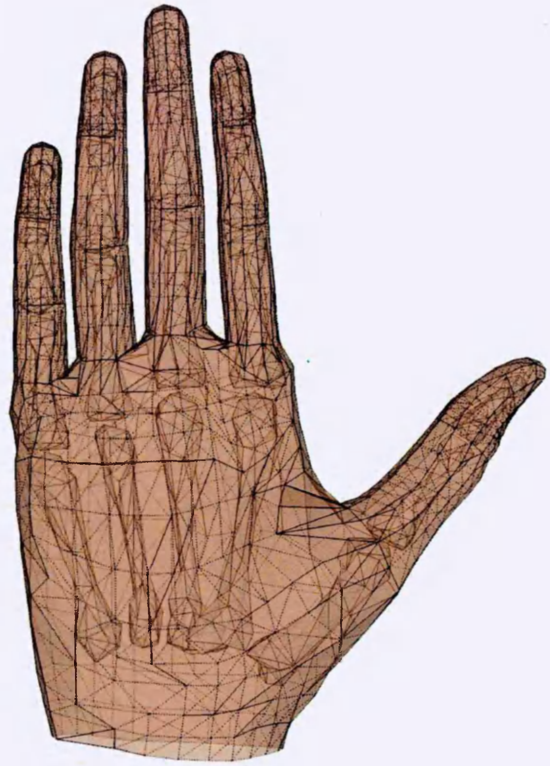


Figure A.3: Hand model fitted with modified skin model

Particularly, to model the fingers, the mesh for the middle finger segments are isolated and scaled to create other fingers; however, the thumb mesh from the original model is used to create the thumb.

Alexander and Viktor (2010) describes the length of the "soft tip", i.e the distance from the end of the distal bone to the end of the externally visible finger. They also describe the "web height", i.e the distance from the MCP joint to the beginning of the externally visible finger. These values are reported in the original literature in different metrics, they are converted to percentage of the distal and proximal segments for use with the human hand model (Table A.3).

Figure A.3 shows the hand model with the modified skin model.

Digit	Tip length (%DP)	Web height (%PP)
Thumb	26.17%	-
Index finger	24.27%	27.63%
Middle finger	22.70%	27.49%
Ring finger	22.83%	33.29%
Small finger	23.37%	42.70%

Table A.3: Tip length and web height (adapted from Alexander and Viktor (2010))

B

Descriptions Of Tasks In The Action Manifold

THIS APPENDIX describes the tasks in the *action manifold of the anthropomorphic hand* using the task description syntax proposed in Section 5.2

INTRODUCTION

In Section 5.1, seventy-eight tasks were selected to comprise the *action manifold of the anthropomorphic hand*, which is defined as the set of all hand tasks that a hypothetical ideal *anthropomorphic* hand can do. The tasks are categorised into five groups, which were analysed to determine how to simulate the tasks of each group. Section 5.2 presents a syntax to describe individual tasks, which enables describing tasks not included in the *action manifold* and can be used as an input argument to a single-task simulation and evaluation program. This appendix uses this syntax to describe sixty-four tasks comprising three of the five groups of tasks in the *action manifold*.

B.1 ACTIVE HAPTIC SENSING FUNCTIONALITIES

All Exploratory Procedures (EP) make contact with the surface or edges of an object. Example objects for simulation are: a sphere of 80 mm diameter for the *Enclosure EP* and the surface of a flat 2mm thick sheet for the remaining four EPs. Each EP is associated with a specific perceived object property, thus requires the acquisition of some information (*information exchange*) about the object. None of the five EPs selected for the *action manifold* involve prehension. Only *Pressure*

EP requires applying forces (*force exchange*) on the object in contact. All EPs, except *Enclosure EP*, have associated postures. All EPs do not have temporal constraints.

Table B.1 shows the descriptions of the five EPs in the *action manifold*. Note that *information exchange* and *force exchange* are abbreviated as I.EX and F.Ex respectively.

B.2 Prehensile functionalities

B.2.1 Grasping

The grasps in Feix et al. (2009) taxonomy are used for the grasping tasks in the *action manifold*. The posture for each grasp is determined from the graphical illustrations provided in the literature. Feix et al. (2013) report the objects used during their experiments with different grasps, all objects have primitive geometric shapes of box, cylinder, or sphere with different dimensions. Contact relations are determined from the graphical illustrations and grasp type, object pose is determined based on the contact relations and object dimensions. All grasps have no temporal constraints, are single-hand tasks, and do not involve *information* or *force exchange*. Tables B.2 and B.7 show the descriptions of the thirty-one grasps in the *action manifold of the anthropomorphic hand*.

B.3 Non-prehensile functionalities

B.3.1 Gesturing and pointing

Gestures and *"pointing and aiming" functionalities* are mainly single handed tasks that do not involve any contact with objects, and subsequently no prehension, information, or force exchange. These tasks can usually be performed in any speed, therefore there are no timing constraints. Therefore,only postures descriptions are required for these tasks.

For these tasks, the ten counting signs and the seventeen "basic handshapes" signs of BSL are used for the *guesturing* functionality, and a pointing gesture for *"pointing and aiming" functionality*. The descriptions of the counting signs of BSL are provided in Table B.8. The description of the pointing gesture is provided in Table B.9. The descriptions of the postures of BSL "basic handshapes" are provided in Table B.10.

Task Name	Lateral Motion EP	Characteristics	C-NP-M-NW-A-R-D-NF
Hand ID	0	Digits	001100
Posture	The hand is closed. The upper fingers are extended and straight. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object Pose	Flat sheet (2mm thickness) [$fD2_{t\_f}$][0 0 1 0 45 0]	Contacts	0-00-03-03-00-00
I.Ex	Force		
Task Name	Pressure EP	Characteristics	C-NP-M-NW-NA-R-D-F
Hand ID	0	Digits	001000
Posture	The hand is closed. The index finger is extended and straight. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object Pose	Flat sheet (2mm thickness) [$fD2_{t\_f}$][0 0 1 0 45 0]	Contacts	0-00-03-00-00-00
I.Ex	Force	F.Ex	[$fD2_{t\_f}$][0 0 1 0 45 0][0 0 1 0 0 0]
Task Name	Static Contact EP	Characteristics	C-NP-NM-NW-NA-R-D-NF
Hand ID	0	Digits	111111
Posture	The hand is open. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object Pose	Flat sheet (2mm thickness) [$fD3_{p\_f}$][0 0 1 0 0 0]	Contacts	3-11-22-22-22-22
I.Ex	Temperature		
Task Name	Enclosure EP	Characteristics	C-P-NM-NW-NA-NR-D-NF
Hand ID	0	Digits	111111
Object Pose	Sphere (80 mmdiameter) ws[P]	Contacts	3-22-22-22-22-22
I.Ex	Force array		
Task Name	Contour Following	Characteristics	C-NP-M-NW-A-R-D-NF
Hand ID	0	Digits	001000
Posture	The hand is closed. The index finger is extended and straight. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object Pose	Flat sheet (2mm thickness) [$fD2_{t\_f}$][0 0 1 0 45 0]	Contacts	0-00-03-00-00-00
I.Ex	Force array		

Table B.1: Description of the EPs in the action manifold

Task Name	Large Diameter	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are together, extended, and curved. The thumb is in opposition, abducted, extended, and slightly bent at second knuckle.		
Object	Cylinder 11cm diameter	Contacts	3 - 3 3 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r[P_d-60~-50] [O] [P_f+54~56] [O+88~92] [O+0~30] [O]		
Task Name	Small Diameter	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are together, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object	Cylinder 3cm diameter	Contacts	3 - 0 0 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r[P_d-20~-10] [O] [P_f+14~16] [O+88~92] [O+0~30] [O]		
Task Name	Medium Wrap	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are together, slightly bent at first knuckle, and curved. The thumb is in retroposition, abducted, adjacent to the palm, and curved.		
Object	Cylinder 3cm diameter	Contacts	3 - 3 3 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r[P_d-20~-10] [O] [P_f+14~16] [O+88~92] [O+0~30] [O]		
Task Name	Adducted Thumb	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are together, slightly bent at first knuckle, and curved. The index finger is extended and curved. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object	Cylinder 3cm diameter	Contacts	3 - 3 3 - 3 3 - 3 3 - 0 3 - 0 3
Pose	r[$D1_p$~P_d-10] [O] [P_f+14~16] [O+88~92] [O+40~50] [O]		
Task Name	Light Tool	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are together, extended, and curled. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object	Cylinder 1cm diameter	Contacts	3 - 0 3 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r[P_d-10~0] [O] [P_f+4~6] [O+88~92] [O-2~+2] [O]		

Table B.2: Descriptions of the grasps in the action manifold

Task Name	Prismatic 4 Finger	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 1 1
Posture	The fingers are together, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object	Cylinder 1 cm diameter	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 3 - 0 3
Pose	ws[$D1_d \cap D2_d$] r[O+45~+135] [O-45~+45] [O]		
Task Name	Prismatic 3 Finger	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 1 0
Posture	The fingers are together, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object	Cylinder 1 cm diameter	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 3 - 0 0
Pose	ws[$D1_d \cap D2_d$] r[O+45~+135] [O-45~+45] [O]		
Task Name	Prismatic 2 Finger	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 0 0
Posture	The fingers are together, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object	Cylinder 1 cm diameter	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 0 - 0 0
Pose	ws[$D1_d \cap D2_d$] r[O+45~+135] [O-45~+45] [O]		
Task Name	Palmar Pinch	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 0 0 0
Posture	The fingers are slightly bent at first knuckle and curved. The index finger is bent at first knuckle and curved. The thumb is in opposition, abducted, bent at first knuckle, and straight.		
Object	Coin	Contacts	0 - 0 3 - 0 3 - 0 0 - 0 0 - 0 0
Pose	ws[$D1_d \cap D2_d$] r[O+45~+135] [O-45~+45] [O]		
Task Name	Power Disk	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are separated, extended, and curled. The thumb is in retroposition, abducted, far from the palm, bent at first knuckle and bent at second knuckle.		
Object	Mini CD	Contacts	3 - 3 3 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r[P_d-60~-20] [P_r~P_u] [P_f+0~2] [O-2~+2] [O-2~+2] [O]		

Table B.3: Descriptions of the grasps in the action manifold (continued)

Task Name	Power Sphere	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are separated, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object	Tennis Ball (67mm diameter)	Contacts	3 - 3 3 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r$[P_d\text{-}39\sim\text{-}29]$ $[P_r\sim P_u]$ $[P_f+33\sim34]$ $[O]$ $[O]$ $[O]$		
Task Name	Precision Disk	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 1 1
Posture	The fingers are separated, slightly bent at first knuckle, and curved. The thumb is in retroposition, abducted, far from the palm, and curved.		
Object	CD (Compact Disc)	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 3 - 0 3
Pose	ws$[P_d]$ r$[O\text{-}2\sim+2]$ $[O\text{-}2\sim+2]$ $[O]$		
Task Name	Precision Sphere	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 1 1
Posture	The fingers are separated, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object	Tennis Ball (67mm diameter)	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 3 - 0 3
Pose	ws$[P_d]$ r$[O]$ $[O]$ $[O]$		
Task Name	Tripod	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 0 0
Posture	The hand is closed. The upper fingers are separated, extended, and curved. The thumb is in opposition, abducted, and curved.		
Object	Golf Ball (43mm diameter)	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 0 - 0 0
Pose	ws$[D1_d \cap D2_d]$ r$[O]$ $[O]$ $[O]$		
Task Name	Fixed Hook	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 0 1 1 1 1
Posture	The fingers are together, slightly bent at first knuckle, and curved. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object	Cylinder 3cm diameter	Contacts	3 - 0 0 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r$[P_d\text{-}20\sim\text{-}10]$ $[O]$ $[P_f+14\sim16]$ $[O+88\sim92]$ $[O+0\sim30]$ $[O]$		

Table B.4: Descriptions of the grasps in the action manifold (continued)

Task Name	Lateral	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 0 0 0
Posture	The hand is closed. The thumb is in retroposition, adducted, adjacent to the palm, slightly bent at first knuckle, and straight.		
Object	Credit Card	Contacts	0 - 0 3 - 3 3 - 0 0 - 0 0 - 0 0
Pose	r$[D2_{m_r}]$ $[D2_{m\_r}$-1~+1] $[D2_{m\_r}]$ $[O$+88~92] $[O]$ $[O]$ $[O]$		

Task Name	Index Finger Extension	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are together, bent at first knuckle, and curved. The index finger is extended and straight. The thumb is in opposition, adducted, extended, and straight.		
Object	Cylinder 3cm diameter	Contacts	3 - 3 3 - 3 3 - 3 3 - 3 3 - 3 3
Pose	r$[D2_p]$ $[D2_p]$ $[P\_{}_f$+14~16] $[O$+88~92] $[O]$ $[O$+60~90] $[O]$		

Task Name	Extension Type	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The fingers are together, slightly bent at the first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object	Plate	Contacts	0 - 0 3 - 3 3 - 3 3 - 3 3 - 0 0
Pose	$r[P\_{}_d$+0~85] $[O]$ $[P\_{}_f$+12~62] $[O$-20~+20] $[O$-20~+20] $[O]$		

Task Name	Writing Tripod	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 0 0
Posture	The hand is closed. The upper fingers are slightly bent at first knuckle and curved. The thumb is in opposition, abducted, and curved.		
Object	Cylinder 1cm diameter	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 0 - 0 0
Pose	ws$[D1_d \cap D2_d]$ r$[O$+45~+135] $[O$-45~+45] $[O]$		

Task Name	Parallel Extension	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 1 1
Posture	The fingers are together, slightly bent at first knuckle, and straight. The thumb is in opposition, adducted, slightly bent at first knuckle, and straight.		
Object	4cm Cube	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 3 - 0 3
Pose	ws$[P_d]$ r$[O$-2~+2] $[O$-45~+135] $[O]$		

Table B.5: Descriptions of the grasps in the action manifold (continued)

Task Name	Abduction Grip	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 0 1 1 0 0
Posture	The fingers are together. The lower fingers are slightly bent at first knuckle and curved. The upper fingers are extended and curved. The thumb is in opposition, abducted, and curved.		
Object	Cylinder 1cm diameter	Contacts	0-00-22-22-00-00
Pose	r[$D2_{m_u}$] [$D2_{m_u}$-5~+5] [$D2_{m_u}$] [O-45~+45] [O+0~180] [O]		

Task Name	Tip Pinch	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 0 0 0
Posture	The fingers are slightly bent at first knuckle and curved. The index finger is bent at first knuckle and curved. The thumb is in opposition, abducted, and curved.		
Object	5mm Cube	Contacts	0-03-03-00-00-00
Pose	ws[$D1_d \cap D2_d$] r[O] [O] [O]		

Task Name	Lateral Tripod	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 0 0
Posture	The hand is closed. The index is bent at first knuckle and curved. The thumb is in retroposition, adducted, adjacent to palm, and curved.		
Object	Bottle Cap	Contacts	0-03-03-03-00-00
Pose	ws[$D1_d \cap D2_d$] r[O+45~+135] [O-45~+45] [O]		

Task Name	Sphere 4 Finger	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 0
Posture	The fingers are separated, slightly bent at first knuckle, and curved. The small finger is bent at first knuckle and curled. The thumb is in opposition, abducted, and curved.		
Object	Tennis Ball (67mm diameter)	Contacts	0-33-33-33-33-00
Pose	r[P_d-39~-29] [P_r~P_u] [P_f+34~54] [O] [O] [O]		

Task Name	Quadpod	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 1 1 0
Posture	The fingers are separated, slightly bent at first knuckle, and curved. The small finger is bent at first knuckle and curled. The thumb is in opposition, abducted, and curved.		
Object	Golf Ball (43mm diameter)	Contacts	0-03-03-03-03-00
Pose	ws[P] r[O] [O] [O]		

Table B.6: Descriptions of the grasps in the action manifold (continued)

Task Name	Sphere 3 Finger	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 0 0
Posture	The lower fingers are together, bent at first knuckle, and curled. The upper fingers are separated, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, and curved.		
Object Pose	Tennis Ball (67mm diameter) r[P_d-39~-29] [P_r~P_u] [P_f+34~54] [O] [O] [O]	Contacts	0 - 3 3 - 3 3 - 3 3 - 0 0 - 0 0

Task Name	Stick	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The hand is closed. The index finger is extended and curved. The thumb is in opposition, abducted, slightly bent at first knuckle, and straight.		
Object Pose	Cylinder 1 cm diameter r[P_d] [O] [P_f+10~20] [O+88~92] [O+40~50] [O]	Contacts	0 - 0 3 - 3 0 - 0 3 - 0 3 - 0 3

Task Name	Palmar	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The hand is closed. The thumb is in retroposition, adducted, far from the palm, extended, and straight.		
Object Pose	Plate r[P_d-90~-80] [O] [P_f+2~3] [O-2~+2] [O-2~+2] [O]	Contacts	3 - 0 0 - 1 3 - 1 3 - 1 3 - 1 3

Task Name	Ring	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 0 0 0
Posture	The hand is open. The index finger is extended and curved. The thumb is in opposition, abducted, and curved.		
Object Pose	Cylinder 64mm diameter r[P_d-37~-27] [O] [P_f+31~33] [O+88~92] [O+0~30] [O]	Contacts	1 - 3 3 - 3 3 - 0 0 - 0 0 - 0 0

Task Name	Ventral	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	1 1 1 1 1 1
Posture	The hand is closed. The index finger is extended and straight. The thumb is in opposition, adducted, slightly bent at first knuckle, and straight.		
Object Pose	Cylinder 1 cm diameter r[P_d] [O] [P_f+10~20] [O+88~92] [O+40~50] [O]	Contacts	0 - 0 3 - 0 3 - 0 3 - 0 3 - 0 3

Task Name	Inferior Pincer	Characteristics	C-P-NM-NW-NA-R-ND-NF
Hand ID	0	Digits	0 1 1 0 0 0
Posture	The hand is open. The index finger is bent at first knuckle and straight. The thumb is in opposition, abducted, extended, and straight.		
Object Pose	Golf Ball (43mm diameter) ws[$D1_d \cap D2_d$] r[O] [O] [O]	Contacts	0 - 0 3 - 0 3 - 0 0 - 0 0 - 0 0

Table B.7: Descriptions of the grasps in the action manifold (continued)

Sign	Description
One	The hand is tightly closed. The index finger is extended and straight. The thumb is in opposition, abducted, curved, and touches the back of the lower fingers.
Two	The hand is tightly closed. The upper fingers are separated, extended, and straight. The thumb is in opposition, abducted, curved, and touches the back of the lower fingers.
Three	The hand is open. The small finger is bent at first knuckle and bent at second knuckle. The thumb is in opposition, abducted, curved, and touches the back of the small finger.
Four	The hand is open. The thumb is in opposition, abducted, and curved.
Five	The hand is open. The thumb is in retroposition, adducted, far from the palm, and straight.
Six	The hand is tightly closed. The thumb is in retroposition, adducted, far from the palm, extended and bent at second knuckle.
Seven	The hand is tightly closed. The index finger is extended and straight. The thumb is in retroposition, adducted, far from the palm, and straight.
Eight	The hand is tightly closed. The upper fingers are separated, extended, and straight. The thumb is in retroposition, adducted, far from the palm, and straight.
Nine	The hand is flat. The small finger is bent at first knuckle and bent at second knuckle. The thumb is in retroposition, adducted, far from the palm, and straight.
Ten	The hand is open. The thumb is in retroposition, adducted, far from the palm, and straight.

Table B.8: Posture description of BSL counting signs

Gesture	Description
Pointing	The hand is tightly closed. The index finger is extended and straight. The thumb is in opposition, abducted, curved, and touches the back of the lower fingers.

Table B.9: Posture description of pointing gesture

Sign	Description
Fist	The hand is tightly closed. The thumb is in opposition, abducted, curved, and touches the back of the fingers.
Bunched Hand	The fingers are together, bent at first knuckle, and straight. The thumb is in opposition, abducted, straight, and touches the fingertips.
Closed Hand	The hand is closed. The thumb is in retroposition, adducted, adjacent to the palm, and straight.
Flat Hand	The fingers are together, extended, and straight. The thumb is in retroposition, adducted, far from the palm, and straight.
Open Hand	The fingers are separated, extended, and straight. The thumb is in retroposition, adducted, far from the palm, and straight.
Clawed Hand	The fingers are separated, extended, and bent at second knuckle. The thumb is in retroposition, adducted, far from the palm , and bent at second-knuckle.
Bent Hand	The fingers are together, bent at first knuckle, and straight. The thumb is in retroposition, adducted, adjacent to the palm, and straight.
'C' Hand	The hand is closed. The index finger is extended and slightly curved. The thumb is in opposition, abducted, and slightly curved.
'O' Hand	The fingers are together, extended and slightly curved. The index finger is slightly bent at first knuckle and curved. The thumb is in opposition, abducted, slightly curved, and touches the index fingertip
'L' Hand	The hand is closed. The index finger is extended and straight. The thumb is in retroposition, adducted, far from the palm, and straight.
'M' Hand	The hand is flat. The small finger is bent at first knuckle and bent at second knuckle. The thumb is in opposition, abducted, curved, and touches the back of the small finger.
'N' Hand	The hand is flat. The lower fingers are bent at first knuckle and bent at second knuckle. The thumb is in opposition, abducted, curved, and touches the back of the lower fingers.
Irish 'T' Hand	The hand is closed. The index finger is extended and curved. The thumb is in opposition, adducted, straight, and touches the pad of the index finger middle phalanx.
'V' Hand	The lower fingers are bent at first knuckle and bent at second knuckle. The thumb is in opposition, abducted, curved, and touches the back of the lower fingers.
'Y' Hand	The hand is closed. The small finger is extended and straight. The thumb is in retroposition, adducted, far from the palm, and straight.
Full 'C' Hand	The fingers are together, extended, and slightly curved. The thumb is in opposition, abducted, and slightly curved.
Full 'O' Hand	The fingers are together, slightly bent at first knuckle, and curved. The thumb is in opposition, abducted, slightly curved, and touching the index distal phalanx.

Table B.10: Posture description of basic BSL handshapes

C

Texture Recognition Using Force Sensitive Resistor

THIS APPENDIX presents a proof that a single point force sensor provides enough information to detect surface texture roughness when the sensor is moved across the surface.

INTRODUCTION

Humans perform a repetitive lateral rubbing motion across a surface to feel its texture, an action known as *Lateral Motion Exploratory Procedure*. The physiology of the human sense of touch suggests that the information the human Central Nervous System (CNS) receives during this motion is coming from force sensory elements embedded in the skin.

Tan et al. (2014) were able to interface a Force Sensing Resistor (FSR) sensor, installed on a fingertip of a prosthetic hand, with the user's nerves. The user reported the ability to perceive "texture" of surfaces. This suggests that the single point force data acquired by the FSR hold enough information to perceive surface texture.

The work presented in this appendix proposes that the same ability can be replicated in an artificial system using the same sensor. It would be particularly useful to achieve this ability using FSRs due to their low cost and low thickness that enables superficial installation on robotic hands.

This appendix presents the results of an experiment conducted on four surface samples that shows that the signal from the FSR does contain enough information to recognise at least one surface with above chance accuracy.

C.1 Experimental setup

C.1.1 FSR working principle

An FSR acts as a resistor whose resistance changes when *pressure* is applied on the sensor's active area. It is made of two flexible layers joined by an adhesive spacer (Figure C.1). One layer contains a printed open circuit, while the other contains a printed semi-conductor layer whose conductivity increases with pressure. When pressure is applied, the two layers come in contact thus closing the circuit. The circuit's resistance is inversely proportional to the applied pressure with a non linear relation (Figure C.2).

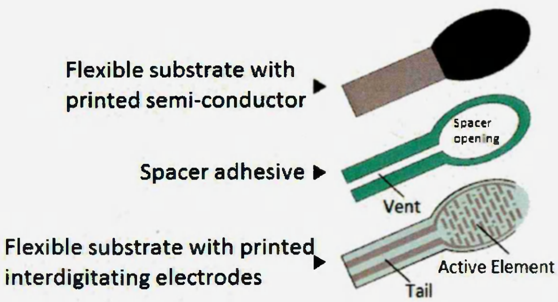


Figure C.1: Exploded view of FSR (Limor Fried, 2012)

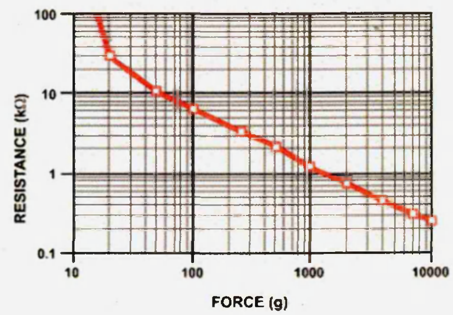


Figure C.2: FSR resistance-force relation (Limor Fried, 2012)

C.1.2 Data acquisition

During the experiment, the sensor readings were recorded using an oscilloscope and an operational amplifier circuit (Figure C.3). The signals were sampled at 10kHz.

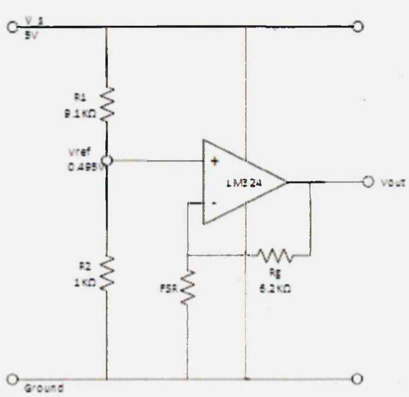


Figure C.3: FSR data acquisition circuit

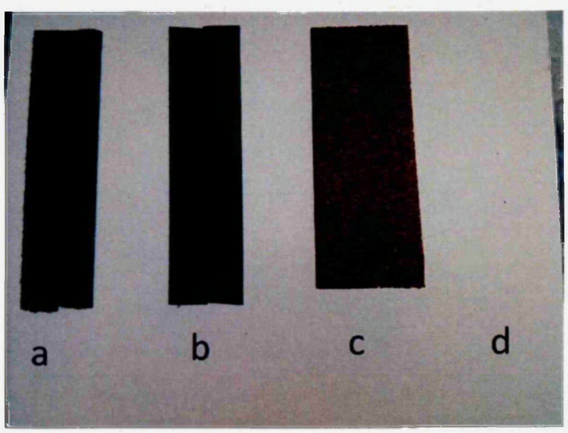


Figure C.4: Surface samples

C.1.3 Surface samples

Four sample surfaces were selected for the experiment. The surfaces were selected to have textures that vary from smooth to rough. The selected surfaces are shown in Figure C.4: a) Velcro loops, b) Velcro hooks, c) rough sandpaper, and d) smooth plastic-coated cork.

C.1.4 Motion

The *Lateral Motion Exploratory Procedure* is performed by bringing the sensitive part of the hand in contact with the surface then moving it across the surface. In the human case, it is possible that this motion is conducted with variable speed and contact pressure. Therefore, our experiment aims to investigate the presence of patterns in the signal acquired during motion with non-constant speed and contact pressure. For this reason, one set of signals was recorded while performing the motion by holding the sensor and manually moving it across the surfaces. However, for verification purposes, a pressure set was recorded while the motion is performed using a robotic arm to minimise variation in speed and contact force.

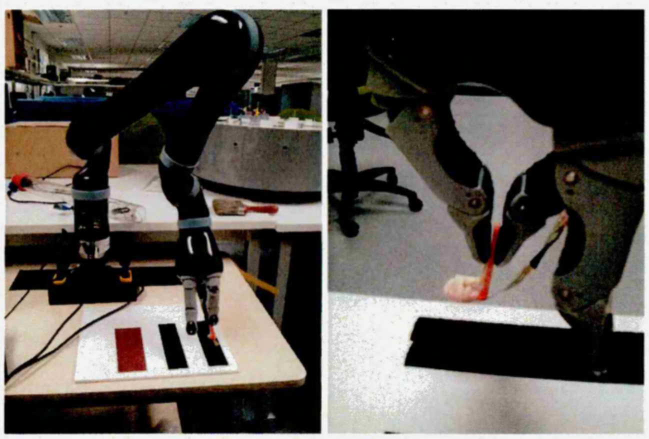


Figure C.5: FSR attached to a robot arm

C.2 Results

The recorded samples were initially processed using fast Fourier transform (FFT) to look for patterns in the signal frequency response. The data varied between samples of the same surfaces; however, most samples showed a relatively consistent pattern of very high magnitude at low frequencies followed by low magnitude at higher frequency with a region of relatively high magnitude at frequencies between 2250 Hz and 3250 Hz (Figures C.6-C.9). Surprisingly, this pattern only appeared in samples recorded with non constant motion speed and contact pressure but not in samples recorded with constant motion speed and contact pressure.

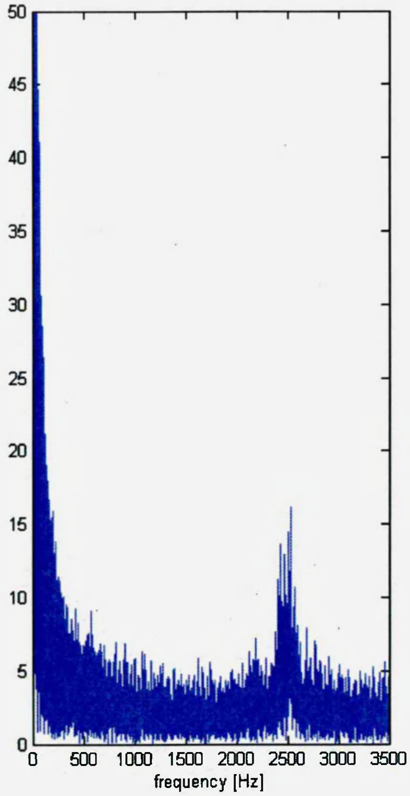


Figure C.6: Velcro Loops FFT analysis

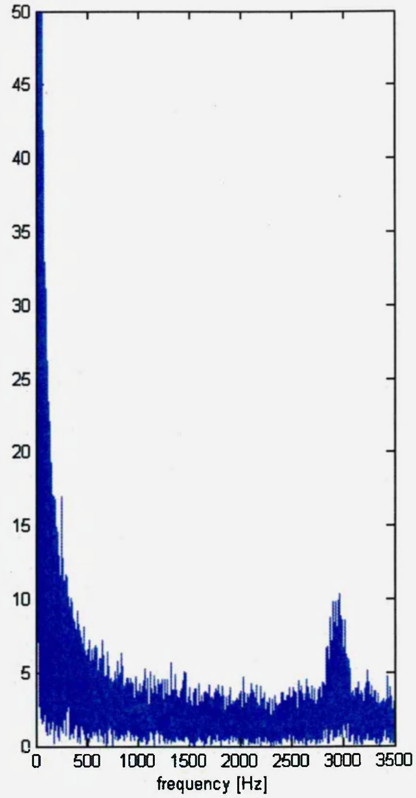


Figure C.7: Velcro Hooks FFT analysis

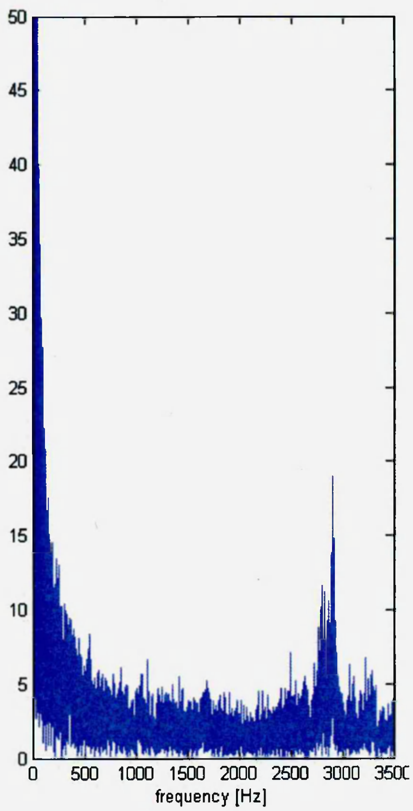


Figure C.8: Sandpaper FFT analysis

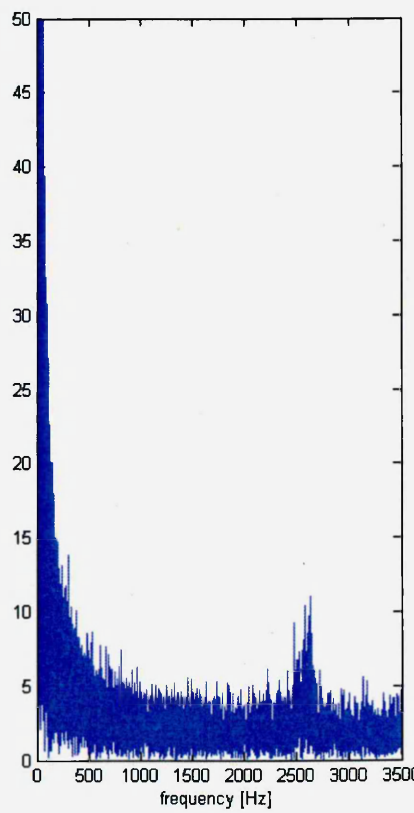


Figure C.9: Cork FFT analysis

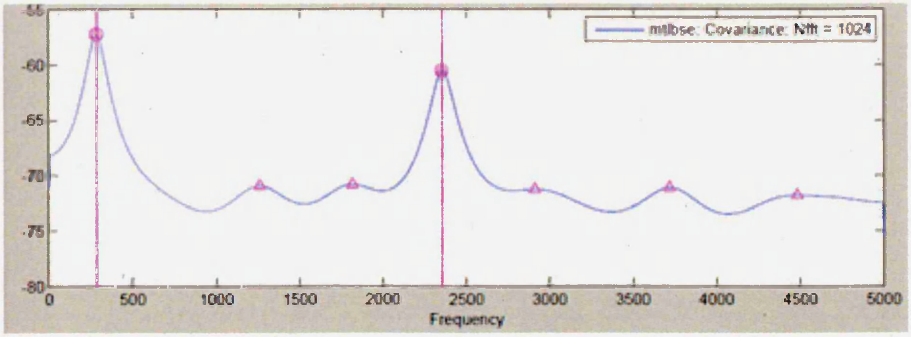


Figure C.10: Velcro loops Covariance Spectrum Filter analysis

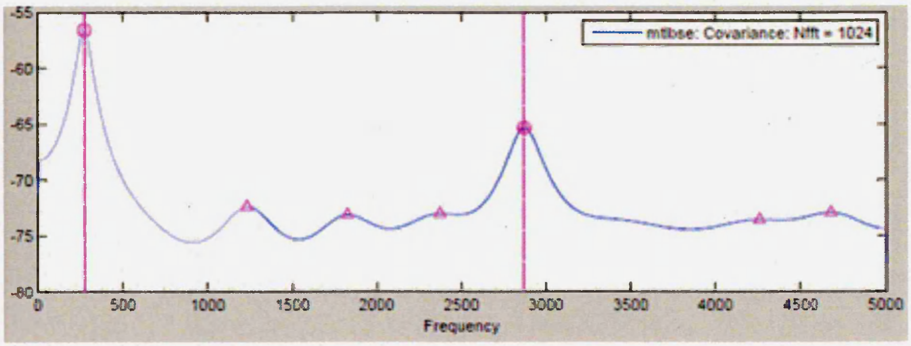


Figure C.11: Velcro hooks Covariance Spectrum Filter analysis

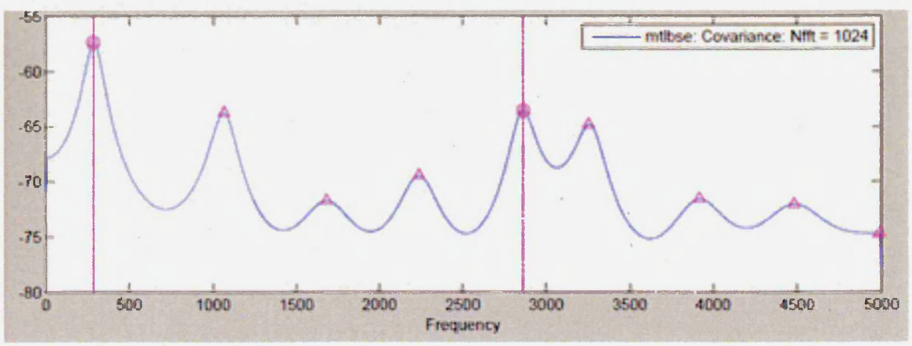


Figure C.12: Sandpaper Covariance Spectrum Filter analysis

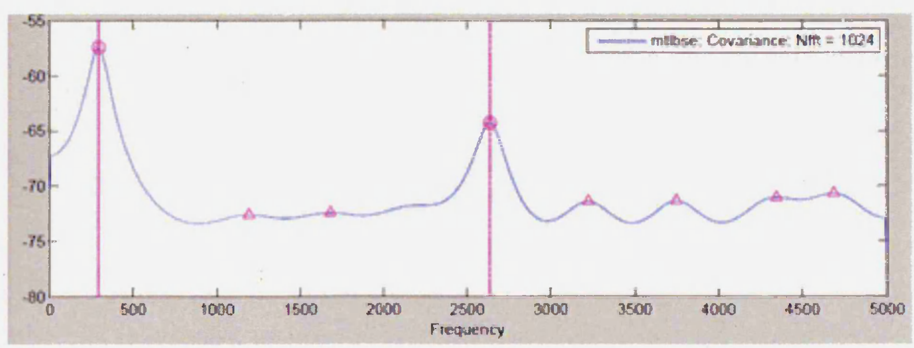


Figure C.13: Cork Covariance Spectrum Filter analysis

The very high magnitude at low frequencies is probably due to variation in contact pressure. The regions of high magnitude at high frequencies appears to be related to surface texture. The regions are centred around 2500 Hz for smoother surfaces (Velcro loops and cork) and 3000 Hz for rougher surfaces (Velcro hooks and sandpaper).

The results of the FFT analysis prompted a second analysis; therefore, the data was processed using the Covariance Spectrum Filter (Figures C.10-C.13). The Covariance Spectrum Filter analysis results show the same peaks of activity close to 2500 Hz for smooth surfaces and the peaks close to 2800-3000 Hz for rough surfaces.

The results also suggest another region with potential identifying features within the range of 900 Hz to 1600 Hz (Figure C.14). The peaks and valley points between the two frequencies for 120 samples (30 samples for each surface) were identified and plotted (Figures C.15-C.16). The plots show that the points are apparently randomly distributed; however, there is a large area (about 50% in either plots) that is exclusively occupied by sandpaper data points. In case of peaks points, this area contains 18 of the 30 data points from sandpaper samples. Also more than 60 points of the other surfaces' samples lie outside the sandpaper area. In case of valley points, the exclusive sandpaper area contains only 11 of the 30 sandpaper data points, and only 40 of the other surfaces data points lie outside the sandpaper area.

C.3 Discussion and conclusions

The results show that some information do exist in the signal from a single point FSR to differentiate between surfaces of different textures. One particularly interesting observation is that the observed patterns mainly exist in samples recorded with non-constant motion speed and contact pressure.

While the experiment would not completely isolate these features, the obtained results clearly show a potential to differentiate between textures, particularly between rough and smooth tex-

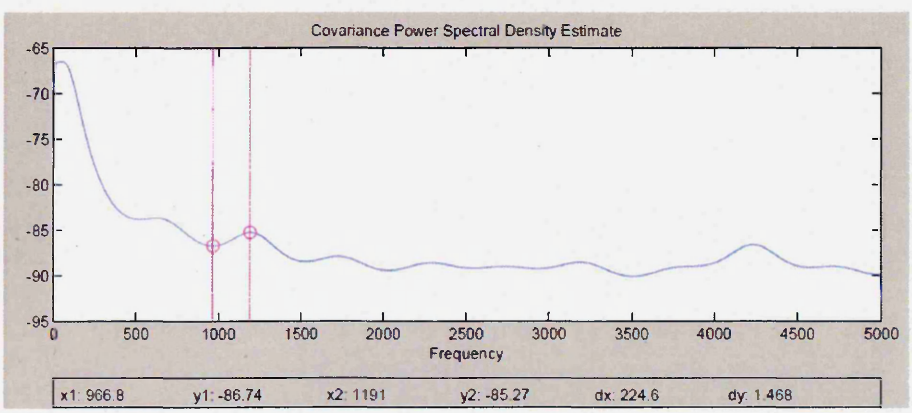


Figure C.14: Potential features in the results of Covariance Spectrum Filter analysis

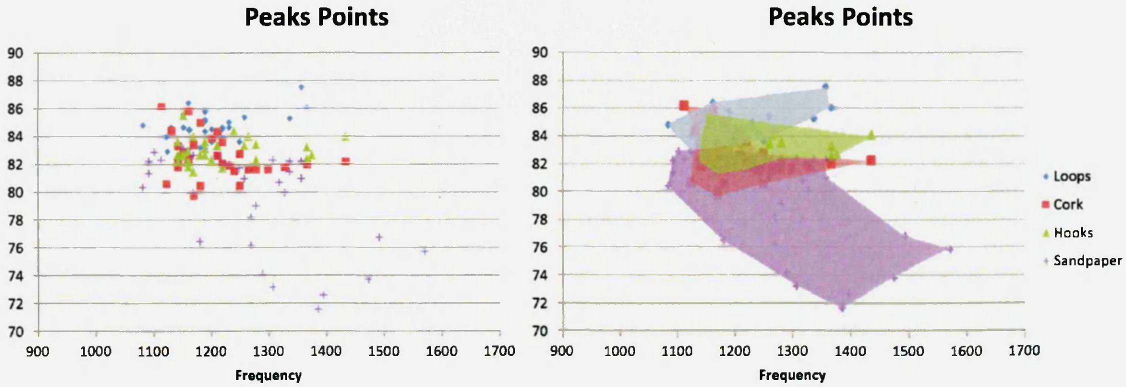


Figure C.15: Distribution map of peaks points

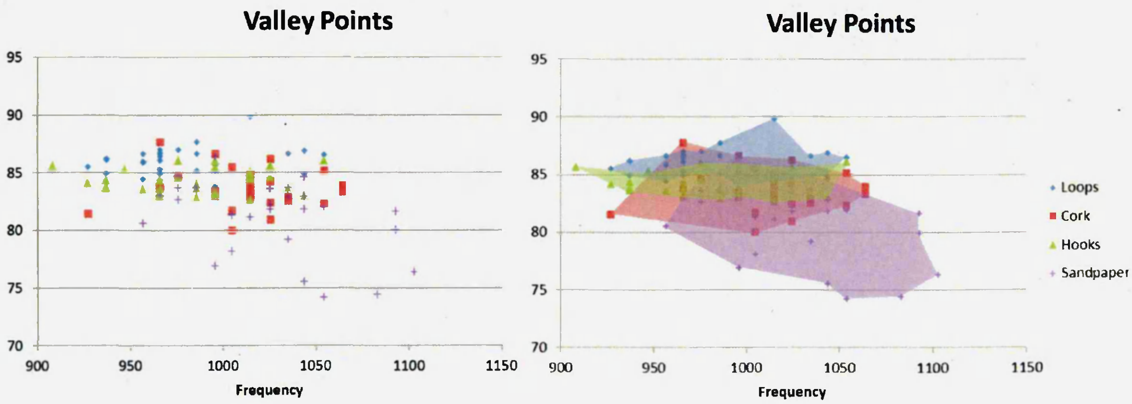


Figure C.16: Distribution map of valley points

tures. Note that the aim of the experiment involves the ability to differentiate between textures in a similar manner to humans, and not to precisely quantify the texture using standard metrics.

Sandpaper in particular showed promising results. The distribution of the peaks points in Figure C.15 suggest that sandpaper can be positively detected 60% of the time, while it can be correctly ruled out 67% of the time.

In conclusion, a single point FSR sensor provides enough information to detect difference in roughness of surface texture when the sensor is moved in a lateral motion across the surface with non-constant speed and contact pressure. This information is not sufficient to precisely quantify the roughness of the surface texture.

D

Codes For System Implementation

THIS APPENDIX presents the link to the online repository containing the MATLAB implementation codes for the proposed processes

INTRODUCTION

All the codes used in this thesis (including external dependencies) can be downloaded from the online repository which can be found at:

https://github.com/Muhammad-Sayed/hand-evaluation.git

Figure D.1: Barcode containing the link to the online repository

E

Comparison between existing artificial hands

THIS APPENDIX presents comparison tables for different existing artificial hands

INTRODUCTION

This appendix presents comparison tables for examples of existing artificial hands. The tables present a review of the specifications, mechanical properties, and intended functionalities the hands. Selected examples include anthropomorphic and non-anthropomorphic hands.

The comparison parameters include hand components, such as structure, surface, sensors, and actuators (Chapter 3), and key mechanical properties and functionalities. The size parameters compare the overall size to that of the human hand and indicates whether the developers maintained or ignored the differences between the sizes of fingers and phalanges. The "surface" parameters indicate the locations available for contact, which can be *fingertips, phalanges,* or *palm,* and an indication of the extension or continuity of the contact surfaces at these locations. For the mechanical properties, the tables indicate if the mechanism contains compliant or back-drivable components and if it is underactuated. For underactuation, the tables indicate if the system uses rigid coupling, adaptive mechanisms, or loosely coupled (for example several joints actuated by one tendon). Functionalities can be *grasping, [within-hand] manipulation,* and *gesturing.*

Hand Name	Robonaut Hand	Robonaut Hand 2
Organisation	NASA JSC and others	NASA and General Motors
Type of project	Research	Research
Resources	Lovchik et al. (1999),Ambrose et al. (2000)	Bridgwater et al. (2012), Diftler et al. (2012)
Structure	Endoskeletal	Exoskeletal
Integration	Integrated	Integrated
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✓	✓
Fifth finger	✓	✓
Overall size	bigger	equal
Size ratios	-	-
Contact Surfaces	Fingertips, Phalanges, Palm	Fingertips, Phalanges, Palm
C. S. extension	Good	Good
Actuator location	Remote	Remote
No. Actuators	14	18
No. Joints	22	20
Type of actuators	Brushless DC motors	DC motor with leadscrew assembly
Transmission type	-	Tendons
State sensors		
Motor position	✓(incremental)	✓(incremental hall effect)
Joint position	✓(absolute)	✓(absolute hall effect)
Tendon tension	✗	✓
Joint torque	✗	✗
Motor effort	✗	Current and temperature
Other	Transmission instrumented as load cells	-
Interaction sensors		
Tactile array	✗	✗
Other	-	Tactile load sensor
Stiffness	Compliant joints	Stiff mechanism
Underactuation	Coupled lower fingers	Coupled
Adaptive mechanism	-	-
Grasping	✓	✓
Manipulation	✓	✓
Gesturing	-	-
Notes	Fingers arranged into grasping set and dexterous manipulation set. Palm has an active DoF	-

Hand Name	DLR Hand	DLR Hand II
Organisation	DLR German Aerospace Cnter	DLR German Aerospace Centre
Type of project	Research	Research
Resources	Butterfass et al. (1998), Liu et al. (1998), Liu et al. (1999)	Butterfass et al. (2001), Borst et al. (2003), Butterfnr et al. (2004), Haidacher et al. (2003)
Structure	Exoskeletal	Endoskeletal
Integration	Modular	Modular
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✓	✓
Fifth finger	✗	✗
Overall size	much bigger	much bigger
Size ratios	ignored	-
Contact Surfaces	Fingertips, Phalanges, Palm	Fingertips, Phalanges, Palm
C. S. extension	Average	Good
Actuator location	Palm, Fingers	Palm, Fingers
No. Actuators	12	13
No. Joints	16	18
Type of actuators	Linear Actuator (BLDC-based)	DC and BLDC motors
Transmission type	Tendons	Gears and belts
State sensors		
Motor position	✓(commutation hall effect)	✓(commutation hall effect)
Joint position	✓(optical)	✓(potentiometer)
Tendon tension	✗	✗
Joint torque	✓(strain gauge based)	✓(strain gauge based)
Motor effort	✗	✗
Other	Temperature (for safety)	Temperature (for safety)
Interaction sensors		
Tactile array	✗	✗
Other	FSR	-
Stiffness	-	-
Underactuation	Coupled	Coupled
Adaptive mechanism	-	-
Grasping	-	-
Manipulation	-	-
Gesturing	-	-
Notes	Stereo camera in the palm aided by laser project from fingertips. 6-axis force/torque sensor in the wrist	6-axis force/torque sensor in the wrist

Hand Name	Shaddow Dexterous Hand	InMoov Robot Hand
Organisation	Shaddow Robot Company	
Type of project	Commercial	Hobby Project
Resources	ShadowRobot, Shadow Robot Company (2013)	Langevin (2012)
Structure	Exoskeletal	Exoskeletal
Integration	Integrated	Integrated
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✓	✓
Fifth finger	✓	✓
Overall size	equal	equal
Size ratios	maintained	maintained
Contact Surfaces	Fingertips, Phalanges, Palm	Fingertips, Phalanges, Palm
C. S. extension	Good	Good
Actuator location	Remote	Remote
No. Actuators	20	6
No. Joints	24	18
Type of actuators	Air muscles or electric motors	RC servo motor
Transmission type	Tendons	Tendons
State sensors		
Motor position	✗	✓(internal servo potentiometer)
Joint position	✓	✗
Tendon tension	✓(motor version only)	✗
Joint torque	✗	✗
Motor effort	✓(temp. & current, used internally)	✗
Other	Air muscle pressure	-
Interaction sensors		
Tactile array	✓(optional BioTac sensor)	-
Other	Single region pressure sensor	✗
Stiffness	-	Very low
Underactuation	DIP joints coupled to PIP joints	Loosely coupled
Adaptive mechanism	✓	-
Grasping	✓	✓
Manipulation	✓	✗
Gesturing	✓	✓
Notes	-	-

Hand Name	Adaptive Robot Gripper	Barret Hand
Organisation	Robotiq	Barrett Technology
Type of project	Commercial	Commercial
Resources	Robotiq (2012b)	Barrett Technology (2010)
Structure	Exoskeletal	Exoskeletal
Integration	Modular	Modular
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✗	✗
Fifth finger	✗	✗
Overall size	bigger	bigger
Size ratios	ignored	ignored
Contact Surfaces	Fingertips, Phalanges, Palm	Fingertips, Phalanges, Palm
C. S. extension	Good	Good
Actuator location	Palm	Palm / Fingers / Remote
No. Actuators	-	4
No. Joints	11	8
Type of actuators	-	Brushless electric motor
Transmission type	-	-
State sensors		
Motor position	-	✓
Joint position	-	-
Tendon tension	-	-
Joint torque	✓	✓ (fingertip joint torque sensor)
Motor effort	-	-
Other	-	-
Interaction sensors		
Tactile array	-	✓
Other	-	-
Stiffness	Compliant joints	-
Underactuation	Coupled	
Adaptive mechanism	✓	-
Grasping	✓	✓
Manipulation	✓	✓
Gesturing	✗	✗
Notes	-	-

Hand Name	LARM Hand 3	LARM Hand 4
Organisation	LARM	LARM
Type of project	Research	Research
Resources	Carbone and Ceccarelli (2008)	Carbone and Ceccarelli (2008), Luo (2013)
Structure	Exoskeletal	Exoskeletal
Integration	Modular	Modular
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✗	✗
Fifth finger	✗	✗
Overall size	Equal	Bigger
Size ratios	Maintained	Maintained
Contact Surfaces	Phalanges, Palm	Phalanges, Palm
C. S. extension	Good	Good
Actuator location	Palm	Palm
No. Actuators	3	3 (or 4, see notes)
No. Joints	9	9 (or 11)
Type of actuators	DC motors	DC motors
Transmission type	Mechanical linkage	Mechanical linkage
State sensors		
Motor position	-	-
Joint position	-	-
Tendon tension	-	-
Joint torque	-	-
Motor effort	-	-
Other	-	-
Interaction sensors		
Tactile array	✗	✗
Other	Piezoresistive force sensors	Piezoresistive force sensors
Stiffness	High stiffness	High stiffness
Underactuation	Coupled	Coupled
Adaptive mechanism	✓	✓
Grasping	✓	✓
Manipulation	✗	✓
Gesturing	✗	✗
Notes	-	Recent design modification allows some within-hand manipulation (Luo, 2013)

Hand Name	DLR/HIT Dexterous Hand	DLR/HIT Dexterous Hand II
Organisation	DLR & HIT	DLR & HIT
Type of project	Research / Commercial	Research
Resources	Liu et al. (2008a), Liu et al. (2007), Jiang et al. (2003), Gao et al. (2003)	Liu et al. (2008b)
Structure	Exoskeletal	Exoskeletal
Integration	Modular	Modular
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✓	✓
Fifth finger	✗	✓
Overall size	much bigger	much bigger
Size ratios	maintained	maintained
Contact Surfaces	Fingertips, Phalanges, Palm	Fingertips, Phalanges, Palm
C. S. extension	Good	Good
Actuator location	Fingers	Fingers
No. Actuators	13	15
No. Joints	17	20
Type of actuators	BLDC	BLDC
Transmission type	Gears	Timing belt and steel wires
State sensors		
Motor position	✓(hall effect)	✓(hall effect)
Joint position	✓(hall effect)	✓(hall effect)
Tendon tension	✗	✗
Joint torque	✓(strain gauge)	✓(strain gauge)
Motor effort	✗	✗
Other	Temperature	Temperature
Interaction sensors		
Tactile array	✗	✗
Other	6-axis force/torque sensor at finger-tips	6-axis force/torque sensor at finger-tips
Stiffness	-	-
Underactuation	mechanically coupled by rigid link	mechanically coupled
Adaptive mechanism	-	-
Grasping	✓	✓
Manipulation	-	-
Gesturing	-	-
Notes	Commercially distributed as SAH	2-axis accelerometer in palm to measure absolute orientation

Hand Name	Hoshino Hand 1	Hoshino Hand 2
Organisation	University of Tsukuba, TechExperts Inc.	University of Tsukuba, TechExperts Inc.
Type of project	Research	Research
Resources	Hoshino and Kawabuchi (2006), Hoshino and Kawabuchi (2005)	Hoshino et al. (2004), Hoshino and Kawabuchi (2006)
Structure	Exoskeletal	Exoskeletal
Integration	Modular	Modular
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✓	✓
Fifth finger	✓	✓
Overall size	equal	-
Size ratios	-	maintained
Contact Surfaces	Fingertips, Phalanges, Palm	Fingertips
C. S. extension	Average	Average
Actuator location	Palm, Fingers	Fingers
No. Actuators	8	-
No. Joints	14 (19)	21
Type of actuators	coreless DC motors	electric motor
Transmission type	gears, wire-pulley, mechanical linkage	-
State sensors		
Motor position	✓	✓
Joint position	✗	✓
Tendon tension	✗	-
Joint torque	✗	-
Motor effort	✗	-
Other	-	-
Interaction sensors		
Tactile array	✗	✗
Other	-	-
Stiffness	-	-
Underactuation	Rigid coupling	
Adaptive mechanism	-	-
Grasping	-	✓
Manipulation	-	-
Gesturing	✓	-
Notes	Research aim to perform sign language by a robot hand	Pinching. Twisting thumb. Fingertips actively actuated

Hand Name	NAIST Hand	NAIST Hand 2
Organisation	NAIST	NAIST
Type of project	Research	Research
Resources	Ueda et al. (2005), Ueda et al. (2010)	Kurita et al. (2009), Kurita et al. (2011)
Structure	Exoskeletal	Exoskeletal
Integration	Modular	Integrated
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✓	✓
Fifth finger	✗	✓
Overall size	much bigger	equal
Size ratios	ignored	maintained
Contact Surfaces	Fingertips, Phalanges, Palm	Fingertips, Phalanges, Palm
C. S. extension	Poor	Good
Actuator location	Palm, Fingers	Remote
No. Actuators	12	16
No. Joints	12 (16)	21
Type of actuators	DC and servo (DC) motors	Servo motors
Transmission type	Gear and link mechanism	Tendons, gears
Trans. routeing	-	Pulleys
State sensors		
Motor position	✓	✓ (servo internal encoders)
Joint position	-	✓ (rotary potentiometer)
Tendon tension	-	✗
Joint torque	-	✗
Motor effort	-	✗
Other	-	-
Interaction sensors		
Tactile array	✗	✗
Other	Vision-based fingertip tactile sensor	-
Stiffness	-	-
Underactuation	Rigid mechanical coupling	Coupled by rigid linkage
Adaptive mechanism	-	-
Grasping	-	-
Manipulation	-	-
Gesturing	-	-
Notes	-	-

Hand Name	Universal Robot Hand	Yamano Five Fingered Robot Hand
Organisation	Multiple academic collaborators	Keio University, Japan
Type of project	Research	Research
Resources	Nakamoto et al. (2006)	Yamano et al. (2003), Yamano and Maeno (2005)
Structure	Exoskeletal	Exoskeletal
Integration	Modular	Modular
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✓	✓
Fifth finger	✓	✓
Overall size	much bigger	equal
Size ratios	-	maintained
Contact Surfaces	Fingertips, Phalanges	Fingertips
C. S. extension	Average	Average
Actuator location	Fingers	Palm, Fingers
No. Actuators	15	20
No. Joints	20	20
Type of actuators	miniature DC motor	ultrasonic motors
Transmission type	gears	elastic tendons
State sensors		
Motor position	✓(rotary encoder)	✓(potentiometer)
Joint position	✗	✓(potentiometer)
Tendon tension	✗	✗
Joint torque	✓	✗
Motor effort	✗	✗
Other	-	-
Interaction sensors		
Tactile array	✓	✗
Other	-	-
Stiffness	-	Compliant joints and transmission
Underactuation	Rigid coupling	
Adaptive mechanism	-	-
Grasping	-	-
Manipulation	-	-
Gesturing	-	-
Notes	Hand used as test bed for stiffness control and tactile object recognition research	Force control achieved by comparing motor and joint position taking in account tendon elasticity

Hand Name	Anthropomorphic Robot Hand	Compact Dexterous Robot Hand
Organisation	University of Malta	University of Malta, Industrial Automation Laboratory
Type of project	Research	Research
Resources	Saliba et al. (2005)	Saliba and Axiak (2007)
Structure	Exoskeletal	Exoskeletal
Integration	Integrated	Integrated
Main upper fingers	✓(index replaced by ring finger)	✓
Opposable thumb	✓	✓
Forth finger	✗	✓
Fifth finger	✗	✗
Overall size	equal	equal
Size ratios	-	ignored
Contact Surfaces	Fingertips, Phalanges	Fingertips, Phalanges, Palm
C. S. extension	Average	Poor
Actuator location	Remote	Remote
No. Actuators	5	8
No. Joints	8	12
Type of actuators	DC motor with servo controller	DC motors
Transmission type	Flexible sheathed cables	Flexible sheathed cables
State sensors		
Motor position	✓	✓(cable position at actuator side)
Joint position	✗	-
Tendon tension	-	✓
Joint torque	-	-
Motor effort	-	-
Other	-	-
Interaction sensors		
Tactile array	-	✗
Other	-	-
Stiffness	Compliant transmission and coupling (springs)	Compliant transmission
Underactuation	Mechanically coupled	Mechanically coupled
Adaptive mechanism	-	-
Grasping	-	-
Manipulation	-	-
Gesturing	-	-
Notes	-	-

Hand Name	Seguna Dexterous Robot Hand	Elu2 Hand
Organisation	University of Malta	Elumotion
Type of project	Research	Commercial
Resources	Seguna and Saliba (2001)	(Elumotion), (Elumotion, 2010)
Structure	Exoskeletal	Exoskeletal
Integration	Modular	Modular
Main upper fingers	✓	✓
Opposable thumb	✓	✓
Forth finger	✗	✓
Fifth finger	✗	✓
Overall size	-	equal
Size ratios	maintained	maintained
Contact Surfaces	Fingertips, Phalanges	Fingertips, Phalanges, Palm
C. S. extension	Poor	Good
Actuator location	Remote	Palm, Fingers
No. Actuators	1	9
No. Joints	9 (plus manual rotation at finger base)	11
Type of actuators	Stepper motor	Servo motors
Transmission type	cable and pulley / sheathed cable	-
State sensors		
Motor position	✗	-
Joint position	✗	-
Tendon tension	✗	-
Joint torque	✗	-
Motor effort	✗	-
Other	-	-
Interaction sensors		
Tactile array	✗	-
Other	FSR on fingertips	-
Stiffness	-	-
Underactuation		
Adaptive mechanism	-	-
Grasping	-	-
Manipulation	-	-
Gesturing	-	-
Notes	Infrared proximity sensors and electro-mechanical tension limiting mechanism	-

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