



Some Placeholder Title

A Master Thesis

written by

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The code for this project is available at
https://github.com/vmstavens/in_hand_pose_estimation

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Abstract

Some abstract text explaining the goal, methods and conclusion of the project.

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Acronyms

AEBM analytical elasticity-based models.

cobots collaborative robots.

CP correspondence problem.

CV computer vision.

DL deep learning.

DOF degrees of freedom.

EE end effector.

EFM elastic foundation models.

FEM finite element models.

HF hard finger.

IEP Inverse Elasticity Problem.

MIM Matrix Inversion Method.

PE pose estimation.

PNP pick-and-place.

PwoF point-contact-without-friction.

SF soft finger.

SOTA state of the art.

Terms

collaborative robots (cobots) are robots which facilitate human-robot collaboration [1].

computer vision (CV) is a field of artificial intelligence (AI) that enables computers and systems to derive meaningful information from digital images, videos and other visual inputs - and take actions or make recommendations based on that information [2].

correspondence problem (CP) is the problem where one aims at finding correspondences between the pixels in two (or more) images [3].

deep learning (DL) are methods which allow computational models that are composed of multiple processing layers to learn representations of data with multiple levels of abstraction [4].

end effector (EE) is a generic term for all functional units involved in direct interaction of the robot system with the environment or with a given object [5].

manipulator : A serial robot mechanisms. The robot manipulator is represented by a serial chain of rigid bodies, called robot segments, connected by joints [6].

pose estimation (PE) A particular instance of feature-based alignment, which occurs very often, is estimating an object's 3D pose from a set of 2D point projections. This pose estimation problem is also known as extrinsic calibration [7].

Chapter 1

Introduction

1.1 Context

As of 2022 most of the industrialized world has developed tools for unprecedented growth in wealth and technology on a global scale [8, Chapter 4]. In such times a great deal of consumerism and interconnection is present with people needing products produced faster and more consistently than ever before [8, Chapter 4]. As one would expect, this creates a high demand for manufacturers to reliably and consistently provide products, while also remaining flexible as the demand for different product change rapidly. In order to accommodate the need for ever greater volumes of products, consistent, reliable and flexible labor is essential in assembly, transport and manipulation processes in the production pipeline. Due to these types of manual labor being largely done by unskilled workers, automation alternatives are being adopted which provides benefits [8, Chapter 4]. This different approach to manufacturing has been labeled the fourth industrial revolution or i4.0 for short. The beneficiaries being the employer and employee, with the employer having the benefits: Avoid paying monthly salaries to unskilled laborers doing manual tasks, here the automation alternative only requires electrical energy and potential supervision by few qualified individuals. Potential risks are also involved when hiring humans as the workforce can be inconsistent due to human error [9] or left out due to illness etc. Considerations with regards to workers rights such as working conditions and wage also needs not to be considered. Workers furthermore cause production limitations in the form of stand still hours, such as bathroom and lunch breaks along with after work hours and holidays. This replacement of manual labor also potentially benefits the employee, as boring and physically wearing work is automated, enabling the employees to take on different and less wearing and potentially dangerous roles. While the issue of labor unemployment becomes apparent solutions which provide support to already hired workers have been developed, such as collaborative robots (cobots) [10] which would negate this problem.

When implementing automation of production lines using robotics, certain categories of problems are revealed. These include: Assembly, alteration and pick-and-place (PNP), the last being the one of interest in this project.

1.2 Problem Description

Pick-and-place manipulators are used in a wide variety of different fields such as sorting of waste [11] handling of food [12] [13] and factory bin picking [14] [15] [16]. The solutions in these industries are examples of subcategories under the PNP problem, namely sorting and bin picking. Since both of these are subcategories of the PNP problem, they fundamentally follow the same sequential four phases from start to end. These phases being pre-grasping, grasping, transport, and placement [15] for traditional implementations of the PNP pipeline. The pre-grasp phase involves localizing the object(s), potentially estimating their pose and executing the trajectory to move the end effector (EE) grasp, collision free to said object(s). Here different potential grasps can be considered in order to determine the best pose for the EE. In the grasping phase the EE grasps the object in such a manner that the object's entire weight is supported by the EE, and ends when the object no longer is in contact with the environment, which often is the container holding the object. The transportation phase involves the motion of the manipulator to move from the pose achieved after the grasping phase, to a pose ready for placement of the object in the desired placing area or fixture. Here considerations may be needed with regards to how much force and torque the EE's grasp can tolerate while moving without losing the object. Finally the goal of the placing phase is to place the object within

the placing area or fixture in a desired end pose. Here the constraints on the end pose might differ significantly based on the application, as the pose of greens in a crate might need less precision than if the manipulator hands a bolt to the another robotics system in the pipeline.

While these phases make up a traditional PNP systems, certain assumptions are made regarding the objects of interest in order for this pipeline to function. Specifically the localization and pose estimation (PE) of the pre-grasp phase are assumed possible due to either ensured object poses or estimated poses through computer vision (CV) sensory system. Due to CV being a mature research field a wide range of solution proposals to these problems have been generated [17]. These include classic vision [18] [19], deep learning based [20] and combinations of these [21]. However, while these may be sufficient for certain tasks they fundamentally suffer from the weaknesses introduced by vision techniques. These being a great number of outliers caused by: occlusions, reflecting, transparent or homogeneous surfaces, and repetitive structures when solving the correspondence problem (CP). Within factory settings the common ones are transparent and reflective objects, due to metallic, plastic and glass product often being the materials used. While deep learning (DL) solutions have been developed for both for reflective [22] and transparent [23] objects, these are use case specific and show limited results in a wider range of applications.

This project suggests a different PNP pipeline for cases where the object's starting pose is unknown. In this PNP pipeline the PE is moved from the pre-grasping phase to a new phase between the grasping and transportation phase, called the PE phase. The specific goal of this project is to develop a solution to this phase using tactile sensors in the EE to determine the object's pose. By using the tactile sensing rather than visual the problems presented above will be eliminated. This will be done using a humanoid gripper as the EE with tactile sensors in each finger, more specifically a Shadow Dexterous Hand [24] with 20 degrees of freedom (DOF).

The alternative pipeline this project will enable can be seen in the upper row of Fig. 1.1 compared to the traditional pipeline in the lower row.

In Fig. 1.1(a) the pre-grasping phase can be seen for both pipelines. Here the traditional pipeline in cases of multiple objects often will employ custom finger tips or grippers entirely to facilitate form closure grasps, due to the grippers not having the flexibility to perform reliable force closure. On the contrary force closure can be performed with a humanoid gripper on a wide range of object with no need for changing gripper equipment.

In Fig. 1.1(b) the grasping phase can be seen which introduces a greater level of complexity when using the suggested pipeline due to the humanoid gripper being a more complex physical system to represent and control. This is compared to the simplicity of executing potential binary commands in the traditional pipeline e.g. open and close.

In Fig. 1.1(c) the transportation phase can be seen, which introduces one of the benefits with using the suggested pipeline. Here through tactile sensors in a humanoid gripper can pose estimate the object and manipulations can be performed to change the objects pose such that easier placement can be performed in the following phase. This form of object manipulation is not feasible for the simple pneumatic grippers used in a traditional pipeline.

In Fig. 1.1(d) the placement phase can be seen, which demonstrates the result of the previous phase, as the traditional pipeline now has to change the grip about the object in order to properly place it in the socket, while the humanoid gripper simply can insert the part, as it is already oriented properly.

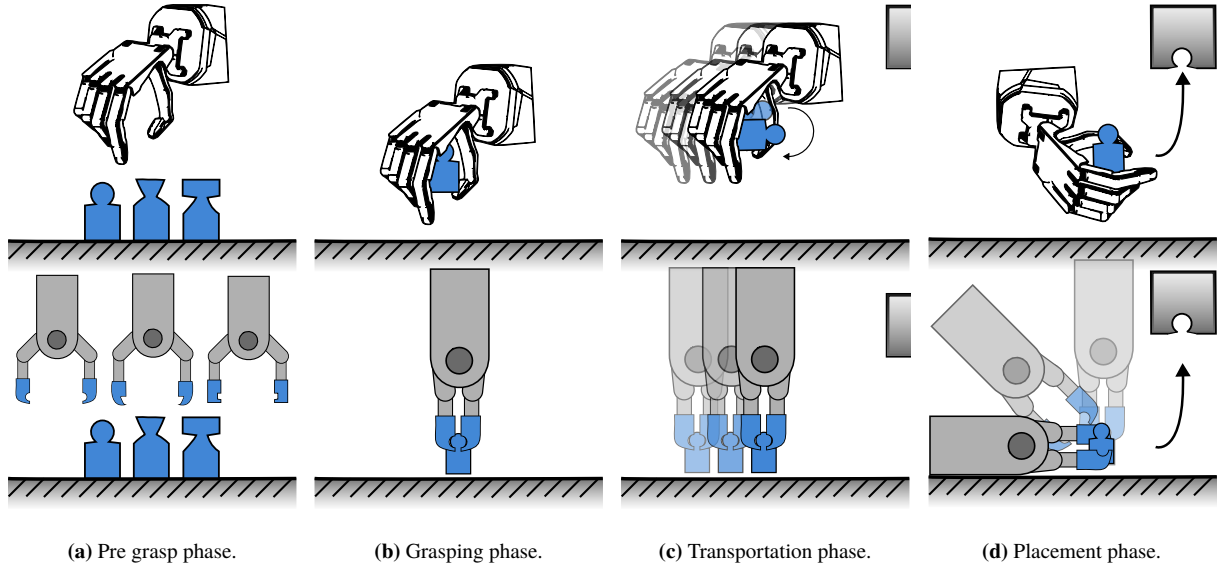


Fig. 1.1: A comparison between the traditional and suggested PNP pipeline.

In order to solve this PE problem, three sub problems are identified and labeled problem 1, 2 and 3.

Problem 1 involves modeling the contact between the gripper's tactile sensors and the object, also referred to as tactile perception.

Problem 2 is to convert the collected data from problem 1 to estimated pose candidates.

Problem 3 involves in-hand manipulation. Since the initial grasp of the object might not be oriented in a manner where the recognizable features make context with the tactile sensors, manipulating the object within the EE's grasp will enable further information gathering. Thus the final problem is to control the EE in such a manner that the tactile sensors make context with the object in intelligently decided areas for a better pose estimate.

To test if the developed system successfully solves the PE problem, it is hypothesized that the intelligent probing method provides a statistically significant faster average PE convergence, along with a statistically significant greater success rate when determining the correct pose. A correct pose is here defined as the pose being greater than or equal to 95% of the ground truth pose, and statistically significant is defined by an α -level of 95%. This hypothesis will be referred to as H_1 , while the null hypothesis H_0 being that there is no statistically significant difference between intelligent and random probing's PE performance as described above.

1.3 Thesis Overview

To present the work done in this project, the system modeling is done in Chapter 2 and state of the art (SOTA) is presented in Chapter 3 for each of the problems presented above. Here the solutions best suited for this project's gripper are chosen. Each solution is described in detail, how they are applied, their performance tested and finally evaluated and conclude upon in their respective chapters i.e. chapter Chapter 4, Chapter 5 and Chapter 6. In Chapter 7 the three methods are combined in the final integration and finally the project is discussed and concluded upon in Chapter 8 and Chapter 9 respectively.

Chapter 2

Modeling

In order to model the contact between the EE's tactile sensors, eight different model categories are present [25] whereas three most common ones within the field of robotics [26, Chapter 37] are point-contact-without-friction (PwoF), hard finger (HF) and the soft finger (SF) model as shown in Fig. 2.1.

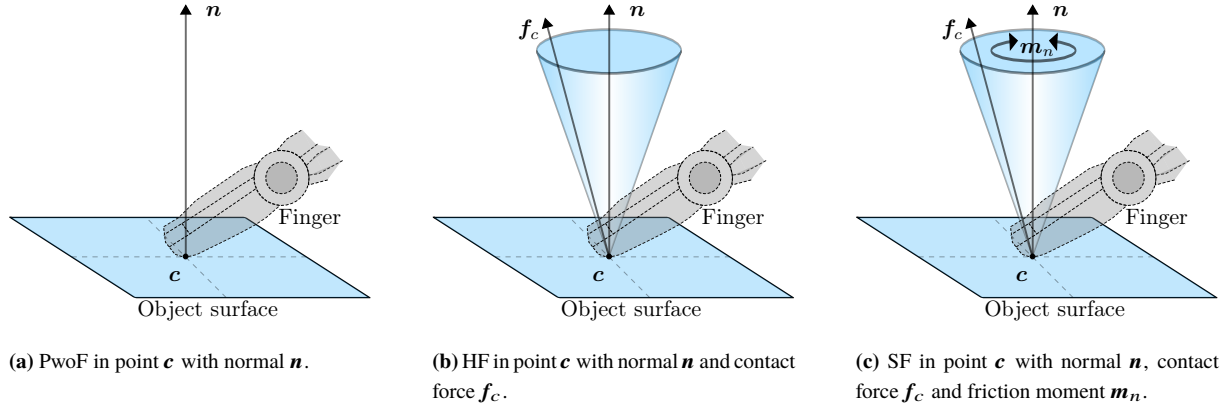


Fig. 2.1: The three most commonly used contact models.

The PwoF model, as shown in Fig. 2.1(a), can only represent forces along with the normal of the object's surface at the point of contact and thus the model does not support surface deformations between the two contacting objects. This model is applied in cases where very little deformation is present, along with the contact having a friction coefficient approximately equal to zero [26, Chapter 38].

The HF model, as shown in Fig. 2.1(b), is representative when the friction between objects is great enough to be significant, while the contact deformation is small enough to ignore friction moments and deformations [26, Chapter 38]. To model the friction acting on the contact point a great number of methods exist, a very common one being the Coulomb friction with different modifications depending on the use case [27]. Since this model is described in terms of a Coulomb friction, the friction cone $C_{f, \text{HF}}$ can be mathematically formulated as

$$C_{f, \text{HF}} = \{ f_c \mid f_t \leq \mu f_z, \mu f_z \geq 0 \} \quad , \quad f_t = \sqrt{f_x^2 + f_y^2}, \quad (2.1)$$

where f_c is the magnitude of the contact force, f_t is the magnitude of the tangential force, f_x , f_y and f_z are the magnitudes of the x , y and z components of the contact force and μ is the friction coefficient [26, Chapter 37]. The angle of the cone β can be computed based on μ as

$$\beta = \tan^{-1}(\mu). \quad (2.2)$$

The SF model, as shown in Fig. 2.1(c), is used to represent scenarios where both friction and surface deformations are great enough to be impactful in the systems behavior. Due to deformations of the finger an additional torsional moment about the contact normal will be present [26, Chapter 38]. While an analytical formulation for the SF relation depends on the pressure distribution inside the contact, and can only be derived for a limited number of special cases, the general case is approximated using

$$C_{f, \text{SF}} = \left\{ f_c \mid f_t^2 + \frac{m_n^2}{e_n^2} \leq \mu^2 P^2 \right\} \quad , \quad f_t = \sqrt{f_x^2 + f_y^2}. \quad (2.3)$$

This formulation forms an ellipsoid $C_{f, \text{SF}}$ describing the relation between the tangential force f_t and friction moment m_n . Here f_c is the magnitude of the contact force, f_t is the magnitude of the of the tangential force, m_n is the magnitude of the frictional moment, e_n is the eccentricity parameter i.e. the height of the aforementioned ellipsoid, μ is the friction coefficient and P is the magnitude of the load applied from the contact point along the contact normal \mathbf{n} [28] [29].

Based on the contact model categories described above, the most representative is the SF models since these can provide descriptions of the contact surface topology, and thus enable the reconstruction of the contact shape from the application of a force distribution [30] i.e. the Inverse Elasticity Problem (IEP). Furthermore friction is crucial in order to manipulate objects in-hand, which is also provided by these models. An illustration of the system as a SF with friction cone and pressure distribution can be seen in Fig. 2.2, while Fig. 2.3 shows the model enabling force closure i.e. the composite wrench cone contains the entire wrench space, so that any external wrench \mathbf{w}_{ext} on the body can be balanced by contact forces [31].

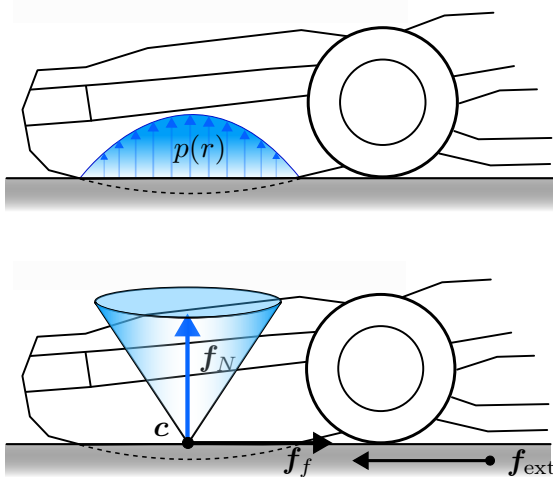


Fig. 2.2: Contact pressure distribution and friction cone for a SF model in the context of a robotic finger.

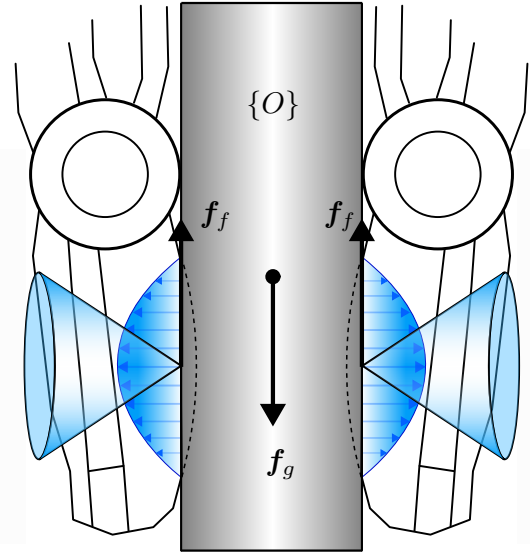


Fig. 2.3: Contact pressure distribution and friction cone causing force closure to prevent the object $\{O\}$ from falling due to gravity.

When modeling the kinematics of a humanoid gripper with frame $\{H\}$ in world frame $\{W\}$ interacting with an object with frame $\{O\}$ the different parameters and modeling is necessary. In this system the object with position $\mathbf{p} \in \mathbb{R}^3$ and pose $\mathbf{u} \in \mathbb{R}^6$, with the orientation either being represented as a four dimensional quaternion or a three dimensional Euler angle, makes contact with the gripper in points \mathbf{c}_i . Said contact points has have frames $\{C_i\}$ with axes $\{\mathbf{n}_i, \mathbf{t}_i, \mathbf{o}_i\}$, where \mathbf{n}_i points perpendicular to the contact plant towards the object while the remaining are contained within the contact plane. The twist of $\{O\}$ described in $\{W\}$ is denoted $\mathbf{v} = [\mathbf{v}^\top \ \boldsymbol{\omega}^\top]^\top$ while the wrench is $\mathbf{w} = [\mathbf{f}^\top \ \mathbf{m}^\top]^\top$

The gripper has n_q joint named $\mathbf{q} = [q_1, q_2, \dots, q_{n_q}]^\top \in \mathbb{R}^{n_q}$ with loads $\boldsymbol{\tau} = [\tau_1, \tau_2, \dots, \tau_{n_q}]^\top \in \mathbb{R}^{n_q}$ About the object $\{O\}$, where the external force is represented as gravity which is a common occurrence.

Within these figures $p(r)$ is the pressure distribution often as a function of the contact surface's radius r assuming a non-conforming contact case. f_N is the normal force of the object acting on the EE in the contact point \mathbf{c} , f_f is the friction force opposing the external force \mathbf{f}_{ext} which often comes in the form of gravity \mathbf{f}_g as seen in Fig. 2.3.

With the contact model described, a segment of the kinematic tree of the EE can be seen in Fig. 2.4. Here q_{thi} is the angle of the i 'th joint in the thumb which here is the only finger depicted, τ_{thi} is the torque exerted by said joint,

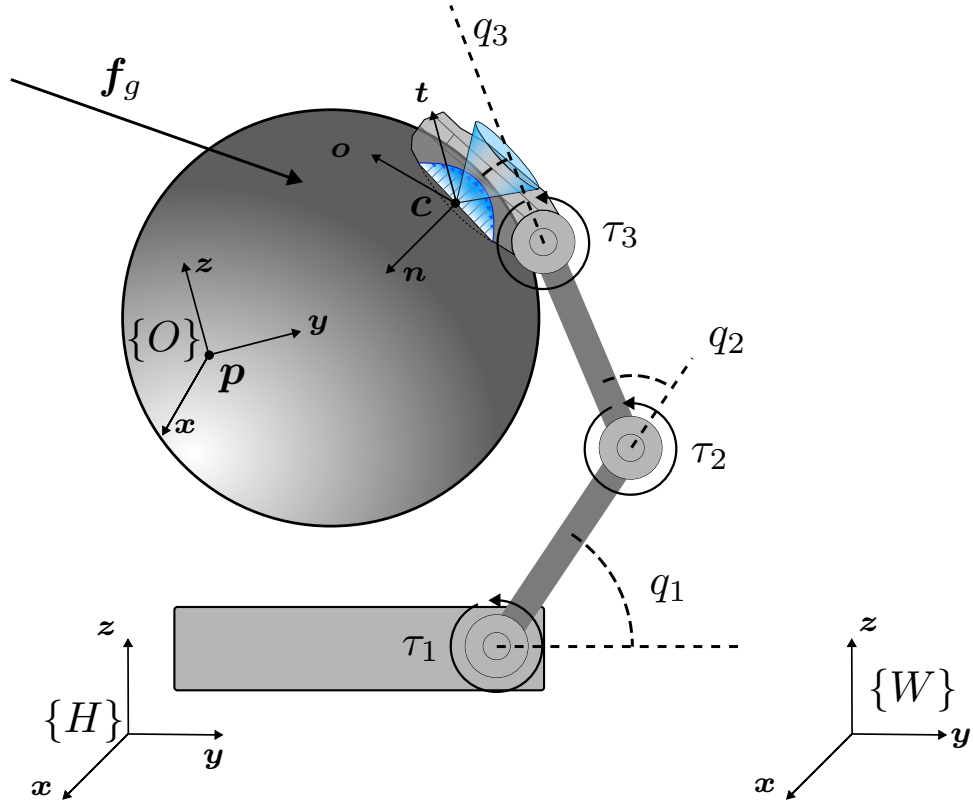


Fig. 2.4: The model of the world representation for this project.

$\{W\}$ is the world frame, $\{O\}$ is the object's frame and $\{H\}$ is the robotic hand's frame. While only a single finger here is illustrated the naming conventions and representations simply scale to all the EE's DOFs.

To determine which methods best describe the models presented above for this project, the SOTA will be presented in Chapter 3.

Chapter 3

State of the Art

3.1 Problem 1 - Tactile Perception

Based on the contact model categories described above, the most representative is SF since these can provide descriptions of the contact surface topology, and thus enable the solving of the IEP by deriving surface features for pose estimation. Furthermore these represent friction forces and moments which are needed in order to manipulate objects in-hand and ensuring force closure.

Within the category of SF models a method fit for this project's use case is to be chosen to solve problem 1. SF models can furthermore be divided up into three different categories: analytical elasticity-based models (AEBM), elastic foundation models (EFM) and finite element models (FEM) [32].

AEBM are theoretical formulations of elastic contact areas and the stresses on both the surfaces and the sub-surfaces of the contacting bodies. These types of formulations however are often restricted to describing simple contact geometries. The first of such models was introduced by Heinrich Rudolf Hertz in 1882 [33] and is still used for simple contact cases. In the formulation of the Hertzian contact model two assumptions are made: Objects in contact are made of linear elastic materials and only small contact deformations occur compared to the dimension of object. However, robotic EE fingertips are often made of nonlinear elastic materials and for that reason the Hertzian contact model does not represent the type of contact in this project [26, Chapter 37]. To improve on the Hertzian model, a more generic formulation can be made which extends the model from linear to nonlinear elastic contacts [34] [35]. This power-law formulation subsumes the Hertzian contact theory while assuming a circular contact area. Other models have been purposed which combine the descriptions of both friction-contact and the shear-torsion as experienced by the bodies [36].

However, in order to more accurately describe the contacts involving robot fingers, viscoelastic soft contact model appear more relevant due to such fingers often being made of materials which show viscoelastic properties e.g., rubber, silicone and polymers. Simple models such as Kelvin-Voigt's [37] and Maxwell's [38] models describe the interaction between strain and stress as a spring damper system in a serial or in a parallel configuration respectively. Models which expand on this idea describe the reacting force as the product of the temporal and the elastic response, while incorporating previous stress responses [39]. To simplify this formulation alternatives have been developed to assume no past stress [40] [41] [42]. Upon these, more modern techniques have been developed which have seen use in similar use cases as the ones of interest in this project. One method attempts to expand the description of contacts between rigid indentors and elastic half-spaces, using the Matrix Inversion Method (MIM) as introduced by Kalker [43], to viscoelastic half-spaces as well. Assuming the surfaces are frictionless, the relationship is described in terms of the pressure distribution, the resultant force on the indenter and the penetration [44]. Attempts involving solutions to Boussinesq's problem for polynomial pressures acting over polygonal domains [45] have also been developed and modernized by combining it with Cerruti's solution [46]. However due to numerical singularities being present, modifications are made to threshold the model. For a more complete description without singularities, Love's formulation has been added leading to a more accurate analytical representation but with the cost of an increased computational complexity [47]. In order for these Boussinesq based approaches to be representative two assumptions are made 1) There exists a linear relation between stress and strain, referred to as deformation, and 2) strains are infinitesimal [48, Chapter 6].

EFM are methods developed to build upon AEBM by allow a simple discrete contact calculation in more general

surface geometries. Here the deformable part of the contact as a layer over a rigid base is modelled along with a series of discrete and independent springs in the contact normal. A widely used example of this method is the Winkler's elastic foundation model [49], which have been used structural engineering for modeling different properties of beams such as stability [50], vibrations and buckling [51]. Other EFM methods have shown accurate modeling performance when applied within the field of medical engineering. Here a comparative study between AEBM, EFM and FEM demonstrate the suggested modified EFM performs better than the alternatives in 3D knee models when predicting prosthetic knee performance [32]. A different method attempts to attain vivo contact pressure predictions for improved knee replacement designs [52] Within the field of robotics EFM have provided solutions to problems such as slip [36], compliance, sliding [53] [28], stiffness and contact mechanics [54] of humanoid grippers. One such method derives friction constraints based on general expressions for non-planar contacts of elastic bodies, where the local geometry and structure of the objects in contact are taken into account. Using these, a linear complementary problem is formulated and solved, resulting in the normal and frictional forces applied at each contact, as well as the relative velocity of the bodies involved [29].

FEM are popular general tools for solving PDE [55] and have seen contact applications in a wide range of engineering discipline due to the assumptions made in AEBM and EFM not being applicable in these cases. A great number of these cases exist within the manufacturing industry [56] whereas one example is the metal forming processes. Specifically the the estimation of wheel rail profiles [57] has been addressed using FEM due to the estimation of contacts over a greater surface is needed than what is assumed in AEBM and EFM. Other applications such as quality control through sliding wear estimation [58], analysis of the responses of fully coupled thermo-elasto-plastic solids in contact [59] and performing diagnostics of failures in induction motors [60]. Due to the complexity of modeling the contacts within robotics, FEM have become a popular choice and enabled tactile applications such as cobots tactile skin for ensuring collaborative behavior when in contact [61], performance estimation of new tactile sensor technologies [62] and evaluating complex contact types by extending simulations and analysis systems [63]. The modelling complexity has furthermore inspired using FEM as ground truth results when synthesizing machinelearning data in simulations for deep learning models, which has enabled execution speeds 75 times greater than simply evaluating FEM [64] [65] [66].

The contact model chosen for this project is the AEBM Love's formulation due to its capabilities of representing contact surface displacements with great precision [47].

3.2 Problem 2 - Pose Estimation

3.3 Problem 3 - In-Hand Manipulation

Chapter 4

Tactile Perception

4.1 Introduction

Here we write the introduction for problem 1.

4.2 Related Work

Here we cite the related work by `\cite{source-label}` like this [67]

Chapter 5

Pose Estimation

5.1 Introduction

Here we write the introduction for problem 2.

5.2 Related Work

Here we cite the related work by `\cite{source-label}` like this [67]

Chapter 6

In-Hand Manipulation

6.1 Introduction

Here we write the introduction for problem 3.

6.2 Related Work

Here we cite the related work by `\cite{source-label}` like this [67]
For history see hand book of robotics chapter 38, the first section.

Chapter 7

System Integration

7.1 Introduction

Here we write the introduction for the system integration.

Chapter 8

Discussion

Chapter 9

Conclusion

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Appendix A

Appendix A Title
