Title  Pressure Sensor Array Model for Collecting
User’s Responses to Test Action in Active
Robot Learning

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PRESSURE SENSOR ARRAY MODEL FOR COLLECTING USER’S RESPONSES TO TEST ACTION IN ACTIVE ROBOT LEARNING

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ABSTRACT

Active robot learning (ARL) is an approach to the development of beliefs of the robots on their users’ intentions and preferences, which is needed by the robots to facilitate the seamless cooperation with users. Such approach allows the robots to perform tests on its users and to form high-order beliefs according to the users’ responses.

This study carried out primary research on designing a pressure sensor array model attached to the robot’s finger tips to collect the user’s responses to test action in the ARL system. A mathematical model and the reference value threshold which decides the pressure distribution were proposed through a benchmark scenario experiment. The robot holds an object and presents it to the user. When the user does not take over the object, the pressure distribution on the robot’s finger tips shown on the pressure sensor array is uneven. When the user takes over the object, the pressure distribution on the robot’s finger tips is even. According to the relationship between the pressure distribution and the user’s responses, the user’s responses to test action can be recognized by the robot.

Two cases of the benchmark scenario which is the robot passing an object to the user is simulated in a simulation software, GraspIt, in this study. The simulation results proved the developed pressure sensor array model can successfully collect the user’s responses to test actions in the ARL.
DECLARATION

I declare that this thesis is my own unaided work. It is being submitted for the degree of Master of Science by Research at the University of Bedfordshire.

It has not been submitted before for any degree or examination in any other university.

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Date: __________________________________________
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CHAPTER 1. INTRODUCTION

1.1 Background

Service robots have been widely used in many areas such as homecare, healthcare, rescue assistance, tour guiding, etc. One of the features of these robots is that they are often required to cooperate with their human users. In order to better cooperate with the users, these robots have to predict what the user will do next. Developing cognitive ability will enable service robots to recognize their users’ intentions based on which the predictions can be made.

Active Robot Learning (ARL) (Li, et al, 2008) is an approach for service robots to develop such cognitive ability. Inspired by discovery learning theory which is a method that encourages learners to acquire information through carrying out their own experiments, the ARL allows a service robot to perform guided tests on its user and to recognize the user’s intentions, which is also known as high-order belief, according to the users’ responses. Collecting the users’ responses is therefore important for an ARL system.

To demonstrate the ARL framework, Liu (2008) employed a benchmark scenario in which a robot and its human user cooperatively lift a stick. In this demonstration, an idea of installing a tilt sensor on the stick was proposed for the robot to capture the user’s responses to the test actions applied by the robot. In Liu’s work, the robot applied a test action of “slightly lifting up the stick” when the user kept the stick at a
certain height and captured the user’s response through the tilt sensor readings which
give changes in the angle between the stick and the ground. The increase in the angle
means that the user did not follow the robot to continuously lift up the stick, whilst the
decrease means the opposite.

1.2 Motivation

Although the idea does allow the robot to capture its user’s responses in Liu’s
simulations, it is arguable that the sensors may not be installed on all objects that the
service robots will handle. On the other hand, Liu’s work shows the possibility of
capturing the users’ responses using sensory systems.

Robot artificial skin technology, proposed by many researches such as Hoshi, et al,
(2006) and Maggiali, et al, (2008), were a distributed pressure sensory systems which
are installed on the surface of a robot body. Such a system allows the robot to obtain
pressure distribution information when the contacts between the robot and touched
object including a human user takes place. This may also enable an ARL system to
capture the users’ responses to test actions performed by the robots. This research is a
pilot study on how pressure sensors should be arranged on the surface of the robot
body in such a way that the pressure distribution obtained can reflect users’ responses
information in an ARL system.

This study also contributes to the robot artificial skin technology itself. A way of
arranging the pressure sensors is related to obtaining rich information from the
sensors, which is one of the key issues in this area.
1.3 Aim and Objectives

This study aims to find a way to arrange pressure sensors on the robot’s fingers to recognize the user’s responses to test actions in an ARL system.

Objectives are the following:

- To investigate the existing robot artificial skin techniques.
- To find pressure distributions on the robot’s finger tips in different cases by using film sensor.
- To develop a mathematical model that represents the relationship between a robot finger tips pressure distribution and the user’s response to a test action the robot applies.
- To evaluate various robot simulation software, namely, GraspIt, Adams, and Matlab.
- To create simulation environment using the most suitable simulation software and to demonstrate how users’ responses to test actions can be captured through the pressure distributions.

1.4 Methodology

This research is based on a benchmark scenario in which a robot passes on an object to its user. Pressure sensor films were suited to simulate the robot’s artificial skin. They were installed on finger tips of a robot hand to collect pressure distribution information.
Two cases were considered in this scenario. The first is that the user does not have intention to take over the object, and the second is that the user wants to take over the object.

1.5 Scope

In this research, because no real robot hand was available, a human hand was used as a robot hand.

The robot hand model in simulation software (GraspIt) can understand the commands entered via a keyboard.

The variation of a tiny flexible element which was used as a pressure sensor connected with the robot hand model in GraspIt can be read during the simulation.

The simulation environment is safe and closed enough that there are no other factors which can disturb the simulation process.

1.6 Structure of Dissertation

Chapter 2 provides a literature review on the robot artificial sensor skin technology and the ARL framework for recognizing the user’s intentions. This chapter describes three kinds of robot learning methods which help robots to recognise the user’s
intentions. The ARL framework is emphasised and introduced as a new approach to the development of cognitive capabilities of a robot. The robot artificial skin technology was investigated to find a method that allows a robot to recognise user’s responses to test actions within the ARL framework. The robot artificial skin is classified into two categories, namely, a capacitive sensor skin and a resistive sensor skin. Advantages and disadvantages of these two categories of the sensors are then analysed.

Chapter 3 presents a pressure sensor array model which is used to measure the pressure distributions on finger tips and to create a mathematical model to calculate whether the pressure distributions are even or not. A scenario that a robot passes a glass of water on to the user, which corresponds to the benchmark scenario that a robot passes an object on to the user, was given. In this scenario, the distributed pressure sensor system which was designed by using pressure sensor film was used to consider the relationship between pressure distribution of the robot’s finger tips and its user’s responses to a test action at five defined moments in two cases. Based on an imitation of one piece of a pressure sensor film which was divided into nine areas in this scenario, a pressure sensor array model including nine pressure sensors was developed to collect pressure distributions. The mathematical model was presented to consider whether the pressure distributions collected by the pressure sensor array are even or not. The threshold of the mathematical model was determined to check whether the pressure distribution is even or uneven.

Chapter 4 evaluates three robot hand modelling software programs for simulating the process of collecting the user’s responses to a test action using the proposed
distributed pressure sensor arrays. Two aspects are considered. The first one is how easy a robot hand can be modelled, and the second is that the pressure sensor array can be easily simulated and added to the finger tips of the robot hand model. The components and functions of the software were defined. The robot hand model was created in each of the three software to check whether it is easy to create a robot hand model. The program of the pressure sensor and the pressure distribution of the pressure sensor array were developed to test which robot hand model can be connected easily.

Chapter 5 gives simulation scenario to test the proposed distributed pressure sensor array for user responses collection. A distributed pressure sensor array which consists of nine pressure sensors and arranged in a $3 \times 3$ array was integrated with the model of a robot hand taken from GraspIt robot hand bank. The passing on an object benchmark scenario was employed. A decision-making unit was developed to read the distributed pressure sensor array, to calculate $F(S_i)$ and to decide the corresponding action for the robot. In the unit, a threshold was used to decide whether pressure distribution on the finger of the robot was even. Two cases were designed in this simulation scenario. In the first one, the robot holds an object and presents it to its user. The user, however, does not take over the object. In the second case, after recognising the object being presented to the user, the user stretches his arm and holds the object. In both cases, the robot applies the test action of slightly releasing the object. It then reads the readings of the sensor array and calculates the distribution features (even or uneven).

Chapter 6 gives conclusions and further work.
CHAPTER 2. LITERATURE REVIEW

According to the IFR (International Federation of Robotics), a service robot is a robot which operates semi or fully autonomously to perform services useful to the well being of humans and equipment, excluding manufacturing operations (SRIC-BI, 2008). The service robots include home or personal service robots, entertainment robots, education robots, medical robots, healthcare and rehabilitation robots and rescue robots. They are expected to provide services to their human users at home and within the workplace. For example, they will be able to assist aging population in terms of living in their homes, to assist health workers to perform routine procedures, to increase the effectiveness of surgical procedures in hospitals, etc.

The service robotics is an area of increasing interest and investment, especially in many countries that are facing challenges of an aging society, such as US, UK and Japan. In future societies, with the development of service robotics, the service robots have the potential to help elderly people to live longer independently. The robots can cook or fetch meals for the elderly, clean their rooms, toilets and even handle tasks such as bathing, dressing or supporting the users walking, sitting down or standing up. Equipped with special sensors, a service robot can monitor the users’ health condition on a regular basis, it can take blood pressure, measure body temperature and heartbeat rate; these functions are very useful for healthcare service robots.

The service robot can provide both the elderly and the rest of us with a great deal of services. It can also be used in hospitals to help to carry medicine, blood samples,
assist surgeons in surgeries, in areas such as household assistance and tasks dangerous for humans, such as fire fighting and bomb-disposal, in space applications where the human astronauts and the robots need to collaboratively assemble parts.

In the rapidly expanding service robotics research area, how to make the robot adaptable to new tasks and environments, and how to enable robots capable to interact with humans is becoming increasingly important, as more and more tasks will require cooperation between the robots and their human users. Thus, it is important to address cooperation between a robot and its user. When working with human users, the robots inevitably need to share the human environment and to participate in joint activities with the users. That is, human-robot cooperation is needed. Since the human environments are complex, dynamic, uncontrolled, and difficult to perceive reliably, to achieve human-robot cooperation, the robots are required to understand humans’ intentions and preferences. Based on their understanding, the robots can coordinate and adjust their behaviours to provide desired assistance and services to the users as effective partners. However, the robots’ understanding of the users’ intentions is still an exceptionally difficult challenge.

2.1 Robot Learning for Intention Recognition

The robots learning plays an important role in background knowledge building, motivations establishment and preferences identification. The current robot learning approaches include imitation learning, conversation learning and on-line learning.
The imitation based learning uses social cues such as pointing and gazing to indicate what the user has intended to do next (Dillmann 2004, Breazeal et al. 2005, Calinon and Billard 2006). The user first teaches a robot by demonstrating gestures, for example, pointing to and gazing at an object. These gestures serve as social cues of the user’s interest about an object. Then the robot imitates the gestures to obtain the user’s approval. This imitation process enables the robot to recognize the user’s intentions by capturing the same gestures. Experiments carried out in Calinon and Billard (2006) are described next. During the first phase of the interaction, the designer demonstrates a gesture in front of the robot. The robot then observes the designer’s gesture. Joint angle trajectories are collected from a motion sensor. The second phase begins when the robot collected different movements of the user. The robot compares the gestures it collected with the gesture stored earlier and finds the required cues. Then the robot points at an object that the user is likely to be interested in. The robot then turns to the user for approval of its selection. The designer signals to the robot whether the same object has been selected by nodding/shaking his/her head.

Conversation is a direct way to let the robot to understand the users’ intentions. Hassch et al. (2004) developed a Bielefeld Robot Companion (BIRON) which is a robot who resembles a human. It consists of cameras, microphones, laser range finders, speech recognition system, and other components. This robot is able to understand the users’ intention through oral instructions and by observations of the user's sight. The BIRON employs a human concern system to decide which user is interested in the robot. When someone is talking while watching the robot, the robot’s attention will be transferred to this person. When individuals are talking at the same
time and no one is watching the robot, the robot will pay attention to the persons who have not been concerned for the longest time.

A Dialogue Manager is also included in the robot, which is responsible for receiving the instructions from the users. The Dialogue Manager can interact with users and solve ambiguous cases by asking questions. A speech recognition system is used to understand the users’ intentions by analyzing the received sound information from the microphone. The speech understanding component deals with the spontaneous speech phenomena during conversations between a user and the robot. For example, large pauses and incomplete utterances can occur in such task oriented and embodied communications. However, missing information in an utterance can often be acquired from the scene. For example the utterance “Look at this” and pointing gestures to the table is interpreted as “Look at the table”.

On-line learning is a model of induction that learns one instance at a time (Anderson and Elloumi, 2004). The goal in online learning is to predict labels of instances. For example, the instances could describe the current conditions of the stock market, and the online learning algorithm predicts the tomorrow's value of a particular stock. The key defining characteristic of online learning is that soon after the prediction is made, the true label of the instance is discovered. This information can be then used to refine the prediction hypothesis used by the algorithm. The goal of the algorithm is to make predictions that are close to the true labels.

Cognitive robots are meant to behave in the real world and to interact smoothly with the users and their environments. While off-line learning is well established to
implement basis modules of such systems and many learning methods work well in toy domains, in concrete scenarios on-line adaptivity is necessary in many respects to cope with inevitable uncertainties of the real world and the limited predictability of the interaction structure, and to acquire new, and enhance pre-programmed behaviours. Online learning is also a main methodological ingredient in the developmental approach to intelligent robotics, aiming at incremental progression from simple to more complex behaviour.

A very important issue in all online learning approaches is the way the results of learning are stored. For example, many motor control architectures use learning to change the parameterization of the basic behaviours and therefore only implicitly store the learning results. Other approaches employ primitive graphical mappings, hash tables, or more sophisticated associative neural mappings to store co-occurrence of sensory inputs and motor outputs for later reuse.

2.2 Active Robot Learning

The process of cognition and learning requires the service robots to have ability of self-modification and detecting information of circumstances. At the same time, they are supposed to judge what to do as a next step and to generate task planning. These approaches have some disadvantages such as:

- They ask the user to remember and exactly repeat actions taught to a robot to allow the robot to recognize the user’s intentions and preferences.

- The existing approaches rely on particular social cues or specifically defined
In this case, they apply only to specific assignments, so they are not universal. In addition, these approaches need to remember many action orders so that it’s not adequate for elder people. Consequently, their applications are limited.

Active Robot Learning (ARL) (Li, et al, 2008) for service robots is an approach to develop beliefs of their users’ intentions and preferences (also known as high-order beliefs). Inspired by discovery learning theory which encourage learners to acquire information by performing their own experiments, this approach allows a robot to perform tests on its users and to build up the high-order beliefs according to the users’ responses. This approach emphasizes the active acquisition of intentions and preferences by robots themselves. The robots are required to neither recognize particular gestures nor to determine specific functions. The framework of ARL is shown in Figure 2.1.

![Figure 2.1 Framework of ARL.](image-url)
The action bank stores all test actions with a cooperative action based approach in order to know the user’s intentions. That is, test actions are associated to the corresponding cooperative actions.

The inference engine selects a test action from the action bank to conduct a specific test. As the actions are associated with conditions in the action bank and the associations actually represent causal relations (implications) from the conditions to the actions, the selection of the action can be carried out by the standard forward reasoning.

The moment determination is used to decide the moment of test from test action bank. This includes allocating a cooperative action into an action plan, and monitoring the environment to see if the action is reached.

The intention identification mechanism is used to interpret responses of the users and to identify their intentions and preferences. The ARL system takes a test action and then start to recognise the user’s intentions according to his responses. If the intention associated with the test action cannot be identified according to the response, the system will take another test action and perform recognition process once again.

The intention model represents intentions that have been judged by taking relevant test actions.

When the ARL system begins to work, the working flow is as follows:
• Decomposition – decomposing a compound task into a sequence of prime tasks.

• Classification – differentiating taught prime tasks and non-taught tasks (This is preparation for making an action plans.).

• Plan-making – making an action plan for each prime task. For taught tasks, action sequence are pre-defined, for non-taught tasks, actions are generated by referring to the “closest” taught prime task.

• Identification – identifying points of cooperation in an action plan (This helps in determination of the moments for testing.).

• Decision-making – determining the moments at which the tests will take place.

• Selection – selecting test actions.

• Testing – performing test actions and collecting the user’s responses.

• Recognition – recognising the user’s intentions.

2.3 Robot Artificial Skin Technology

In the process of cooperation between service robots and humans, for obtaining contact information by the robot from the surrounding environments, the robot artificial skin technologies can be used.

An enormous number of studies have already been done for realization of the robot artificial skin (Hakozaki et al, 1999, Okada et al, 2006, Kaneko et al, 2009). Different sensor technologies have been used, such as various arrays of pressure-sensitive
tactile sensor elements (Shinoda et al, 2002), force sensing resistors embedded in the rubber (Tan et al, 2001), and embedded tactile force sensors (Nicholls and Lee 1989). Robot artificial skin can be classified into the capacitive sensor skin and the resistive sensor skin based on the capacitive sensor technology and resistive sensor used in the design.

2.3.1 Capacitive Sensor Skin

2.3.1.1 Embedded distributed capacitive sensor skin

Maggiali et al (2008) designed a novel robot artificial sensor skin that is realized in distributed capacitive tactile sensor, which was installed on the humanoid robot surface (Figure 2.2). This artificial sensor skin system is based on a conformable mesh of sensors having a triangular shape and being interconnected in order to form a networked structure. Each triangle implemented with 12 capacitive sensors is a flexible substrate allowing the sensors to conform to smooth curved surfaces, such as arms, legs, thorax, elbow, and so on. It consists of a capacitive to digital converter (CDC) that provides twelve 16bits measurements of capacitance and three communications ports. One of the ports is an input from an adjacent triangle, and the other parts are as outputs toward adjacent triangles, placed along its sides. Each triangle is therefore a single sensor module implementing 12 capacitive sensors.
The measurements that come from this artificial skin are sent to a microcontroller using serial bus communication links. A microcontroller board is programmed to set up and read the data coming from a group of modules. The 16 triangles are attached to a single microcontroller. And then, every microcontroller board has a Controller Area Network (CAN) bus link, so that the boards can communicate between them and the PC. The communication structure of this artificial sensor skin is shown in Figure 2.3.

This robot artificial skin provides pressure and shape information about the surfaces of the robot in contact with the surrounding environments.
2.3.1.2 New capacitive sensor skin

A new tactile sensor skin (Figure 2.4) using the touch area receptor (STAR) can cover a whole surface of a robot. It was proposed by Hoshi et al (2006). It consists of sensor elements and sensor/communication chips.

![Figure 2.4 Artificial skin covered on a robot.](image)

As shown in Figure 2.5 (Hoshi et al 2006), the structure of the sensor element consists of two layers of compressible insulators; the upper and lower layers are soft and hard urethane foam respectively, and each layer is 2mm in thickness. There are three pieces of stretchable conductive fabric sheets on the upper layer, between the upper and lower layer, and under the lower layer. The insulator urethane foam layers and the conductive fabric pieces adhere to each other by soft double-faced tape, and two capacitors are formed in the layers. The capacitance of the two capacitors is calculated as (Hoshi et al 2006):

\[
C_n \approx C_{n0} + \varepsilon_n F/d_n E_n \quad n = 1, 2
\]  

(2.1)

where \(n\) is the layer identification; i.e. \(n=1\) means the upper soft layer and \(n=2\) means the lower layer. \(C_n\) is the capacitance of the layer \(n\). \(C_{n0}\) is the initial capacitance of the layer \(n\). \(\varepsilon_n\) is the dielectric constant of the layer \(n\). \(F\) is the pressure that is
pressed on the sensor element. $d_n$ is the initial thickness of the layer $n$. $E_n$ is the Young’s modulus. Therefore, the pressure that is pressed on the sensor element can be measured through measuring the capacitance $C_n$.

![Figure 2.5 Structure of the sensor element.](image)

Sensor/communication chip was developed to measure the capacitance $C_n$ and transmit these values to the host computer. The structure of the sensor skin is shown in Figure 2.6 (Hoshi et al 2006).

![Figure 2.6 Communication structure of sensor skin.](image)

Sensor elements are connected in a row to simplify the communication protocol. Each sensor element has its specific coordinate as shown in Figure 2.6. The elements with
the coordinate (0, 3) is the most upstream, and the element with coordinate (0, 0) connected to the host computer is the most downstream.

Figure 2.7 Equivalent circuit of the measurement system.

The equivalent circuit of the measurement system of the sensor communication chips is shown in Figure 2.7(Hoshi et al 2006). There is the reference capacitor $C_{ref}$ inside the circuit connected through a switch SW to the junction of the capacitors $C_1$ and $C_2$. The circuit measures the divided voltage $V_{out}$ between the power voltage $V_{dd}$ and the ground. The divided voltages are represented as

$$V_{out\ (off)} = \frac{C_1}{C_1 + C_2} V_{dd} \quad (2.2)$$

$$V_{out\ (on)} = \frac{C_1}{C_1 + C_2 + C_{ref}} V_{dd} \quad (2.3)$$

where $V_{out\ (off)}$ and $V_{out\ (on)}$ are the voltages of the junction when the switch SW is off and on, respectively. The circuit sends the values $V_{out\ (off)}$ and $V_{out\ (on)}$ after coding them by an A/D converter on the chip. Therefore, the capacitance of the capacitor $C_1$ and $C_2$ can be calculated by solving equation 2.2 and equation 2.3.
2.3.2 Resistive Sensor Skin

2.3.2.1 Improved resistive sensor skin

A sensitive artificial skin for a humanoid robot has been introduced by Göger et al (2006). First of all, the authors modified the structure of traditional resistive sensor skin to a new structure, as shown in Figure 2.8. Originally, it is a resistive sensor skin with the electrode stripes on the top side of the sensor material forming a plate capacitor with the electrodes on the bottom side. Due to this construction, the capacitor together with the resistance of the sensor material forms an RC element limiting the sampling speed of the sensor matrix. Another problem that rises from the double sided contacting of the pressure sensitive material, that, since the force has to be pressed over one of the electrodes, it is exposed to a bending stress which will result in material fatigue, thus limiting the lifetime of the sensor.

![Figure 2.8 Modification of the measurement electrode.](image)

Therefore, to avoid the problems of the traditional resistive sensor skin, the authors propose a concept that contacts the sensor material only from one side, as shown on the Figure 2.8 (Göger et al 2006).
As shown in Figure 2.9, the authors applied one side contact concept to this sensor skin, using an electrode arrangement whose discrete measurement electrodes are surrounded by a common reference electrode. The sensor material is located above the electrodes.

![Figure 2.9 The Structure of sensitive artificial sensor skin.](image)

According to the structure of this sensitive artificial skin, the resistance measurement of the sensor material is done between the reference and the individual measurement electrodes (Göger et al 2006). The resistance of the sensor material locally over the measurement electrodes can be acquired. Every measurement electrode is connected to a multiplexer, connecting all electrodes sequentially with a resistance measurement circuitry. Since every unit is directly coupled with active electronics for examination, this technique enables building sensor matrices with a medium to high spatial resolution and high sampling speeds.

When a force is applied to the sensor material, the change of resistance between the sensor material and the electrode layer is sampled through the common reference electrode and the discrete measurement electrode. The output voltage signal which can be obtained through measurement circuit is digitized and post-processed by a dedicated sensor controller whose main task is to realize the required sampling timing. The acquired data are supplied via USB port to the data processing unit where it can
be visualized and used for the robot control. The sensor communication system is shown in Figure 2.10 (Göger et al 2006).

![Figure 2.10 USB connection of the artificial skin.](image)

2.3.2.2 Fully embedded resistive force sensor skin

A new embedded resistive force sensor skin was presented by Cannata et al (2005). This sensor skin consists of a matrix of 64 electrodes etched on a flexible PCB covered by a conductive rubber layer (Figure 2.11). It has been designed to be installed on a dexterous robot gripper (Mac-Hand).

![Figure 2.11 A fully embedded resistive force sensor skin.](image)

The electrode consists of a strain sensitive thick-film resistor, three reference resistors, and other measurement circuits. The strain sensitive thick-film resistor and three reference resistors form a circuit bridge (Figure 2.12). When a force is applied on the
strain sensitive thick-film resistor, its resistance is changed. The relationship between
the change of the resistance of $R_s$ and the voltage of $U_0$ can be obtained. Therefore,
the force applied on the resistance $R_s$ can be obtained by measuring the voltage $U_0$
(Cannata et al 2005).

![Bridge measurement circuit](image)

Figure 2.12 A bridge measurement circuit.

The principle of operation of the embedded resistive force sensor skin is a well known
rows-columns scanning. Communications of the sensor skin with the remote hand
ccontroller are based on a Controller Area Network (CAN) bus. All the components
needed for the signal conditioning are placed on the flexible Printed Circuit Board
(PCB) to limit cabling.

2.3.3 Analysis of Two Categories of the Sensor Skin

J. Ulmen and M. Cutkosky (2010) proposed analysis for the capacitive sensor skin
and the resistive sensor skin, and showed advantages and disadvantages of these two
categories.
For capacitive sensor skin, one advantage is that the capacitive sensor is inherently non-contact. Capacitance is purely a geometric property related to relative location of the materials. The capacitive sensor skin can be made into any shape using flexible conductive materials, and can be used effectively even if the conductivity of the used material changes over time.

The capacitive sensor skin also has some disadvantages. It suffers from noise problems and hysteresis problem.

For the resistive sensor skin, the resistive sensors work better at low frequency measurements. A disadvantage of the resistive sensors is that they often demonstrate unpredictable properties or have large hysteresis.
CHAPTER 3. PRESSURE DISTRIBUTION MODEL

3.1 Benchmark Scenario

Transferring of objects between the robots and the humans is assumed to be a benchmark scenario where the robots and the humans need to coordinate their activities in order to cooperatively complete the task, such as, handing an object between a robot and the human (Pramila, R. 2003, Edsinger and Kemp, 2007, Schrempf, Oliver. C. et al, 2005). Consider a case where a robot works alongside an elderly person living at his/her home. When the person needs an object but finds difficult to reach it, he/she can ask the robot to get the object. After successfully finding the requested object, the robot can take the object to the person and hand it to him/her. The object can be a glass of water, a newspaper, an apple or other kind of food. Passing on objects frequently occurs in our daily life.

To naturally and intuitively accomplish the “pass an object” task of cooperation between a robot and its user, the robot must understand its user’s intentions, which means the robot should clearly know whether the user is ready to take the delivered object. If the robot releases the object before the user is ready to hold it, the object will fall to the floor. On the contrary, if the user is ready to take the object but the robot doesn’t release it, the cooperation between them will fail.

In this chapter, the scenario considered is a robot passing on a glass of water to its user.
Under the ARL framework, the robot applies a test action of releasing the glass a bit to see if the user really wants and is ready to take over the glass of water (T. Cao. 2009). The robot will then start to collect the user’s responses to those test actions for the purpose of recognizing the user’s intentions. If he really wants the glass of water and is ready to take it over, the user will touch and hold the glass. Otherwise, the user will not touch and hold the glass at all. These two different responses are reflected differently in terms of the pressure and its distributions between the robot finger tips and the wall of the glass. When a distributed pressure sensor system is installed on the finger tips, the responses can be collected through the system.

3.2 Distributed Pressure Sensor System Design

The aim of the distributed pressure sensor system design is to obtain pressure distribution on the finger tips of a robot hand when the robot passes an object on to its user, and then identifying a relationship between the pressure distributions and the user’s responses to test actions in the following two cases.

3.2.1 Pressure Sensor Film

Pressurex® is a unique, affordable and easy to use tool that reveals the distribution and magnitude of pressure between any two contacting, mating or impacting surfaces (Sipcer et al, 2009). Pressure indicating sensor film is extremely thin (0.1 to 0.2 mm)
which enables it to conform to the curved surfaces. It is ideal for invasive intolerant environments and tight spaces not accessible to conventional electronic transducers.

Pressurex® is a mylar based film that contains a layer of tiny microcapsules (Figure 3.1). The application of force upon the film causes the microcapsules to rupture, producing an instantaneous and permanent high resolution "topographical" image of the pressure variation across the contact area (SPI, 2010).

Pressurex® can be simply placed between any two surfaces that touch, mate or impact. After applying the pressure, the film immediately reveals the pressure distribution profile that occurred between the two surfaces. Like Litmus paper, the colour intensity of the film is directly related to the amount of pressure applied to it (SPI, 2010). The greater the pressure is, the more intense the colour (Figure 3.2).

Pressurex® has a wide array of uses. For example, Pressurex® can be used in a bolted joint interface, composite layup, heat sealing, lamination and press. Our pressure indicating film acts as a force sensing resistor. It can measure surface pressure distribution whether it is used as an impact force sensor, seat pressure sensor, as a strain gauge or even as nip impression paper.

Figure 3.1 Structure of Pressurex® sensor film.
According to the range of the pressure, the Pressurex® sensor film has the following eight classes.

<table>
<thead>
<tr>
<th>Class</th>
<th>Pressure range (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>2-20</td>
</tr>
<tr>
<td>Zero</td>
<td>7.2-28</td>
</tr>
<tr>
<td>Ultra Low</td>
<td>28-85</td>
</tr>
<tr>
<td>Super Low</td>
<td>70-350</td>
</tr>
<tr>
<td>Low</td>
<td>350-1,400</td>
</tr>
<tr>
<td>Medium</td>
<td>1,400-7,100</td>
</tr>
<tr>
<td>High</td>
<td>7,100-18,500</td>
</tr>
<tr>
<td>Super High</td>
<td>18,500-43,200</td>
</tr>
</tbody>
</table>

Table 3.1 The pressure range of different class film sensor.
Pressurex® Micro sensor film (SPI, 2010) with the pressure range 2-20 PSI has been chosen in this study (Figure 3.3).

![Pressurex® Micro sensor film](image)

Figure 3.3 Pressurex® Micro sensor film.

3.2.2 Details of the Design

The hand distributed sensor system contains three pieces of Pressurex® Micro sensor film, which are attached to the finger tips of the index finger, the middle finger and the ring finger of a robot hand, as illustrated in Figure 3.4. Because no real robot hand is available, a human hand was used as a robot hand. Fingers of some state of the art robot hands, such as the Shadow® robot hand and the Care-o-bot robot hand, are coated with a rubber and are in the form of a human finger. Therefore, this “replacement” is reasonable. The reason for using three fingers is to capture sliding motion of the glass held by the hand. One or two fingers were turned out not to be sufficient and thumb also does not contribute to detection of sliding motion.

The robot with the distributed sensor system installed on its finger tips passes a glass of water on to its user as illustrated in Figure 3.5.
To capture “spatial and temporal” data on the pressure distributions in the process of passing on a glass of water, five different moments are defined, namely

- 1) Initial Moment
- 2) Stable Moment
- 3) Critical Moment
- 4) Sliding Moment
- 5) Dropping Moment.

Figure 3.4 Robot hand with the distributed pressure sensor system installed.

Figure 3.5 A hand holding a glass of water.
These five different moments are representative of the whole process of the object passing. The Initial Moment is the moment that the robot hand holds the glass and gets ready to take a test action. The Critical Moment is the moment that the glass is about to slide off from the robot hand if the robot hand releases it a little more. The Stable Moment is the moment between the Initial Moment and the Critical Moment. The Sliding Moment is the moment that the glass slides downwards but not completely off from the robot hand. Finally, the Dropping Moment is the moment that the glass is going to drop off completely from the robot hand.

3.3 Recorded Data Analysis

3.3.1 Pressure Distribution

In the process where a robot passes a glass to its user, two cases are considered. The first case is that the user does not have any intentions to take over the glass. The second case is that the user wants and is ready to receive the glass.

The pressure distributions on the robot’s three finger tips for the defined five moments in the first case are shown in Figure 3.6.
Figure 3.6 Pressure distributions in the first case.

The labels $1_F$, $1_M$ and $1_R$ represent readings from the sensor films on the index finger, the middle finger, and the ring finger, respectively, at the Initial Moment. The labels $2_F$, $2_M$ and $2_R$ represent readings that from the sensor films on the index finger, the middle finger, and the ring finger, respectively, at the Stable Moment. The labels $3_F$, $3_M$ and $3_R$ represent readings that from the sensor films on the index finger, the middle finger, and the ring finger, respectively, at the Critical Moment. The labels $4_F$, $4_M$ and $4_R$ represent readings that from the sensor films on the index finger, the middle finger, and the ring finger, respectively, at the Sliding Moment. The labels $5_F$, $5_M$ and $5_R$ represent readings that from the sensor films on the index finger, the middle finger, and the ring finger, respectively, at the Sliding Moment.
$5_m$ and $5_r$ represent readings that from the sensor films on the index finger, the middle finger, and the ring finger, respectively, at the Dropping Moment.

Then, according to Figure 3.2, the colours of the magnitudes of the pressure, the approximate pressure value of every piece of pressure sensor film in the first case can be obtained, which is shown in Figure 3.7.

![Figure 3.7 The approximate pressure value of every piece of pressure sensor film in the first case.](image)

The pressure distribution on the robot’s three finger tips at the defined five moments in the second case is shown in Figure 3.8.
Figure 3.8 Pressure distributions in the second case.

The approximate pressure value of every piece of pressure sensor film in the second case is shown in Figure 3.9.
Figure 3.9 The approximate pressure value of every piece of pressure sensor film in the second case.

In order to obtain more details whether the pressure distributions are even or not in those two cases, analysis of the pressure distribution of those pressure sensor films was carried out.

3.3.2 Analysis

In order to get a clear picture about the pressure distributions, every piece of the pressure sensor film showing the pressure distributions was divided into small areas, and the pressure values in these areas are compared with one another. In this analysis, every piece of the pressure sensor film was divided into nine areas.
The glass of water in this scenario is less weight, so that robot can hold it with little strength and the pressure presses on the glass is also little. In addition, according to a simple experiment to measure the pressure on finger by using force sensing resistor (FSR) when hand holds a glass of water, the approximate pressure value ranges from 3 Psi to 19 Psi. Therefore, in this study, Micro pressure sensor film with the measurement range little (2-20Psi) was used. According to the colour correlation chart of the Micro pressure sensor film, approximate values of the nine pieces were decided.

3.3.2.1 Analysis of the Initial Moment

At the Initial Moment, the robot hand holds a glass and writs for the user to receive it. The pressure distributions for the two cases are compared with each other in Figure 3.10.

Figure 3.10 Pressure distributions of the two cases at the Initial Moment.
The pressure distributions of the index finger for the two cases, $1_F$ and $1'_F$, are shown in Figure 3.11.

![Figure 3.11 Pressure distribution of the index finger in two cases at the Initial Moment.](image)

According to the colour correlation chart, approximate values of the nine pieces of $1_F$ and $1'_F$ were decided as follows:

$$P_{1_F} = \begin{pmatrix} P_{1_{F11}} & P_{1_{F12}} & P_{1_{F13}} \\ P_{1_{F21}} & P_{1_{F22}} & P_{1_{F23}} \\ P_{1_{F31}} & P_{1_{F32}} & P_{1_{F33}} \end{pmatrix} = \begin{pmatrix} 14.3 & 15.5 & 15.2 \\ 15.3 & 16.4 & 15.8 \\ 14.7 & 16.1 & 15.1 \end{pmatrix}$$

represents the pressure values of the nine pieces of $1_F$.

$$\tilde{P}_{1_F} = \begin{pmatrix} \tilde{P}_{1_{F11}} & \tilde{P}_{1_{F12}} & \tilde{P}_{1_{F13}} \\ \tilde{P}_{1_{F21}} & \tilde{P}_{1_{F22}} & \tilde{P}_{1_{F23}} \\ \tilde{P}_{1_{F31}} & \tilde{P}_{1_{F32}} & \tilde{P}_{1_{F33}} \end{pmatrix} = \begin{pmatrix} 16.3 & 17.2 & 17.1 \\ 17.3 & 18.5 & 17.9 \\ 16.6 & 18.2 & 17.1 \end{pmatrix}$$

represents the pressure values of the nine pieces of $1'_F$. 

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The pressure values of nine pieces of pressure sensor film in the first case and in the second case can be indicated in Figure 3.12 and Figure 3.13. The Figure 3.12 and the Figure 3.13 can also indicate the pressure distribution of the index finger of the robot at the Initial Moment in the first case and in the second case, respectively.

Because some external conditions are different, such as the material of the glass, the shape of the robot hand, a state of the pressure, a normalized value $\alpha_i = \frac{P_i}{P}$ was used.
to represent the pressure magnitude. In $\alpha_i = \frac{P_i}{P}$, the denominator $P$ is the maximum value of the measurement range of the pressure sensor film, which is 20 Psi in this study.

Then, the normalized pressure distributions are:

$$
\begin{align*}
\alpha_{1P} &= \begin{pmatrix}
\alpha_{1P_{11}}, & \alpha_{1P_{12}}, & \alpha_{1P_{13}} \\
\alpha_{1P_{21}}, & \alpha_{1P_{22}}, & \alpha_{1P_{23}} \\
\alpha_{1P_{31}}, & \alpha_{1P_{32}}, & \alpha_{1P_{33}}
\end{pmatrix} = \frac{P_{1P}}{P} = \begin{pmatrix}
0.715 & 0.775 & 0.760 \\
0.765 & 0.820 & 0.790 \\
0.735 & 0.805 & 0.755
\end{pmatrix}, \\
\alpha'_{1P} &= \begin{pmatrix}
\alpha'_{1P_{11}}, & \alpha'_{1P_{12}}, & \alpha'_{1P_{13}} \\
\alpha'_{1P_{21}}, & \alpha'_{1P_{22}}, & \alpha'_{1P_{23}} \\
\alpha'_{1P_{31}}, & \alpha'_{1P_{32}}, & \alpha'_{1P_{33}}
\end{pmatrix} = \frac{P'_{1P}}{P} = \begin{pmatrix}
0.815 & 0.860 & 0.855 \\
0.865 & 0.925 & 0.895 \\
0.830 & 0.910 & 0.855
\end{pmatrix}.
\end{align*}
$$

The pressure distributions of the middle finger in the two cases, $1_m$ and $1'_m$, are shown in Figure 3.14.

![Figure 3.14](image-url)
The Figure 3.15 and the Figure 3.16 indicate the pressure distribution of the middle finger of the robot at the Initial Moment in the first case and in the second case, respectively.

![Figure 3.15](image1.png)

Figure 3.15  Pressure distribution of the middle finger at the Initial Moment in the first case.

![Figure 3.16](image2.png)

Figure 3.16  Pressure distribution of the middle finger at the Initial Moment in the second case.

The normalized pressure distributions are:

\[
\alpha_{\text{Mf}} = \begin{pmatrix}
\alpha_{11} & \alpha_{12} & \alpha_{13} \\
\alpha_{21} & \alpha_{22} & \alpha_{23} \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix} = \frac{1}{P} \begin{pmatrix}
0.790 & 0.770 & 0.765 \\
0.765 & 0.855 & 0.830 \\
0.755 & 0.840 & 0.825
\end{pmatrix}.
\]  

(3.3)
\[ \alpha'_{1R} = \begin{pmatrix} \alpha'_{1R11} & \alpha'_{1R12} & \alpha'_{1R13} \\ \alpha'_{1R21} & \alpha'_{1R22} & \alpha'_{1R23} \\ \alpha'_{1R31} & \alpha'_{1R32} & \alpha'_{1R33} \end{pmatrix} = \frac{p'_R}{P} = \begin{pmatrix} 0.880 & 0.870 & 0.865 \\ 0.885 & 0.965 & 0.905 \\ 0.875 & 0.950 & 0.935 \end{pmatrix}. \] (3.4)

The pressure distributions of the ring finger in the two cases, $1_R$ and $1'_R$, are shown in Figure 3.17.

![Figure 3.17](image)

Figure 3.17  The pressure distributions of the ring finger in the two cases at the Initial Moment.

The Figure 3.18 and the Figure 3.19 indicate the pressure distribution of the ring finger of the robot at the Initial Moment in the first case and in the second case, respectively.
Figure 3.18 Pressure distribution of the ring finger at the Initial Moment in the first case.

Figure 3.19 Pressure distribution of the ring finger at the Initial Moment in the second case.

The normalized pressure distributions are:

$$\alpha = \begin{pmatrix} \alpha_{121} & \alpha_{122} & \alpha_{123} \\ \alpha_{121} & \alpha_{122} & \alpha_{123} \\ \alpha_{121} & \alpha_{122} & \alpha_{123} \end{pmatrix} = \frac{P}{P_a} = \begin{pmatrix} 0.710 & 0.755 & 0.745 \\ 0.760 & 0.865 & 0.785 \\ 0.795 & 0.885 & 0.830 \end{pmatrix}.$$
\[ \alpha_{r} = \begin{pmatrix} \alpha_{r_{11}}' & \alpha_{r_{12}}' & \alpha_{r_{13}}' \\ \alpha_{r_{21}}' & \alpha_{r_{22}}' & \alpha_{r_{23}}' \\ \alpha_{r_{31}}' & \alpha_{r_{32}}' & \alpha_{r_{33}}' \end{pmatrix} = \frac{P_{r}}{\overline{P}} = \begin{pmatrix} 0.835 & 0.865 & 0.840 \\ 0.860 & 0.960 & 0.895 \\ 0.900 & 0.955 & 0.940 \end{pmatrix}. \quad (3.6) \]

3.3.2.2 Analysis of the Stable Moment

At the Stable Moment, in the first case, the robot hand holds the glass and releases it slowly while the user does not take it, and the glass does not slide from robot hand. In the second case, the robot hand holds the glass and releases it slowly while the user is ready to have the glass. The pressure distributions of the two different cases are shown in Figure 3.20.

Figure 3.20 Pressure distributions of the two cases at Stable Moment.

The pressure distributions of the index finger in the two cases, \( F \) and \( F' \), are given in Figure 3.21.
Figure 3.21 The pressure distributions of the index finger in the two cases at the Stable Moment.

The Figure 3.22 and the Figure 3.23 indicate the pressure distribution of the index finger of the robot at the Stable Moment in the first case and in the second case, respectively.

Figure 3.22 Pressure distribution of the index finger at the Stable Moment in the first case.
Figure 3.23  Pressure distribution of the index finger at the Stable Moment in the second case.

The normalized pressure distributions are:

\[
\alpha_{\alpha} = \begin{pmatrix}
\alpha_{\alpha 11} & \alpha_{\alpha 12} & \alpha_{\alpha 13} \\
\alpha_{\alpha 21} & \alpha_{\alpha 22} & \alpha_{\alpha 23} \\
\alpha_{\alpha 31} & \alpha_{\alpha 32} & \alpha_{\alpha 33}
\end{pmatrix} = \frac{P_{\alpha}}{P} = \begin{pmatrix}
0.660 & 0.640 & 0.625 \\
0.675 & 0.695 & 0.665 \\
0.685 & 0.720 & 0.660
\end{pmatrix}.
\] (3.7)

\[
\alpha'_{\alpha} = \begin{pmatrix}
\alpha'_{\alpha 11} & \alpha'_{\alpha 12} & \alpha'_{\alpha 13} \\
\alpha'_{\alpha 21} & \alpha'_{\alpha 22} & \alpha'_{\alpha 23} \\
\alpha'_{\alpha 31} & \alpha'_{\alpha 32} & \alpha'_{\alpha 33}
\end{pmatrix} = \frac{P'_{\alpha}}{P} = \begin{pmatrix}
0.675 & 0.680 & 0.660 \\
0.680 & 0.680 & 0.675 \\
0.670 & 0.675 & 0.670
\end{pmatrix}.
\] (3.8)

The pressure distributions of the middle finger in the two cases, \(M\) and \(M'\), are shown in Figure 3.24.
Figure 3.24 The pressure distributions of the middle finger in the two cases at the Stable Moment.

The Figure 3.25 and the Figure 3.26 indicate the pressure distribution of the middle finger of the robot at the Stable Moment in the first case and in the second case, respectively.

Figure 3.25 Pressure distribution of the middle finger at the Stable Moment in the first case.
The normalized pressure distributions are:

\[
\alpha_{2M} = \begin{pmatrix}
\alpha_{2M11} & \alpha_{2M12} & \alpha_{2M13} \\
\alpha_{2M21} & \alpha_{2M22} & \alpha_{2M23} \\
\alpha_{2M31} & \alpha_{2M32} & \alpha_{2M33}
\end{pmatrix}
= \frac{P_{2M}}{P} = \begin{pmatrix}
0.670 & 0.665 & 0.575 \\
0.715 & 0.735 & 0.645 \\
0.730 & 0.740 & 0.655
\end{pmatrix}.
\]

(3.9)

\[
\alpha'_{2M} = \begin{pmatrix}
\alpha'_{2M11} & \alpha'_{2M12} & \alpha'_{2M13} \\
\alpha'_{2M21} & \alpha'_{2M22} & \alpha'_{2M23} \\
\alpha'_{2M31} & \alpha'_{2M32} & \alpha'_{2M33}
\end{pmatrix}
= \frac{P'_{2M}}{P} = \begin{pmatrix}
0.705 & 0.710 & 0.705 \\
0.705 & 0.710 & 0.710 \\
0.700 & 0.710 & 0.705
\end{pmatrix}.
\]

(3.10)

The pressure distributions of the ring finger in the two cases, \(2_R\) and \(2'_R\), are displayed in Figure 3.27.
Figure 3.27 The pressure distributions of the ring finger in the two cases at the Stable Moment.

The Figure 3.28 and the Figure 3.29 indicate the pressure distribution of the ring finger of the robot at the Stable Moment in the first case and in the second case, respectively.

Figure 3.28 Pressure distribution of the ring finger at the Stable Moment in the first case.
The normalized pressure distributions are:

\[
\alpha_{2x} = \begin{pmatrix}
\alpha_{2x1} & \alpha_{2x2} & \alpha_{2x3} \\
\alpha_{2x21} & \alpha_{2x22} & \alpha_{2x23} \\
\alpha_{2x31} & \alpha_{2x32} & \alpha_{2x33}
\end{pmatrix}
= \frac{P_{2x}}{P} = \begin{pmatrix}
0.680 & 0.690 & 0.660 \\
0.780 & 0.765 & 0.795 \\
0.785 & 0.760 & 0.735
\end{pmatrix}.
\] (3.11)

\[
\alpha'_{2x} = \begin{pmatrix}
\alpha'_{2x1} & \alpha'_{2x2} & \alpha'_{2x3} \\
\alpha'_{2x21} & \alpha'_{2x22} & \alpha'_{2x23} \\
\alpha'_{2x31} & \alpha'_{2x32} & \alpha'_{2x33}
\end{pmatrix}
= \frac{P'_{2x}}{P} = \begin{pmatrix}
0.695 & 0.700 & 0.695 \\
0.700 & 0.705 & 0.700 \\
0.695 & 0.705 & 0.695
\end{pmatrix}.
\] (3.12)

3.3.2.3 Analysis of the Critical Moment

At the Critical Moment, the pressure distributions of the two different cases are given in Figure 3.30.
Figure 3.30  The pressure distributions of the two cases at the Critical Moment.

The pressure distributions of the index finger in the two cases, $3_F$ and $3'_F$, are shown in Figure 3.31.

Figure 3.31  The pressure distributions of the index finger in the two cases at the Critical Moment.
The Figure 3.32 and the Figure 3.33 indicate the pressure distribution of the index finger of the robot at the Critical Moment in the first case and in the second case, respectively.

Figure 3.32  Pressure distribution of the index finger at the Critical Moment in the first case.

Figure 3.33  Pressure distribution of the index finger at the Critical Moment in the second case.

The normalized pressure distributions are:

$$\alpha_{xy} = \begin{pmatrix} \alpha_{y_{11}} & \alpha_{y_{12}} & \alpha_{y_{13}} \\ \alpha_{y_{21}} & \alpha_{y_{22}} & \alpha_{y_{23}} \\ \alpha_{y_{31}} & \alpha_{y_{32}} & \alpha_{y_{33}} \end{pmatrix} = \frac{P_y}{P} = \begin{pmatrix} 0.425 & 0.465 & 0.435 \\ 0.440 & 0.480 & 0.490 \\ 0.535 & 0.565 & 0.575 \end{pmatrix}. \quad (3.13)$$
The pressure distributions of the middle finger in the two cases, \(3_M\) and \(3'_M\), are displayed in Figure 3.34.

![Figure 3.34](image)

**Figure 3.34** The pressure distributions of the middle finger in the two cases at the Critical Moment.

The Figure 3.35 and the Figure 3.36 indicate the pressure distribution of the middle finger of the robot at the Critical Moment in the first case and in the second case, respectively.
Figure 3.35 Pressure distribution of the middle finger at the Critical Moment in the first case.

Figure 3.36 Pressure distribution of the middle finger at the Critical Moment in the second case.

The normalized pressure distributions are:

\[
\alpha_{3M} = \begin{pmatrix}
\alpha_{3M_{11}} & \alpha_{3M_{12}} & \alpha_{3M_{13}} \\
\alpha_{3M_{21}} & \alpha_{3M_{22}} & \alpha_{3M_{23}} \\
\alpha_{3M_{31}} & \alpha_{3M_{32}} & \alpha_{3M_{33}}
\end{pmatrix} = \frac{P_{3M}}{p} = \begin{pmatrix}
0.520 \\
0.540 \\
0.575
\end{pmatrix},
\]

(3.15)

\[
\alpha'_{3M} = \begin{pmatrix}
\alpha'_{3M_{11}} & \alpha'_{3M_{12}} & \alpha'_{3M_{13}} \\
\alpha'_{3M_{21}} & \alpha'_{3M_{22}} & \alpha'_{3M_{23}} \\
\alpha'_{3M_{31}} & \alpha'_{3M_{32}} & \alpha'_{3M_{33}}
\end{pmatrix} = \frac{P'_{3M}}{p} = \begin{pmatrix}
0.570 \\
0.575 \\
0.570
\end{pmatrix},
\]

(3.16)
The pressure distributions of the ring finger in the two cases, $3_R$ and $3'_R$, are shown in Figure 3.37.

Figure 3.37  The pressure distributions of the ring finger in the two cases at the Critical Moment.

The Figure 3.38 and the Figure 3.39 indicate the pressure distribution of the ring finger of the robot at the Critical Moment in the first case and in the second case, respectively.
The normalized pressure distributions are:

\[
\begin{align*}
\alpha_{3g} &= \begin{pmatrix} \alpha_{311} & \alpha_{312} & \alpha_{313} \\ \alpha_{321} & \alpha_{322} & \alpha_{323} \\ \alpha_{331} & \alpha_{332} & \alpha_{333} \end{pmatrix} = \begin{pmatrix} 0.475 & 0.510 & 0.485 \\ 0.525 & 0.590 & 0.590 \\ 0.530 & 0.605 & 0.595 \end{pmatrix}, \\
\alpha'_{3g} &= \begin{pmatrix} \alpha'_{311} & \alpha'_{312} & \alpha'_{313} \\ \alpha'_{321} & \alpha'_{322} & \alpha'_{323} \\ \alpha'_{331} & \alpha'_{332} & \alpha'_{333} \end{pmatrix} = \begin{pmatrix} 0.535 & 0.535 & 0.525 \\ 0.535 & 0.535 & 0.535 \\ 0.530 & 0.530 & 0.525 \end{pmatrix},
\end{align*}
\]

(3.17)  (3.18)
3.3.2.4 Analysis of the Sliding Moment

At the Sliding Moment, the pressure distributions of the two different cases are shown in Figure 3.40.

Figure 3.40  The pressure distributions of the two cases at the Sliding Moment.

The pressure distributions of the index finger in the two cases, $4_F$ and $4'_F$, are given in Figure 3.41.

Figure 3.41  The pressure distributions of the index finger in the two cases at the Sliding Moment.
The Figure 3.42 and the Figure 3.43 indicate the pressure distribution of the index finger of the robot at the Sliding Moment in the first case and in the second case, respectively.

![Figure 3.42](image1)

**Figure 3.42** Pressure distribution of the index finger at the Sliding Moment in the first case.

![Figure 3.43](image2)

**Figure 3.43** Pressure distribution of the index finger at the Sliding Moment in the second case.

The normalized pressure distributions are:

\[
\alpha_4 = \begin{pmatrix}
\alpha_{4_11} & \alpha_{4_12} & \alpha_{4_13} \\
\alpha_{4_21} & \alpha_{4_22} & \alpha_{4_23} \\
\alpha_{4_31} & \alpha_{4_32} & \alpha_{4_33}
\end{pmatrix} = \frac{1}{P} \begin{pmatrix}
0.325 & 0.335 & 0.355 \\
0.395 & 0.385 & 0.435 \\
0.330 & 0.440 & 0.410
\end{pmatrix}.
\] (3.19)
\[
\alpha_{4r} = \begin{pmatrix}
\alpha_{4r_{11}} & \alpha_{4r_{12}} & \alpha_{4r_{13}} \\
\alpha_{4r_{21}} & \alpha_{4r_{22}} & \alpha_{4r_{23}} \\
\alpha_{4r_{31}} & \alpha_{4r_{32}} & \alpha_{4r_{33}} 
\end{pmatrix} = \begin{pmatrix}
P_{4r_{11}} & P_{4r_{12}} & P_{4r_{13}} \\
P_{4r_{21}} & P_{4r_{22}} & P_{4r_{23}} \\
P_{4r_{31}} & P_{4r_{32}} & P_{4r_{33}} 
\end{pmatrix} = P = \begin{pmatrix}
0.440 & 0.445 & 0.440 \\
0.450 & 0.450 & 0.445 \\
0.450 & 0.450 & 0.440 
\end{pmatrix}.
\tag{3.20}
\]

The pressure distributions of the middle finger in the two cases, \(4_M\) and \(4'_M\), are shown in Figure 3.44.

![Figure 3.44](image)

**Figure 3.44** The pressure distributions of the middle finger in the two cases at the Sliding Moment.

The Figure 3.45 and the Figure 3.46 indicate the pressure distribution of the middle finger of the robot at the Sliding Moment in the first case and in the second case, respectively.
The normalized pressure distributions are:

\[
\begin{aligned}
\alpha_4 &= \begin{pmatrix}
\alpha_{4,11} & \alpha_{4,12} & \alpha_{4,13} \\
\alpha_{4,21} & \alpha_{4,22} & \alpha_{4,23} \\
\alpha_{4,31} & \alpha_{4,32} & \alpha_{4,33}
\end{pmatrix}
\end{aligned}
\]

\[
\begin{aligned}
\frac{P_{4,\mu}}{P} &= \begin{pmatrix}
0.415 & 0.460 & 0.370 \\
0.440 & 0.445 & 0.405 \\
0.360 & 0.455 & 0.435
\end{pmatrix}.
\end{aligned}
\]  \hspace{1cm} (3.21)

\[
\begin{aligned}
\alpha_4' &= \begin{pmatrix}
\alpha_{4,11}' & \alpha_{4,12}' & \alpha_{4,13}' \\
\alpha_{4,21}' & \alpha_{4,22}' & \alpha_{4,23}' \\
\alpha_{4,31}' & \alpha_{4,32}' & \alpha_{4,33}'
\end{pmatrix}
\end{aligned}
\]

\[
\begin{aligned}
\frac{P'_{4,\mu}}{P} &= \begin{pmatrix}
0.400 & 0.410 & 0.405 \\
0.410 & 0.410 & 0.405 \\
0.410 & 0.410 & 0.400
\end{pmatrix}.
\end{aligned}
\]  \hspace{1cm} (3.22)
The pressure distributions of the ring finger in the two cases, $4_R$ and $4'_R$, are shown in Figure 3.47.

Figure 3.47  The pressure distributions of the ring finger in the two cases at the Sliding Moment.

The Figure 3.48 and the Figure 3.49 indicate the pressure distribution of the ring finger of the robot at the Sliding Moment in the first case and in the second case, respectively.
Figure 3.48 Pressure distribution of the ring finger at the Sliding Moment in the first case.

Figure 3.49 Pressure distribution of the ring finger at the Sliding Moment in the second case.

The normalized pressure distributions are:

\[
\alpha_{4g} = \begin{pmatrix}
\alpha_{4x11} & \alpha_{4x12} & \alpha_{4x13} \\
\alpha_{4x21} & \alpha_{4x22} & \alpha_{4x23} \\
\alpha_{4x31} & \alpha_{4x32} & \alpha_{4x33}
\end{pmatrix} = \frac{P_{4g}}{P} = \begin{pmatrix}
0.420 & 0.445 & 0.435 \\
0.435 & 0.475 & 0.450 \\
0.410 & 0.470 & 0.435
\end{pmatrix}.
\] (3.23)

\[
\alpha_{4g}' = \begin{pmatrix}
\alpha_{4x11}' & \alpha_{4x12}' & \alpha_{4x13}' \\
\alpha_{4x21}' & \alpha_{4x22}' & \alpha_{4x23}' \\
\alpha_{4x31}' & \alpha_{4x32}' & \alpha_{4x33}'
\end{pmatrix} = \frac{P_{4g}'}{P} = \begin{pmatrix}
0.400 & 0.405 & 0.400 \\
0.405 & 0.410 & 0.405 \\
0.400 & 0.405 & 0.400
\end{pmatrix}.
\] (3.24)
3.3.2.5 Analysis of the Dropping Moment

At the Dropping Moment, the pressure distributions of the two cases are given in Figure 3.50.

![Figure 3.50 The pressure distributions of the two cases at the Dropping Moment.](image)

The pressure distributions of the index finger in the two cases, $5_F$ and $5'_F$, are shown in Figure 3.51.

![Figure 3.51 The pressure distributions of the index finger in the two cases at the Dropping Moment.](image)
The Figure 3.52 and the Figure 3.53 indicate the pressure distribution of the index finger of the robot at the Dropping Moment in the first case and in the second case, respectively.

The normalized pressure distributions are:

\[
\alpha_s = \begin{pmatrix} \alpha_{s_{11}} & \alpha_{s_{12}} & \alpha_{s_{13}} \\ \alpha_{s_{21}} & \alpha_{s_{22}} & \alpha_{s_{23}} \\ \alpha_{s_{31}} & \alpha_{s_{32}} & \alpha_{s_{33}} \end{pmatrix} = \frac{P_s}{P} = \begin{pmatrix} 0.175 & 0.205 & 0.170 \\ 0.130 & 0.175 & 0.210 \\ 0.185 & 0.195 & 0.155 \end{pmatrix}.
\] (3.25)
The pressure distributions of the middle finger in the two cases, $5_M$ and $5'_M$, are displayed in Figure 3.54.

The Figure 3.55 and the Figure 3.56 indicate the pressure distribution of the middle finger of the robot at the Dropping Moment in the first case and in the second case, respectively.
Figure 3.55 Pressure distribution of the middle finger at the Dropping Moment in the first case.

Figure 3.56 Pressure distribution of the middle finger at the Dropping Moment in the second case.

The normalized pressure distributions are:

\[
\alpha_{5m} = \begin{pmatrix}
\alpha_{5m11} & \alpha_{5m12} & \alpha_{5m13} \\
\alpha_{5m21} & \alpha_{5m22} & \alpha_{5m23} \\
\alpha_{5m31} & \alpha_{5m32} & \alpha_{5m33}
\end{pmatrix} = \frac{P_{5m}}{P} = \begin{pmatrix}
0.175 & 0.220 & 0.195 \\
0.195 & 0.215 & 0.285 \\
0.205 & 0.240 & 0.185
\end{pmatrix}.
\]  (3.27)

\[
\alpha'_{5m} = \begin{pmatrix}
\alpha'_{5m11} & \alpha'_{5m12} & \alpha'_{5m13} \\
\alpha'_{5m21} & \alpha'_{5m22} & \alpha'_{5m23} \\
\alpha'_{5m31} & \alpha'_{5m32} & \alpha'_{5m33}
\end{pmatrix} = \frac{P'_{5m}}{P} = \begin{pmatrix}
0.200 & 0.200 & 0.195 \\
0.200 & 0.205 & 0.200 \\
0.200 & 0.205 & 0.195
\end{pmatrix}.
\]  (3.28)
The pressure distributions of the ring finger in the two cases, $5_R$ and $5'_R$, are displayed in Figure 3.57.

![Figure 3.57](image)

Figure 3.57 The pressure distributions of the ring finger in the two cases at the Dropping Moment.

The Figure 3.58 and the Figure 3.59 indicate the pressure distribution of the ring finger of the robot at the Dropping Moment in the first case and in the second case, respectively.

![Figure 3.58](image)

Figure 3.58 Pressure distribution of the ring finger at the Dropping Moment in the first case.
Figure 3.59 Pressure distribution of the ring finger at the Dropping Moment in the second case.

The normalized pressure distributions are:

\[
\alpha_\alpha = \begin{pmatrix}
\alpha_{511} & \alpha_{512} & \alpha_{513} \\
\alpha_{521} & \alpha_{522} & \alpha_{523} \\
\alpha_{531} & \alpha_{532} & \alpha_{533}
\end{pmatrix} = \frac{P_{sa}}{P} = \begin{pmatrix}
0.125 & 0.160 & 0.165 \\
0.110 & 0.155 & 0.160 \\
0.105 & 0.170 & 0.220
\end{pmatrix}.
\]  

(3.29)

\[
\alpha_\alpha' = \begin{pmatrix}
\tilde{\alpha}_{511} & \tilde{\alpha}_{512} & \tilde{\alpha}_{513} \\
\tilde{\alpha}_{521} & \tilde{\alpha}_{522} & \tilde{\alpha}_{523} \\
\tilde{\alpha}_{531} & \tilde{\alpha}_{532} & \tilde{\alpha}_{533}
\end{pmatrix} = \frac{P_{sa}'}{P} = \begin{pmatrix}
0.150 & 0.155 & 0.155 \\
0.160 & 0.160 & 0.155 \\
0.150 & 0.160 & 0.160
\end{pmatrix}.
\]  

(3.30)

3.3.2.6 Relationship between the pressure distribution and the user’s responses

At the Initial Moment, pressure distributions in the nine areas of the index finger, the middle finger and the ring finger in two cases are given in Equations (3.1) to (3.6).

The \( \alpha_i \) multiplied by a constant 1.13, \( \tilde{\alpha}_i \) represents:
\[ \bar{\alpha}_r = \alpha_j \times 1.13 = \begin{pmatrix} 0.810 & 8.875 & 0.859 \\ 0.865 & 0.926 & 0.893 \\ 0.831 & 0.910 & 0.853 \end{pmatrix}. \]

Comparing \( \bar{\alpha}_r \) and \( \bar{\alpha}'_r \), the corresponding elements are roughly the same. This means that the pressure distributions given by \( \alpha_j \) and \( \alpha'_j \) are the same.

Similarly, the pressure distributions given by \( \bar{\alpha}_w \) and \( \bar{\alpha}'_w \) are the same. The pressure distributions given in \( \bar{\alpha}_x \) and \( \bar{\alpha}'_x \) are the same. Therefore, in the first and in the second case, the pressure distributions of all the three finger tips are the same.

At the Stable Moment, the pressure distributions on the nine areas of the index finger, the middle finger and the ring finger in the two cases are given by Equation (3.7) to (3.12).

In the first case of the Stable Moment, the robot hand releases the glass slowly, but the glass does not slide off the robot hand. Because the user does not have intention to receive the glass, the user does not take it. The pressure distributions on the nine areas of the index finger are not the same with one another. So is the pressure distribution of the nine areas of the middle finger and of the ring finger.

In the second case of the Stable Moment, the robot hand releases it the glass slowly. The glass does not slide off the robot hand since the user receives it. The pressure distributions of the nine areas of the index finger are almost the same with one
another, and so is the pressure distribution of the nine areas of the middle finger and of the ring finger.

At the Critical Moment, the pressure distributions of the nine areas of the index finger, the middle finger and the ring finger in the two different cases are given by Equation (3.13) to (3.18).

In the first case of the Critical Moment, the robot hand releases the glass slowly. This is the critical state that the glass will slide off the robot hand if the robot hand releases it a little more. Because the user does not have intention to receive the glass, the user does not take it. The pressure distributions of the nine areas of the index finger are not the same with one another, and so is the pressure distribution of the nine areas of the middle finger and of the ring finger.

In the second case of the Critical Moment, the robot hand releases the glass slowly. The glass does not slide off the robot hand since the user receives it. The pressure distribution of the nine areas of the index finger is almost the same with one another, and so is the pressure distribution on the nine areas of the middle finger and of the ring finger.

At the Sliding Moment, the pressure distributions of the nine areas of the index finger, the middle finger and the ring finger in the two cases are given by Equation (3.19) to (3.24).
In the first case of the Sliding Moment, the robot hand releases the glass slowly. The glass begins to slide off the robot hand slowly. The pressure distribution of the nine areas of the index finger is not the same with one another, and so is the pressure distribution of the nine areas of the middle finger and of the ring finger.

In the second case of the Sliding Moment, the robot hand releases the glass slowly. Although this is the moment that the glass slides off the robot hand, the glass does not slide off the robot hand since the user receives it. The pressure distribution of the nine areas of the index finger is almost the same with one another, and so is the pressure distribution of the nine areas of the middle finger and of the ring finger.

At the Dropping Moment, the pressure distributions of the nine areas of the index finger, the middle finger and the ring finger in the two cases are given by Equation (3.25) to (3.30).

In the first case of the Dropping Moment, the robot hand releases the glass slowly, the glass slides off and drop from robot hand if the robot hand releases a little more. The pressure distribution of the nine areas of the index finger is not the same with one another, and so is the pressure distribution on the nine areas of the middle finger and of the ring finger.

In the second case of the Dropping Moment, the robot hand releases the glass slowly. Although this is the moment that the glass slides off the robot hand, the glass does not slide off the robot hand since the user receives it. The pressure distribution of the nine
areas of the index finger is almost the same with one another, and so is the pressure distribution of the nine areas of the middle finger and of the ring finger.

In summary, if the user does not have intention to receive the glass that the robot hand passes, then when the test action of the robot which is releasing the glass a bit is executed, the user’s responses to this test action is that the user will not take the glass. In this case, the pressure distribution of finger tips of the robot hand is different with one another. In other words, the pressure distribution is uneven on the finger tips of the robot hand. This pressure distribution is uneven in different areas at the five moments in the first case.

If the user wants to receive the glass that the robot hand passes, when the test action of the robot which is releasing the glass a bit is executed, the user’s responses to this test action is that the user will take the glass. In this case, the pressure distribution on the finger tips of the robot hand is almost the same in different areas. In other words, the pressure distribution is even on the finger tips of the robot hand. Such pressure distribution is even in different areas at the last four moments in the second case.

3.4 Model Development

3.4.1 Pressure Sensor Array Model

According to the analysis of the pressure distributions on the robot’s finger tips at the five defined moments in the two cases, the relationship between the pressure
distributions on the finger tips and the user’s responses to the test action of slightly releasing the glass can be collected. Uneven pressure distributions on the robot’s finger tips when the robot executes the test action mean that the user does not take over the glass. On the other hand, even pressure distributions on the robot’s finger tips mean the user is ready to take over the glass. Therefore, pressure distributions on the robot’s finger tips reflect the use’s responses to the test action.

A distributed pressure sensor system that arranges individual pressure sensors in the form of an array can be developed and attached to a robot’s finger tips to collect the responses of the user of the robot to the test actions. The structure of the pressure sensor array is shown in Figure 3.60.

![Figure 3.60 Structure of the pressure sensor array.](image)

In this pressure sensor array, nine pressure sensors, $S_{11}$, $S_{12}$, $S_{13}$, $S_{21}$, $S_{22}$, $S_{23}$, $S_{31}$, $S_{32}$, and $S_{33}$, are distributed in nine small areas on a finger tip. Three such sensor arrays are needed to fix on to the three finger tips of a robot hand.
Unlike the pressure sensor film, these individual pressure sensors have their individual pressure readings $P_{11}$, $P_{12}$, $P_{13}$, $P_{21}$, $P_{22}$, $P_{23}$, $P_{31}$, $P_{32}$, and $P_{33}$. When a robot passes an object on to its user, it can test the user to find out his/her responses by calculating the pressure distributions based on the readings collected from the sensor array. Even distributions from all three sensor arrays suggest that the user is ready to take over the object, whilst uneven distributions mean that the user is not ready or even does not want to take over the glass.

### 3.4.2 Mathematical Model for Detecting Pressure Distribution

As discussed in the last section, the user’s different responses to test actions are reflected through even and uneven pressure distributions on the robot’s finger tips. There is a need to have an indicator, so that a robot is able to realize whether the pressure distribution is even or not. In this section, a mathematic model that serves as such indicator is developed.

Consider one of the three pressure sensor arrays. Pressure values $P_{11}$, $P_{12}$, $P_{13}$, $P_{21}$, $P_{22}$, $P_{23}$, $P_{31}$, $P_{32}$, and $P_{33}$ are defined for pressure sensors $S_{11}$, $S_{12}$, $S_{13}$, $S_{21}$, $S_{22}$, $S_{23}$, $S_{31}$, $S_{32}$, and $S_{33}$, respectively. If the pressure distribution on the robot’s finger tips is even, the pressure of the nine individual sensors are similar, that is, $P_{11} \approx P_{12} \approx P_{13} \approx P_{21} \approx P_{22} \approx P_{23} \approx P_{31} \approx P_{32} \approx P_{33}$. Therefore, the average of these nine pressure values approximately equals to all of these nine values. Using any of the nine values minus the average value approximately yields zero. If the pressure distribution on the robot’s finger tips is uneven, pressure readings of some sensors will be very
different from those of others. Therefore, the difference between the average and any of these nine values will not be zero.

Based on this analysis, a mathematic formula is developed as following:

\[
A(S_y) = P_y - \frac{\sum_{i=1}^{3} \sum_{j=1}^{3} P_{ij}}{3 \times 3} \quad (i = 1, 2, 3, j = 1, 2, 3) \tag{3.31}
\]

where \(P_y\) is one of the nine pressure values of the pressure sensor array, \(\sum_{i=1}^{3} \sum_{j=1}^{3} P_{ij} \) is the average, and \(A(S_y)\) is the difference between the average and one of the nine pressure values.

when \(A(S_y)\) \((i = 1, 2, 3, j = 1, 2, 3)\) approximately equals to zero, the pressure distribution of the robot’s finger tip is even. In other words, the user’s response to a test action is that the user is holding the object that the robot passes on. When some of \(A(S_y)\) \((i = 1, 2, 3, j = 1, 2, 3)\) are approximately not equals to zero, the pressure distribution on the robot’s finger tip is uneven. In other words, the user’s response to the test action is that the user is not holding the object.

Because conditions such as the material of the object and the shape of the robot fingers can vary from case to case, the state of pressure, \(\alpha_i = \frac{P_i}{P}\), which is a normalized value is used to represent the pressure magnitude, where, the denominator \(P\) is the maximum value of the pressure range of the pressure sensor.

For the pressure sensor array model,
\[
\alpha_{ij} = \frac{P_{ij}}{P}
\]

(3.32)

where \( P_{ij} \) represents the pressure reading of a pressure sensor, \( P \) is the maximum value of the pressure range, and \( \alpha_{ij} \) is the normalized value of the pressure.

As the normalized value \( \alpha_{ij} \) is used to represent the pressure values \( P_{ij} \), Equation (3.1) can be changed to:

\[
F(S_{ij}) = \alpha_{ij} - \frac{\sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_{ij}}{3 \times 3} \quad (i = 1, 2, 3, j = 1, 2, 3)
\]

(3.33)

where \( \alpha_{ij} \) is the normalized value, \( \sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_{ij} \) is the average, and \( F(S_{ij}) \) is the difference between one of the normalized values and the average.

In perfect cases, when the pressure distribution on a robot’s finger tip is even, all \( F(S_{ij}) = 0 \) \((i = 1, 2, 3, j = 1, 2, 3)\) and when the pressure distribution is uneven, some of \( F(S_{ij}) \neq 0 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

3.4.3 Results calculation

In real world, the pressure distribution on the robot’s finger tip is not absolutely even, that is, \( F(S_{ij}) \) only approximately equals to zero. In order to decide whether the pressure distribution is even or not, a threshold for \( F(S_{ij}) \) must be decided.
In order to decide the threshold, data collected from the benchmark scenario given in Section 3.1 were used.

At the Initial Moment, the pressure distributions in the two cases are similar. Therefore, the difference in pressure distributions between the two cases cannot be detected at this moment.

From the Stable Moment, Critical Moment, Sliding Moment to Dropping Moment in the first case, the data of the normalized values can be used to calculate $F(S_y)$ using Equation (3.33).

At the Stable Moment, the pressure sensor film was attached on the index finger:

$F(S_{11}) = -0.009, F(S_{12}) = -0.029, F(S_{13}) = -0.029, F(S_{21}) = 0.006, F(S_{22}) = 0.026,$

$F(S_{23}) = -0.004, F(S_{31}) = 0.016, F(S_{32}) = 0.051, F(S_{33}) = -0.009$

For the pressure sensor film attached on the middle finger:

$F(S_{11}) = -0.011, F(S_{12}) = -0.016, F(S_{13}) = -0.106, F(S_{21}) = 0.034, F(S_{22}) = 0.054,$

$F(S_{23}) = 0.036, F(S_{31}) = 0.049, F(S_{32}) = 0.059, F(S_{33}) = -0.026.$

For the pressure sensor film attached on the ring finger:

$F(S_{11}) = -0.059, F(S_{12}) = -0.049, F(S_{13}) = 0.079, F(S_{21}) = 0.041, F(S_{22}) = 0.026,$

$F(S_{23}) = 0.056, F(S_{31}) = 0.046, F(S_{32}) = 0.021, F(S_{33}) = -0.004.$

At the Critical Moment, the pressure sensor film was attached on the index finger:
\[ F(S_{11}) = -0.065, \quad F(S_{12}) = -0.025, \quad F(S_{13}) = -0.055, \quad F(S_{21}) = -0.050, \quad F(S_{22}) = -0.010, \]
\[ F(S_{23}) = 0.000, \quad F(S_{31}) = 0.045, \quad F(S_{32}) = 0.075, \quad F(S_{33}) = 0.085. \]

For the pressure sensor film attached on the middle finger:

\[ F(S_{11}) = 0.001, \quad F(S_{12}) = -0.004, \quad F(S_{13}) = -0.049, \]
\[ F(S_{21}) = 0.021, \quad F(S_{22}) = 0.056, \quad F(S_{23}) = -0.024, \quad F(S_{31}) = 0.056, \quad F(S_{32}) = 0.001, \]
\[ F(S_{33}) = -0.059. \]

For the pressure sensor film attached on the ring finger:

\[ F(S_{11}) = -0.070, \quad F(S_{12}) = -0.035, \quad F(S_{13}) = -0.060, \quad F(S_{21}) = -0.020, \quad F(S_{22}) = 0.045, \]
\[ F(S_{23}) = 0.045, \quad F(S_{31}) = -0.015, \quad F(S_{32}) = 0.060, \quad F(S_{33}) = 0.050. \]

At the Sliding Moment, the pressure sensor film was attached on the index finger:

\[ F(S_{11}) = -0.054, \quad F(S_{12}) = -0.044, \quad F(S_{13}) = -0.024, \quad F(S_{21}) = 0.016, \quad F(S_{22}) = 0.006, \]
\[ F(S_{23}) = 0.056, \quad F(S_{31}) = -0.049, \quad F(S_{32}) = 0.061, \quad F(S_{33}) = 0.031. \]

For the pressure sensor film attached on the middle finger:

\[ F(S_{11}) = -0.006, \quad F(S_{12}) = 0.039, \quad F(S_{13}) = -0.051, \quad F(S_{21}) = 0.019, \quad F(S_{22}) = 0.024, \]
\[ F(S_{23}) = 0.016, \quad F(S_{31}) = 0.061, \quad F(S_{32}) = 0.034, \quad F(S_{33}) = 0.014. \]

For the pressure sensor film attached on the ring finger:

\[ F(S_{11}) = -0.022, \quad F(S_{12}) = 0.003, \quad F(S_{13}) = -0.007, \quad F(S_{21}) = -0.007, \quad F(S_{22}) = 0.033, \]
\[ F(S_{23}) = 0.008, \quad F(S_{31}) = -0.032, \quad F(S_{32}) = 0.028, \quad F(S_{33}) = -0.007. \]

At the Dropping Moment, the pressure sensor film was attached on the index finger:
\[ F(S_{11}) = -0.003, \quad F(S_{12}) = 0.027, \quad F(S_{13}) = 0.008, \quad F(S_{21}) = -0.048, \quad F(S_{22}) = -0.003, \]
\[ F(S_{23}) = 0.032, \quad F(S_{31}) = 0.007, \quad F(S_{32}) = 0.017, \quad F(S_{33}) = -0.023 \]

For the pressure sensor film attached on the middle finger:
\[ F(S_{11}) = -0.038, \quad F(S_{12}) = 0.007, \quad F(S_{13}) = -0.018, \quad F(S_{21}) = -0.018, \quad F(S_{22}) = 0.002, \]
\[ F(S_{23}) = 0.072, \quad F(S_{31}) = -0.008, \quad F(S_{32}) = 0.027, \quad F(S_{33}) = -0.028. \]

For the pressure sensor film attached on the ring finger:
\[ F(S_{11}) = -0.027, \quad F(S_{12}) = 0.008, \quad F(S_{13}) = 0.013, \quad F(S_{21}) = -0.042, \quad F(S_{22}) = 0.003, \]
\[ F(S_{23}) = 0.008, \quad F(S_{31}) = -0.047, \quad F(S_{32}) = 0.018, \quad F(S_{33}) = 0.068. \]

From the Stable Moment, the Critical Moment, the Sliding Moment to the Dropping Moment in the second case, the data of normalized values can be used to calculate \( F(S_0) \) using Equation (3.33).

At the Stable Moment, the pressure sensor film was attached on the index finger:
\[ F(S_{11}) = 0.000, \quad F(S_{12}) = 0.005, \quad F(S_{13}) = -0.005, \quad F(S_{21}) = 0.005, \quad F(S_{22}) = 0.005, \]
\[ F(S_{23}) = 0.000, \quad F(S_{31}) = -0.005, \quad F(S_{32}) = 0.000, \quad F(S_{33}) = -0.005. \]

Therefore, the threshold of \( F(S_0) \) is: \(-0.005 \leq F(S_i) \leq 0.005 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

For the pressure sensor film attached on the middle finger:
\[ F(S_{11}) = -0.002, \quad F(S_{12}) = 0.003, \quad F(S_{13}) = -0.002, \quad F(S_{21}) = -0.002, \quad F(S_{22}) = 0.003, \]
\[ F(S_{23}) = 0.003, \quad F(S_{31}) = -0.007, \quad F(S_{32}) = 0.003, \quad F(S_{33}) = -0.002. \]
Therefore, the threshold of $F(S_y)$ is: $-0.007 \leq F(S_y) \leq 0.003 \ (i = 1, 2, 3, j = 1, 2, 3)$.

For the pressure sensor film attached on the ring finger:

\[
F(S_{11}) = -0.004, \ F(S_{12}) = 0.001, \ F(S_{13}) = -0.004, \ F(S_{21}) = 0.001, \ F(S_{22}) = 0.006, \\
F(S_{23}) = 0.001, \ F(S_{31}) = -0.004, \ F(S_{32}) = 0.006, \ F(S_{33}) = 0.004.
\]

Therefore, the threshold of $F(S_y)$ is: $-0.004 \leq F(S_y) \leq 0.006 \ (i = 1, 2, 3, j = 1, 2, 3)$.

The threshold of $F(S_y)$ at Stable Moment can be decided as: $-0.007 \leq F(S_y) \leq 0.006$ $\ (i = 1, 2, 3, j = 1, 2, 3)$.

At the Critical Moment, the pressure sensor film was attached on the index finger:

\[
F(S_{11}) = -0.001, \ F(S_{12}) = -0.001, \ F(S_{13}) = -0.001, \ F(S_{21}) = 0.004, \ F(S_{22}) = 0.004, \\
F(S_{23}) = -0.001, \ F(S_{31}) = -0.001, \ F(S_{32}) = -0.001, \ F(S_{33}) = -0.006.
\]

Therefore, the threshold of $F(S_y)$ is: $-0.006 \leq F(S_y) \leq 0.004 \ (i = 1, 2, 3, j = 1, 2, 3)$.

For the pressure sensor film attached on the middle finger:

\[
F(S_{11}) = -0.005, \ F(S_{12}) = 0.005, \ F(S_{13}) = 0.000, \ F(S_{21}) = 0.000, \ F(S_{22}) = 0.005, \\
F(S_{23}) = 0.000, \ F(S_{31}) = -0.005, \ F(S_{32}) = 0.000, \ F(S_{33}) = 0.000.
\]

Therefore, the threshold of $F(S_y)$ is: $-0.005 \leq F(S_y) \leq 0.005 \ (i = 1, 2, 3, j = 1, 2, 3)$.
For the pressure sensor film attached on the ring finger:

\[ F(S_{11}) = 0.003, \quad F(S_{12}) = 0.003, \quad F(S_{13}) = -0.007, \quad F(S_{21}) = 0.003, \quad F(S_{22}) = 0.003, \]
\[ F(S_{23}) = 0.003, \quad F(S_{31}) = -0.002, \quad F(S_{32}) = -0.002, \quad F(S_{33}) = -0.007. \]

Therefore, the threshold of \( F(S_{ij}) \) is: \(-0.007 \leq F(S_{ij}) \leq 0.003 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

The threshold of \( F(S_{ij}) \) at Critical Moment can be decided as: \(-0.007 \leq F(S_{ij}) \leq 0.006 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

At the Sliding Moment, the pressure sensor film was attached on the index finger:

\[ F(S_{11}) = -0.006, \quad F(S_{12}) = -0.001, \quad F(S_{13}) = -0.006, \quad F(S_{21}) = 0.004, \quad F(S_{22}) = 0.004, \]
\[ F(S_{23}) = -0.001, \quad F(S_{31}) = 0.004, \quad F(S_{32}) = 0.004, \quad F(S_{33}) = -0.006. \]

Therefore, the threshold of \( F(S_{ij}) \) is: \(-0.006 \leq F(S_{ij}) \leq 0.004 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

For the pressure sensor film attached on the middle finger:

\[ F(S_{11}) = -0.007, \quad F(S_{12}) = 0.003, \quad F(S_{13}) = -0.002, \quad F(S_{21}) = 0.003, \quad F(S_{22}) = 0.003, \]
\[ F(S_{23}) = -0.002, \quad F(S_{31}) = 0.003, \quad F(S_{32}) = 0.003, \quad F(S_{33}) = -0.007. \]

Therefore, the threshold of \( F(S_{ij}) \) is: \(-0.007 \leq F(S_{ij}) \leq 0.003 \) \((i = 1, 2, 3, j = 1, 2, 3)\).
\[ F(S_{11}) = -0.003, \quad F(S_{12}) = 0.002, \quad F(S_{13}) = -0.003, \quad F(S_{21}) = 0.002, \quad F(S_{22}) = 0.007, \]
\[ F(S_{23}) = 0.002, \quad F(S_{31}) = -0.003, \quad F(S_{32}) = 0.002, \quad F(S_{33}) = -0.003. \]

Therefore, the threshold of \( F(S_{ij}) \) is: \(-0.003 \leq F(S_{ij}) \leq 0.007 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

Threshold of \( F(S_{ij}) \) at the Sliding Moment can be decided as: \(-0.007 \leq F(S_{ij}) \leq 0.007 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

At the Dropping Moment, the pressure sensor film was attached on the index finger:
\[ F(S_{11}) = -0.001, \quad F(S_{12}) = 0.001, \quad F(S_{13}) = -0.001, \quad F(S_{21}) = -0.001, \quad F(S_{22}) = 0.004, \]
\[ F(S_{23}) = 0.004, \quad F(S_{31}) = -0.001, \quad F(S_{32}) = -0.001, \quad F(S_{33}) = 0.001. \]

Therefore, the threshold of \( F(S_{ij}) \) is: \(-0.001 \leq F(S_{ij}) \leq 0.004 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

For the pressure sensor film attached on the middle finger:
\[ F(S_{11}) = 0.000, \quad F(S_{12}) = 0.000, \quad F(S_{13}) = -0.005, \quad F(S_{21}) = 0.000, \quad F(S_{22}) = 0.005, \]
\[ F(S_{23}) = 0.000, \quad F(S_{31}) = 0.000, \quad F(S_{32}) = 0.005, \quad F(S_{33}) = 0.005. \]

Therefore, the threshold of \( F(S_{ij}) \) is: \(-0.005 \leq F(S_{ij}) \leq 0.005 \) \((i = 1, 2, 3, j = 1, 2, 3)\).

For the pressure sensor film attached on the ring finger:
\[ F(S_{11}) = -0.006, \quad F(S_{12}) = -0.001, \quad F(S_{13}) = -0.001, \quad F(S_{21}) = 0.004, \quad F(S_{22}) = 0.004, \]
\[ F(S_{23}) = 0.001, \quad F(S_{31}) = -0.006, \quad F(S_{32}) = 0.004, \quad F(S_{33}) = 0.004. \]
Therefore, the threshold of $F(S_y)$ is: $-0.006 \leq F(S_y) \leq 0.005 \ (i = 1, 2, 3, j = 1, 2, 3)$.

The threshold of $F(S_y)$ at the Dropping Moment can be decided as: $-0.006 \leq F(S_y) \leq 0.006 \ (i = 1, 2, 3, j = 1, 2, 3)$.

In the second case, according to the threshold of $F(S_y)$ at the four defined moments given above, the threshold of $F(S_y)$ in the second case can be decided as: $-0.007 \leq F(S_y) \leq 0.007 \ (i = 1, 2, 3, j = 1, 2, 3)$.

Therefore, when $-0.007 \leq F(S_y) \leq 0.007 \ (i = 1, 2, 3, j = 1, 2, 3)$, the pressure distributions can be considered as evenly distributed.

In the first case, the pressure distributions on the robot’s finger tips are uneven. From these results of calculation of $F(S_y) \ (i = 1, 2, 3, j = 1, 2, 3)$ at the last four defined moments in the first case, some values of $F(S_y) \ (i = 1, 2, 3, j = 1, 2, 3)$ are larger than 0.007 or smaller than -0.007.

Therefore, when one or several values of $F(S_y) \ (i = 1, 2, 3, j = 1, 2, 3)$ are not in the range $-0.007 \leq F(S_y) \leq 0.007 \ (i = 1, 2, 3, j = 1, 2, 3)$, the pressure distribution can be considered as uneven.
CHAPTER 4. EVALUATION OF ROBOT HAND MODELLING SOFTWARE

The aim of this evaluation is to identify the most suitable simulation software for modelling of the robot hands, including the pressure sensor arrays which can be installed on the robot’s finger tips.

In the evaluation, the important criteria are:

1) The robot hand can be specified easily.
2) The pressure sensor array can be simulated and added easily on the finger tips of the robot hand model.

4.1 Modelling Software

4.1.1 Automatic Dynamic Analysis of Mechanical System

Automatic Dynamic Analysis of Mechanical System (Adams) is a widely used mechanical system simulation software which is developed by the MSC software corporation (W.Guo, 2007). It lets its user to create and test virtual prototypes of mechanical systems, realistically simulated on a computer, both visually and mathematically, including the full-motion behavior of a complex mechanical system design. In the process of creation and testing of the virtual prototypes of mechanical systems, Adams can help its user to study the dynamics of moving parts, how loads
are distributed throughout the mechanical systems, and how to improve and optimize the performance of the products.

Adams consists of Adams/View module, Adams/Solver module, Adams/Postprocessor module and Adams/Flex module.

Adams/View is one of the core modules in Adams. Modelling, simulation, animation, result analysis, optimization design can be carried out in this module, and it is also includes which is a interactive graphic environment.

Adams/Solver is also one of the core modules in Adams. It is a simulator that can present kinetics equations of the mechanical system models, and solve the kinematics. It can perform simulations of the rigid body and the flexible body.

Adams/Postprocessor is used to process results of simulations and display animations of simulations. It can also provide the suitable environment for the user to see movements of the model.

Adams/Flex considers the elastic property of components of the model to increase the precision of the simulation.
4.1.2 Matlab/ Simulink

MATLAB is a numerical computing environment. It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, and Fortran (R.Smith, 1988).

Although MATLAB is intended primarily for numerical computing, a package, Simulink, adds graphical multi-domain simulation and Model-Based Design for dynamic and embedded systems.

SimMechanics toolbox in MATLAB can be used to construct robot hand models. As one of the toolboxes in MATLAB, SimMechanics extends Simscape with tools for modelling of the 3-D mechanical systems within the SIMULINK environment. It is a block diagram modelling environment for the engineering design and simulation of rigid body machines and their motions. The 3-D animations are generated automatically, which benefits the visualization of the system dynamics. It can also import models with mass and inertia, constraints, and 3-D geometry from several CAD systems.

In Simulink, a mathematical model is represented in the form of a block diagram. Simulink provides various blocks for modelling the system. Regarding the modelling of a robot hand, Simulink provides the following blocks:
Body block: Represents a user-defined rigid body. Body is defined by its mass, inertia tensor and coordinate origins and axes for the centre of gravity and other user specified body coordinate systems.

Inertial frame block: Grounds one side of a joint to a fixed location in the coordinate system.

Environment block: Defines the mechanical simulation environment for the machine to which the block is connected. The settings include gravity, dimensionality, analysis mode, constraint solver type tolerance, linearization and visualization.

Rotational freedom block: Represents one rotational degree of freedom. The follower body rotates relative to the base body about a single rotational axis going through collocated body coordinate system origins.

Coulomb friction block: Actuates a joint primitive with friction force/torque. Locks if static friction remains within the range of forward and reverse friction limits.

4.1.3 GraspIt

GraspIt was created to serve as a tool for grasping the research. It is a simulator that can accommodate arbitrary hand and robot designs (Miller and Allen, 2004). It can also load robot hand models, objects and obstacles of arbitrary geometry to populate a complete simulation world. The GraspIt engine includes a rapid collision detection and contact determination system that allows a user to interactively manipulate a robot or an object and create contacts between them. Once a grasp is created, one of the key features of the simulator is the set of grasp quality metrics. Each grasp is
evaluated with numeric quality measures, and visualization methods allow the user to see the weak point of the grasp and create arbitrary 3D projections.

GraspIt usually serves one of the two purposes. First, it can be used as a development tool, to execute and test various robot control algorithms. In this sense, it serves as a replacement for the real world: in simulation, an algorithm can be tested on many hand designs, many objects and obstacle configurations, at no cost and much faster than in the real world. Second, GraspIt can be used as a computational platform that backs up a robot that does operate in the real world. For example, a real robot can acquire a model of a target object, then, use GraspIt to quickly evaluate multiple grasping or manipulation scenarios. Often, these scenarios are also combined and the same GraspIt setup used for the development of an algorithm can also be used for computations during the real life execution. GraspIt has many features that can help accomplish these roles.

The most commonly used GraspIt roles include the contact detection and the grasp quality metrics, the dynamics engine and the grasp planning capabilities. The dynamics engine within GraspIt computes the motions of a group of connected robot elements. This allows a user to dynamically simulate an entire grasping task, as well as to test custom robot control algorithms. The grasp planning algorithms rely on the simulated environment to quickly evaluate many hand postures, and find those that lead to stable grasps. There are many possible implementations of this concept; the planners that are included with GraspIt can usually find multiple stable grasps of an object in less than 1 minute, taking into account obstacles and other constraints.
GraspIt is an open-source virtual environment for simulating robotic grasping tasks accompanied by a number of analysis and development tools.

4.2 Robot Hand Creation Using Three Modelling Softwares

4.2.1 Robot Hand Model Creation Using Adams

A robot hand model was created in Adams/view module of Adams. The whole robot hand model is shown in Figure 4.1 and Figure 4.2.

Figure 4.1 Robot hand model.
4.2.2 Robot Hand Model Creation Using Matlab

A robot hand model which is composed of seven parts, including one robot base, four robot links and two fingers was developed. The diagram of this model is given in Figure 4.3.

Figure 4.2  Robot hand model after render.

Figure 4.3  Diagram of robot model.
The details of the robot base are shown in Figure 4.4.

The robot base consists of an environment block, an inertial frame block, a weld block, a body block and a connecting point (follower). The environment block defines the settings of the environment such as gravity and dimensionality in its property window. The inertial frame block defines a fixed point as the origin of an absolute 3-D space. The weld block, considered as a joint with a zero degree of freedom, is used to connect the base to the ground. The Body block defines position, weight, and shape of the base. The settings of the shape parameters of the base are given in Table 4.1.

![Figure 4.4 Structure of the robot base.](image)

<table>
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<tr>
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<th>Port Value</th>
<th>Name</th>
<th>Origin Position Vector XYZ</th>
<th>Units</th>
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<th>Components in Access to</th>
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<td>World</td>
</tr>
</tbody>
</table>

Table 4.1 Settings of the shape parameters of the base.
The Origin Position Vector column shows the position parameters of the base and all the reference points are translated from the origin of the world coordinator.

The four linked robot links form the trunk of the robot arm. They have the same structure as when building a robot model. Any of the bodies consist of a body block, a driver module, an acceleration block and a pair of connecting points (Follower and Base). The details of the structure of a body are shown as Figure 4.5

![Figure 4.5 Structure of a robot body.](image)

Body1 block, which represents the shape of Body1 link, has the same function as the robot base part. Acceleration 1 block is the input part for this robot body. It decides what kind of action this robot body can finish, including the speed and beginning time of the action. The Drive 1 is a mask block with complex links, which make the input to work on the body block effectively. It also contains rotational blocks to decide the number of degrees of freedoms. For these robot body parts, each of them has three degree of freedom.
The drive block of the robot arm has three main blocks (Figure 4.6). They are controller block, motor circuitry block, and input rotation freedom block which represent a gearbox. The trajectory commands are filtered and converted into control signals (current) by the controller block. The control signals are the inputs to the motor. The gearbox is driven by the motor. The coulomb friction block produces friction of the actuator.

Then, two fingers of the robot hand were developed. Two fingers are connected to the robot arm to finish actions such as grasping and releasing. Each finger has three links and two joints that connect the three links together. Each link has a similar structure. Figure 4.7 shows the model of one finger. It consists of three body blocks, three drive blocks and two input control blocks.
According to the above development, a robot model which includes one robot base, four robot links and two fingers was constructed, as shown in Figure 4.8.

Figure 4.7 Structure of a robot finger.

Figure 4.8 Robot hand model.
4.2.3 Robot Hand Model Creation Using GraspIt

As mentioned in 4.1.3, some robot hand models were stored in GraspIt. A robot hand model can be loaded in the work space, as shown in Figure 4.9.

![Figure 4.9 A robot hand model in the work space of GraspIt.](image)

4.3 Pressure Sensor

Pressure sensor was developed using the C program. In simulations, a tiny flexible element is considered as a pressure sensor. When pressure was applied on the pressure sensor, the tiny flexible element was deformed and the length of the element had varied. The pressure can be calculated through measuring the variations of the length of an element.
According to Hooke’s law (Rychlewshi, 1984) in Material Mechanics, the mathematical model of the pressure sensor can be obtained as follows:

Using the Hooke’s Law:

\[ \sigma = E \cdot \varepsilon \]  \hspace{1cm} (4.1)

where \( \sigma \) is a normal stress, \( E \) is the Young's modulus, \( \varepsilon \) is the strain of an element.

\[ \sigma = \frac{F}{A} \]  \hspace{1cm} (4.2)

where \( F \) is the pressure which is pressed on the element, and \( A \) is the area of the section of the element.

\[ \varepsilon = \frac{\Delta l}{l} \]  \hspace{1cm} (4.3)

where \( l \) is the length of the element, and \( \Delta l \) is the variation of the length.

From Equation (4.1) to (4.3), the relationship between the pressure \( F \) and the variation of the length \( \Delta l \) can be obtained as:

\[ F = E \cdot A \cdot \frac{\Delta l}{l} \]  \hspace{1cm} (4.4)

Therefore, the C program of the pressure sensor can be used assuming Equation (4.4).

The program of the pressure sensor which was developed by the C program is as follows:
void main()
{
    float l;
    float E;
    float A;
    float dl;
    float F;

    printf(“Measure the variation of length of the tiny flexible element dl”);
    F = E*A*dl/l;
    printf(“The pressure F is:”)
    printf("%3.1f", F);
}

The pressure can be read by using this program of the pressure sensor.

A distributed pressure sensor array which includes nine individual pressure sensors was attached to the robot’s finger tips. When the robot hand grasps an object, the pressure values of the nine individual pressure sensors can be also read by using the above program of the individual pressure sensor.

Then, the pressure distribution of the robot’s finger tips can be measured by using the values read from the distributed pressure sensor array and using the normalized values of the distributed pressure sensor array.

The program to show the pressure distribution is in the following:
void main()
{
    int i, j;
    float l;
    float E;
    float A;
    float dl[9];
    float F;
    float F[9];
    float S[3][3];

    printf("Measure the variation of the length of every tiny flexible element dl");
    printf("Read the nine pressure values of pressure sensor array:\n");

    for(i=0;i<9;i++)
    {
        F[i]= E*A*dl[i]/l;
    }

    S[0][0]=F[0];
    S[0][1]=F[1];
    S[0][2]=F[2];
    S[1][0]=F[3];
    S[1][1]=F[4];
    S[1][2]=F[5];
    S[2][0]=F[6];
    S[2][1]=F[7];
S[2][2]=F[8];
printf("The nine pressure values of the pressure sensor array is shown:
");
for(i=0;i<3;i++)
{
    for(j=0;j<3;j++)
    {
        printf("%3.1f  ",S[i][j]);
        printf("\n");
    }
}
printf("\nThe normalized values of nine pressure values of pressure sensor
array is shown:\n");
for(i=0;i<3;i++)
{
    for(j=0;j<3;j++)
    {
        printf("%3.3f  ",S0[i][j]/20);
        printf("\n");
    }
}
}

For GraspIt, it is open source software. Its program can be modified for the purpose of
simulation. External programs can be also added into the original programs though an
interface program of GraspIt to do simulations.

The interface program in GraspIt is programmed as follows:

void MainWindow::graspAutoGrasp()
{
    world->getCurrentHand()->autoGrasp(true);

    world->updateGrasps();
The program of the pressure sensor and the pressure distribution of the pressure sensor array were developed in C program, the program of GraspIt is C++ program. Therefore, the program of the pressure sensor and the pressure distribution of the pressure sensor array can be added to the program interface of GraspIt.

4.4 Evaluations of the Used Modelling Software

From the first criterion of evaluation, for Adams and Matlab/Simulink, mechatronic units are available for creating robot hand models, such as in Section 4.2.1 and in Section 4.2.2. GraspIt uses a graphic tool to create the shape of a robot hand. The mechatronic attributes used were added by programming. However, a ready robot hand model was created and stored in GraspIt, so that it can be easily loaded into the work space of GraspIt to do simulations.

From the second criterion, C programs can be connected to both Adams and Matlab/Simulink in principle. However, an interface needs to be developed for each individual application (Zhao, 2009). On the other hand, mechatronics of the links are implemented in a programming language, and GraspIt itself is an open source software. Thus, integration of a C program with GraspIt is straight forward.
CHAPTER 5. SIMULATION AND ANALYSIS

To test the proposed distributed pressure sensor array for the collection of the user responses, a sensor array model was integrated with the model of a robot hand and the passing on object benchmark scenario was simulated.

5.1 Settings

A robot hand model was taken from the GraspIt robot hand bank, as shown in Figure 5.1. The robot hand has a thumb and two fingers. This design is one of the most common designs for a robot hand. It simulates the grasping function of a human hand with a huge simplification.

A distributed pressure sensor array was designed based on the discussion in Section 3.3. It consists of nine pressure sensors which are arranged in a 3×3 array, as displayed in Figure 5.2. The sensor array was attached to one of the fingers of the robot hand model in order for the robot to collect its users’ responses.
A decision-making unit was developed to read the distributed pressure sensor array, to calculate $F(S_{ij})$ and to decide the corresponding actions for the robot. Equation (3.33) and the threshold, $-0.007 \leq F(S_{ij}) \leq 0.007 \ (i = 1, 2, 3, j = 1, 2, 3)$, were used in the unit to decide whether the pressure distributions on the finger of the robot are even. The algorithm is illustrated in Figure 5.3.
A robot passing on an object to its user was assumed as a simulation scenario. Two cases were designed. In the first one, the robot holds an object and presents it to its user. The user, however, does not take over the object. In the second case, after realizing the object being presented to him, the user stretches his arm and holds the object. In both cases, the robot applies test action of slightly releasing the object. It then reads the readings of the sensor array and calculates the distribution features (even or uneven).
5.2 Simulations of the First Case

The first case was simulated as shown in Figure 5.4. The robot hand holds an object and presents it to the user but the user’s hand does not move towards the object.
The initial state is that the robot hand holds the object and the user does not touch the object at all. The values of the distributed pressure sensor array attached to one of the fingers of the robot hand and the normalized values are given in Figure 5.5.

Figure 5.4 Robot hand holds an object.
Then the robot started to apply the test action for the first time. The robot hand released the object slightly and slowly. It read the sensors and normalized the values, which are shown in the top part of Figure 5.6. Then, the robot calculated $F(S_{ij})$ and compared them with the reference values, as shown in the bottom part of the diagram. As most of the values were outside of the reference values, that is, the pressure was not evenly distributed, the robot recognized that the user did not take over the object. The robot grasped the object to prevent the object dropping off from its hand.
Figure 5.6 Results of the first test in the first case.

After the first test, the robot tested the user in the same way for two more times. The results of the second and the third tests are shown in Figures 5.7 and 5.8. As the user did not take over the object in these two tests either, the sensors’ readings are similar to the first test.
This is the second test!

According to the first test, user received the object, robot releases the object slightly and slowly again a little bit more to detect whether user still receives the object or not.

Robot is beginning to detect the value of sensors of nine areas.
The value of nine areas on finger of robot hand:
14.3  15.5  15.2
15.3  16.4  15.8
14.7  16.1  15.1

The normalized value of nine areas:
0.715  0.775  0.760
0.765  0.820  0.790
0.735  0.805  0.755

After calculated by mathematics model
F_{s11}={-0.054}
F_{s12}={-0.006}
F_{s13}={-0.009}
F_{s21}={-0.004}
F_{s22}={-0.051}
F_{s23}={-0.021}
F_{s31}={-0.024}
F_{s32}={-0.036}
F_{s33}={-0.014}

Compare the value which is calculated by mathematics model with the reference value:

most the values are outside of the reference values

According to the comparison, distribution in nine different areas is uneven.
User does not receive the object, robot hand grasps the object again!

Figure 5.7 Results of the second test in the first case.
Simulations of the Second Case

The second case was simulated as shown in Figure 5.9 and Figure 5.10. The robot hand holds an object and presents it to the user. The user stretches his hand and takes over the object.
Figure 5.9  Robot hand holding an object.

Figure 5.10  User hand taking over the object.
The initial state is that the robot hand holds the object and the user does not touch the object. The values of the distributed pressure sensor array attached to one of the fingers of the robot hand and the normalized values are given in Figure 5.11.

![Figure 5.11 Sensor readings of the initial state in the second case.](image)

Then the robot started to apply the test action for the first time. The robot hand released the object slightly and slowly. It reads the sensors and normalized the values, as depicted in the top part of Figure 5.12. It, then, the robot calculated $F(S_{ij})$ and compared them with the reference values, as shown in the bottom part of the diagram. As all the values were inside of the reference values, that is, the pressure was evenly distributed, the robot recognized that the user took over the object.
According to the first test, the robot hand recognized that the user hand has already received the object. However, it needed to release the object a little more to detect whether the user holds the object still. Therefore, the robot hand did the second test.

The result of the second test is shown in Figure 5.13. The robot read the sensors and normalized the values, which are depicted in the top part of Figure 5.13. It, then, calculated $F(S_i)$ and compared them with the reference values, as shown in the
bottom part of the diagram. As all the values were inside of the reference values, that is, the pressure was evenly distributed, the robot recognized that the user took over the object.

Figure 5.13 Result of the second test in the second case.
According to the second test, the robot hand recognized that the user hand has already received the object. However, it needed to release the object a little more to detect whether the user holds the object still. Therefore, the robot hand did the third test. The result of the second test is shown in Figure 5.13. The robot read the sensors and normalized the values, which are depicted in the top part of Figure 5.14. It, then, calculated \( F(S_{ij}) \) and compared them with the reference values, as shown in the bottom part of the diagram. As all the values were inside of the reference values, that is, the pressure was evenly distributed, the robot recognized and confirmed that the user completely took over the object.

![Figure 5.14. Result of the third test in the second case.](image)
5.4 Discussion

The first case of the simulation shows that the robot holds an object and presents it to its user. The user, however, does not take over the object. According to the results of the three tests, most of the values of $F(S_{ij})$ are outside the reference values in every test. Therefore, the pressure is not evenly distributed, and the robot recognizes that the user did not take over the object. The robot grasped the object to prevent the object to drop off from its hand.

The second case of the simulation shows that the robot hand holds an object and presents it to the user. The user stretches his hand and takes over the object. According to the three tests, all the values of $F(S_{ij})$ are inside the reference values in every test. The robot hand needs to release a little more slowly to detect whether the user holds the object still after every test and the robot recognizes that the user completely took over the object which can now be confirmed after the third test.

According to the result of the two cases of the simulation, the user responses to an action test of slightly releasing the object by the robot can be collected by readings of the distributed pressure sensor array and the distribution features (even or uneven) calculated based on the Decision-Making algorithm.
CHAPTER 6. CONCLUSIONS AND FURTHER WORK

6.1 Conclusions

The ARL for service robots is an approach to establish beliefs of their users’ intentions and preferences. This approach allows a robot to perform tests on its users and to build up high-order beliefs according to the users’ responses. This study aims to find a way to arrange pressure sensors on the robot’s figures to recognize its user’s responses to test actions performed in the ARL system. A distributed pressure sensor array consisting of nine pressure sensors arranged in a 3×3 array was designed to attach the fingers to the robot hand in order for the robot to collect its users’ responses to a test action which is releasing an object slightly and slowly.

Whether the pressure distributions on the fingers of the robot which were collected by the distributed pressure sensor array are even decides what was the user’s response to the test action was performed. The robot holds an object and presents it to its user, and applies a test action of slightly releasing the object. When the user does not take over the object at all, the robot can recognize that the pressure distribution is uneven through the readings of the distributed pressure sensor array. Thus, the robot can recognize that the user’s response to a test action is that the user does not take over the object. When the user stretches his arm and holds the object after realizing the object has been presented to him, the robot recognizes that the pressure distribution is even. Then, the robot recognizes the user’s response to the test action and the user takes over the object.
The following tasks have been performed:

- Carried out the experiments using a pressure sensor film which is attached onto the fingers of the robot in the two cases. The first case is that the user does not have intention to take over the glass. The second case is that the user wants and is ready to receive the glass. These results and data of the experiment were obtained to show the relationship between the pressure distributions on the pressure sensor film with the user’s responses.

- Proposed the pressure sensor array model to read the individual pressure readings of nine pressure sensors. The robot can test the user to find out his responses by calculating the pressure distributions based on the readings collected from the sensor array when a robot passes an object on to its user.

- Developed a mathematical model to decide whether the pressure distributions on the robot’s finger tips are even. Obtained a threshold of the mathematical model based on the data of the proposed experiments.

- Compared and evaluated three kinds of the simulation software to model the robot hands: Adams, Matlab and GraspIt.

- Developed a decision-making algorithm to read the distributed pressure sensor array, to calculate \( F(S_{ij}) \) and to decide whether the pressure distributions on the robot’s finger tips are even.

- Designed two cases of the simulation scenario for a robot passing on an object to its user.
All the experiments and simulation results presented in this dissertation show:

- The pressure distribution features on the robot’s finger tips are different (even or uneven) when the user takes over the object which the robot had been holding. When the user does not take over the object at all, the pressure distributions are uneven, when the user takes over the object, the pressure distributions are even.
- The reference values of the threshold that are used for deciding whether the pressure distribution is even or uneven are obtained in this research.
- The GraspIt was identified as the most suitable simulation software for modelling the robot hands in this research by the comparisons and evaluations.
- The pressure sensor array which was used to read the data for calculating the pressure distribution features can be integrated with the robot hand model.
- Two cases in the simulation scenario of a robot passing on an object to its user show that the decision-making algorithm to decide whether the pressure distributions on the robot’s finger tips are even is effective.

6.2 Further Work

In this study, a pressure sensor film attached on the robot’s finger tips to measure the pressure distribution when the robot hand holds an object and presents it to its user was divided to nine areas to calculate the average values of the pressure in different areas. In reality, a film pressure sensor can be divided into more areas, such as sixteen
areas, twenty-five areas, thirty-six areas, even more, or generally $n \times n$ areas. It will make the analysis of the average values of pressure in every area more accurate.

In the experiment in chapter 3 of this study, when the robot hand passes on the glass of water to the user hand, the robot tests whether the user hand takes over the object at five moments (the Initial Moment, the Stable Moment, the Critical Moment, the Sliding Moment, the Dropping Moment). In further work, the robot can test the user in many more moments. Then, the reference value of threshold which can be obtained from the calculation of the results of the experiment will be also more accurate.

For the decision-making algorithm, it only performs three tests in the process of a test whether the user takes over the object or not. It can perform many more tests to shorten the time between the tests to ensure that the robot recognizes the user’s intension promptly.

Two cases in the benchmark scenario simulation are considered in chapter 5. In the further work, many more cases may be required, such as performing the simulations when the user hand receives the object in the beginning, but after the robot hand tests, the user hand opens and does not holds the object. In this case, robot recognises that the pressure distribution in even at first and it will release the object slightly and slowly to test again. Then, as the user hand opens, the robot hand will recognise that the pressure distribution is uneven and it will grasp the object to prevent the object dropping off. The decision-making algorithm can be tested and modified through doing relevant simulations.
In the future, the proposed virtual sensor system which consists of nine pressure sensor should be realized as real equipment for the real experiment. Even, if there were some practical techniques available with which we can mount a million sensor elements in a small space, the sensor system consists of a $n \times n$ pressure sensor. Then, we have optimized how to arrange the sensor system on the real robot fingers to do the experiments.
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