A ROBOTIC GRIPPER FOR HANDLING NON-RIGID PRODUCTS

Paulo Augusto Ferreira de Abreu

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A ROBOTIC GRIPPER FOR HANDLING
NON-RIGID PRODUCTS

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ABSTRACT

Current-day robotic handling applications include a wide variety of production operations, from material transfer and machine loading to assembly and inspection tasks. These industrial applications are typically confined to work in structured environments with products presenting rigid behaviour. To increase the scope of robotic handling applications to a broader range of situations will require intelligent robotic systems embodying sensing capabilities and dexterous mechanisms, able to perform complex manipulation tasks, operating in less well defined environments and dealing with products presenting variable or unknown characteristics.

This research is concerned with the enlargement of robotic handling applications by focusing on the development of robotic grippers capable of handling non-rigid products. The research began by the identification of broad categories of non-rigid products based on industrial handling requirements. A reference architecture for a handling system suitable for dealing with non-rigid products, proposing the integration of perception, grasping and manipulation functions, is then presented.

After looking at the complexities of the behaviour of non-rigid products and establishing the requirements for the development of robotics grippers, the concept of a novel modular gripper is proposed. A prototype of the gripper was then built. It is a finger-type gripper, equipped with a range of sensors to measure finger position, force and contact force, capable of implementing different grasp configurations, controlling the grasp forces and performing in-gripper manipulation. The gripper is suitable for dealing with classes of non-rigid products having bar shape, with the products presented in discrete or continuous form. The sensing systems employed, including a special built tactile sensor, and experimental results of the control strategy used, are presented.

The kinematic analysis of robotic mechanisms is reviewed and applied, together with the analysis of the workspace, to the design and choice of possible configurations for a finger and for a gripper. The kinematic model of the gripper is used for planning and simulating the manipulation of products within the gripper. The simulation results of the manipulation of a rectangular and circular shaped product are presented. A static force analysis of the manipulation is performed, enabling the identification of grasp configurations that can achieve stable grasps.

The developed gripper is used to test and to demonstrate a set of techniques and procedures that are examples of the operational functions that a robotic handling system suitable for non-rigid products must provide. The perception procedures implemented were the identification of product size, of compliance and of product profile. The experimental results showed the gripper to be fully functional and it was possible to identify, measure and control the deformation of products presenting different degrees of stiffness.
DEDICATION

To my mother
ACKNOWLEDGEMENTS

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Finally, I am grateful to my mother and sister for their unquestioning support and who patiently accepted the fact that I could not give them the deserved attention.
AUTHOR'S DECLARATION

The accompanying dissertation entitled “A ROBOTIC GRIPPER FOR HANDLING NON-RIGID PRODUCTS” is submitted in support of an application for the degree of Doctor of Philosophy in Engineering at the University of Bristol.

The dissertation is based on independent work by the candidate - all contributions from others have been acknowledge fully within the dissertation. The supervisors’ contributions were those normally made in a British University. The views expressed within the dissertation are those of the author and not of the University of Bristol.

None of the work has been, or is being, submitted for any other degree or diploma to this or any other institution. A part of this work has formed the basis of two conference papers.

I hereby declare that the above statements are true.

(Paulo Augusto Ferreira de Abreu)

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NOMENCLATURE

\{,\} coordinate frame notation
\mathbf{x} vector (bold and small capital)
\mathbf{A} matrix (bold and capital)
\mathbf{A}^T, \mathbf{x}^T the superscript $^T$ indicates transpose of, matrix or vector
det \mathbf{A} determinant of matrix \mathbf{A}
diag[\ldots] diagonal matrix
\mathbf{1R}_2 Rotation transformation matrix between frames \{1\} and \{2\}
\dot{f} the superscript $\dot{}$ indicates the time derivative of \( f \)
\| \mathbf{x} \| Euclidean norm of vector \mathbf{x}
\mathbf{A} \bullet \mathbf{x} • indicates matrix-vector product
\mathbf{A} \times \mathbf{B} \times indicates matrix multiplication
| a | absolute value of scalar variable a
m_1n_1, \mathbf{m}_1 \cdot \mathbf{n}_1 scalar multiplication of \( \mathbf{m}_1 \) by \( \mathbf{n}_1 \)

a radius of the carrier
b radius of the roller
\mathbf{B} contact constraint matrix
d distance between centres of joints of the carriers
D viscous damping constant
d_r distance between centre of carrier joint and base frame
e radius for locating the centre of rotation of the carrier
\mathbf{F} force
\mathbf{f} force vector
\mathbf{F}_c contact force
\mathbf{G} grasp matrix
\mathbf{\hat{g}}(q) estimated gravitational joint torque
\mathbf{h} generalized force vector applied at the contact points
\mathbf{i}_a armature current in a DC motor
\mathbf{J} Jacobian matrix
\mathbf{K} stiffness constant
\mathbf{K}_d damping matrix
\mathbf{K}_p stiffness matrix
\mathbf{K}_q joint stiffness matrix
\mathbf{K}_s spring stiffness

xx
\( K_r \) proportionality constant, relating torque and armature current in a DC motor
\( l_g \) grasp gap
\( l_{gn} \) nominal grasp gap
\( l_r \) length of the roller
\( m \) mass
\( p, r, x \) position vectors
\( p_{mn} \) position vector defined from contact point \( P_m \) to contact point \( P_n \)
\( P_n \) contact point of finger \( n \)
\( q \) joint vector
\( R_a \) armature resistance in a DC motor
\( T_m \) torque produced by a DC motor
\( u \) torque vector
\( v \) linear velocity vector
\( V \) generalized velocity matrix
\( \tilde{x} \) position error vector

\( \alpha \) angle of rotation of the carrier
\( \beta \) angle of rotation of the roller
\( \epsilon \) angle between coordinate frames
\( \Delta \) transformation operator
\( \delta q \) joint displacement vector
\( \delta F \) variation of force
\( \delta x \) displacement in \( x \) axis
\( \eta \) efficiency of gearbox
\( \phi \) angle between carrier and grasp direction
\( \phi_{\text{min}} \) angle between carrier and grasp direction that minimizes the condition number of \( J^T \) of a finger
\( \lambda \) generalized force vector acting on the object
\( \nu \) contact velocity vector
\( \theta \) orientation angle
\( \rho_{pn} \) nominal diameter of reference product
\( \tau \) joint torque vector
\( \omega \) angular velocity vector
\( \zeta \) angle for locating the centre of rotation of the carrier
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
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<td>AD</td>
<td>analogue to digital</td>
</tr>
<tr>
<td>DA</td>
<td>digital to analogue</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DoF</td>
<td>degrees of freedom</td>
</tr>
<tr>
<td>EP</td>
<td>exploratory procedure</td>
</tr>
<tr>
<td>NRP</td>
<td>non-rigid product</td>
</tr>
<tr>
<td>PRE</td>
<td>piezo resistive elastomer</td>
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1 INTRODUCTION

1.1 SCOPE AND AIMS OF RESEARCH

Current-day robotic handling applications include a wide variety of production operations, from material transfer and machine loading to assembly and inspection tasks. All of these tasks involve the manipulation of objects by grasping, holding and moving from one location to another. These industrial applications are typically confined to work in structured environments. The objects are normally rigid products with known and invariant characteristics and auxiliary tools and equipment are used to support and configure the specific operating conditions. This is well illustrated through the careful planned environment found in a robotic station and through the employment of customized robotic grippers.

To increase the scope of robotic handling applications to a broader range of situations will require robotic systems able to perform complex manipulation tasks, operating in less well-defined environments and dealing with products presenting variable or unknown characteristics. This requires intelligent robotic systems embodying sensing capabilities and dexterous mechanisms, capable of acquiring information on unknown products and environments, and using this knowledge to make autonomous decisions in planning handling strategies to implement the required handling tasks.

This research focuses on the enlargement of robotics handling applications with the emphasis on non-rigid products - NRPs - and on robotic grippers. Rather than concentrating on specific products and deducing the form of appropriate dedicated robotic grippers, a broad approach is adopted to identify the techniques appropriate to a range of NRPs. First it has been necessary to identify broad categories of non-rigid products based on industrial handling requirements. In this research this has led to a dexterous robotic gripper with the methodologies and techniques for
designing and using a robotic handling system. These are presented with results from experimental trials.

The scope of the thesis is covered by the following aims:

- to review current robotic handling applications and identify research opportunities
- to examine non-rigid products as a potential area for the enlargement of robotic handling applications
- to generate ideas for a new generation of robotic handling system and to propose a reference architecture for a system dedicated to non-rigid products
- to produce a novel robotic gripper for demonstration purposes that is capable of tactile perception, grasping and manipulation tasks for a range of non-rigid product types
- to use the experimental gripper to test and demonstrate a set of techniques and technologies to incorporate in robotic handling systems
- to discuss the obtained results with the implication on design requirements set by properties of non-rigid products.

There are six chapters within this thesis which contain the key topics of this research. Within Chapter 1, the introduction, robotic handling systems are reviewed, research opportunities identified, non-rigid products classified and their handling behaviour discussed, and an appropriate architecture for a robotic handling system presented. Chapter 2 reviews current robotic grippers and presents the concept for a novel gripper. Chapter 3 contains the kinematic analysis of the gripper and reviews the basic kinematic theory related to the performance of robotic systems. Chapter 4 presents the prototype of the gripper that was built and describes its constitutive elements, with particular emphasis on the sensing systems and control. Chapter 5 contains the implementation of basic techniques and methodologies and gives the experimental results of the performance trials. The review of results and conclusions are contained within Chapter 6.
1.2 INDUSTRIAL ROBOTIC HANDLING SYSTEMS

Industrial robotic handling applications involve mainly positioning and orientating single discrete products. Typically, it is the robot arm, rather than the gripper, that manipulates the product. The product remains at rest relative to the gripper and it is the movement of the robot arm that produces the desired movement of the product. The characteristics of the products such as shape, size and material properties are known and remain unchanged during the handling task. This assumes that products have a typical rigid behaviour during the handling task. This behaviour coupled with low manipulation needs within the gripper enables deployment of grippers with simple mechanical configurations, low flexibility and limited sensing capabilities. This approach is a cost effective solution for long production runs with consistent products. It cannot cope easily with variability, ruling out a large proportion of industrial handling operations from the benefits of automation. The characteristics of many products in food vary considerably within a batch (Khodabandehloo, 1990). In other cases, as in assembly operations, there may be a requirement to sense, control and to adapt to the interaction between the product being handled and the other external objects. This may require the use of sensing systems, the capability to control the grasp forces and to perform manipulation within the gripper. The current approach to automation of industrial handling tasks often leads to the need for a large auxiliary equipment overhead to control both product and environment. This is costly for rigid products. For non-rigid products the cost would be prohibitive particularly as the solution would be applicable to only the one designated task. A different or even a similar task would require changes in the hardware, software and set up.

Increasing computational speeds now provide the opportunities to move towards autonomous and general purpose handling systems able to deal with products presenting complex handling behaviour (Brett et al., 1991). These systems will need to employ:

- the use of sensors and automatic interpretation methods to measure and monitor product behaviour and environment conditions
• the use of more dexterous grippers capable of dealing with the wide range of products and able to select automatically and implement different grasp conditions

• the integration of the manipulation performed by the robot arm with the manipulation performed within the gripper

• the use of control systems to automatically plan and implement these handling tasks.

1.3 NON-RIGID PRODUCTS

1.3.1 Concept of non-rigid products

One area of enlargement of robotic handling applications will result from the capability to deal with products whose physical and mechanical characteristics can vary substantially and present complex handling behaviour, in particular food and agriculture (Brett et al., 1990).

To simplify the description of static and dynamic behaviour of real products, it is common to use the concept of a 'rigid body': "the distance between any two particles of the body is constant with time and independent of the action of external forces" (in Freiberger, 1960). Considering this mathematical abstraction it is possible to regard the non-rigid behaviour of a product associated with the occurrence of mechanical deformation. The mechanical deformation corresponds to a change in the shape or in the physical dimensions of the product. It results from a conjunction of different factors, from the applied forces to the environment conditions and the material properties. Thus, the non-rigidity of a product must be seen in the context of the specification of the handling task. A product is considered non-rigid where deformations can take place during handling and are large when compared with positional tolerances required for the task.
Examples of non-rigid products are found in many different types of industries: sheets of pre-pregs in the aerospace industry, fabrics in the textile industry, car trims in the automobile industry, fruit in the agricultural sector, meat and dough-like products in food preparation and packaging.

1.3.2 Classification

The concept of non-rigid products taking into consideration product, environment and handling characteristics covers a wide variety of products. Rather than focus on specific non-rigid products and specific tasks, a broad ranging strategy is adopted and classes of non-rigid products defined with a view to the development of gripping devices. After consideration of handling and gripping needs in tasks involving non-rigid products across several sectors of industry - automobile, aeronautics, textile, food packaging - it is concluded that a way to characterise non-rigid products is through geometry. Three basic classes, based on the geometrical aspect of the products, emerge (see Figure 1.1). These are: Bar type, Sheet type and Bulk type. Bar products are further divided into two classes, regular and irregular, according to the cross section. Regular bar type products have constant section - examples of this type of products are cylindrical or prismatic bars, such as rubber tubes, electrical wires or steel cables, cords of explosive materials and pastry products. The same type of sub-classification can be applied to the other classes. Examples of regular sheet type products include sheets of composite materials and pre-pregs, metal sheets, fabrics and slices of meat, fish or bread.

The proposed classification of non-rigid products is in accordance to many handling procedures where it is the shape rather than the material, that dictates the handling behaviour and handling strategy (Evans et al., 1992). This classification is useful to establish grasp requirements and to develop robotic grippers. Each class of non-rigid products has specific handling characteristics. Grasping and handling bar shaped products may require the application of tensile forces coupled with compressive forces, while for bulk products compression forces may be sufficient. To induce a rigid behaviour on a regular bar shaped product, such as an electric cable, it is sufficient the application of tension stresses in a single direction - the axis of the product. But a regular and planar sheet type
product, such as a piece of fabric, requires the use of tension stresses in the two orthogonal directions that define the plane.

<table>
<thead>
<tr>
<th>CLASS TYPE</th>
<th>BAR</th>
<th>SHEET</th>
<th>BULK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular Shape</td>
<td>constant cross section,</td>
<td>constant cross section,</td>
<td>polyhedral, spheric,</td>
</tr>
<tr>
<td></td>
<td>prismatic or cylindrical</td>
<td>prismatic or curved</td>
<td>elliptic</td>
</tr>
<tr>
<td></td>
<td>(rod or shell form)</td>
<td>profile</td>
<td></td>
</tr>
<tr>
<td>Irregular Shape</td>
<td>variable cross section</td>
<td>variable cross section</td>
<td>lump</td>
</tr>
<tr>
<td></td>
<td>(rod or shell form)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 1.1 Classification of non-rigid products*

1.4 HANDLING NON-RIGID PRODUCTS

1.4.1 Complexity in the behaviour of non-rigid products

The classification of non-rigid products, focusing on the shape of the product, recognizes the importance of this particular product feature on the handling behaviour. The flexible nature of some of the shapes of non-rigid products imposes particular care in the choice of grasp configurations and the type of applied forces.
To add to the complexity of handling, many non-rigid products present a viscoelastic or even plastic characteristic. Many food products present this type of behaviour. The handling time can be a constraining factor and surface conditions, such as slippery or sticky conditions can also affect the strategy adopted. Environmental conditions such as temperature, humidity or pressure can also affect the product compliance and its behaviour. For example, a piece of meat will have a non-rigid behaviour at room temperature, but if frozen, it will behave as a rigid body and as the temperature is reduced to approach freezing, the magnitude of deformation is affected by an increased viscous damping component. Very often the shape, size and condition of food products are controlled by customer preferences that are the dominant market influence. This leads to the need for continuously controlling grasp forces and product deformation during the handling process. All these aspects contribute to the complexity of handling non-rigid products, allowing the same product to present different behaviour under different handling conditions.

1.4.2 A reference architecture for a handling system

From the complexities of handling non-rigid products and to successfully handle non-rigid products stems the need to integrate robotic systems with adequate sensing systems, flexible gripping devices and suitable control strategies. The development of expert robot systems for skilled operation has been addressed by several researchers with applications in different areas, such as poultry handling (Khodabandehloo, 1990), robotic meat cutting (Purnell et al., 1990) and robotic handling of dough products (Shacklock et al., 1992). Common to these approaches is the need of the robotic handling system to implement three important functions. These are: product perception, product grasping and product manipulation. Product perception refers to the identification and measurement of product features and product deformation behaviour. Product grasping refers to the selection and implementation of the grasp process. Product manipulation refers to the task of handling the product, moving and placing the product on the desired location. This task requires the conjunction of robot arm movement with in-gripper manipulation. This requirement of performing manipulation within the gripper enables not only the implementation of perception procedures but also the control of product deformation. Figure 1.2 presents a conceptual framework for a robotic handling system suitable for non-rigid products highlighting the need to implement the three operational functions referred: perception, grasping and manipulation. Also shown in this figure are the aspects that are
within the scope of this thesis. For such a robotic handling system the design of the gripper is of fundamental importance. It is the gripper that is in contact with the product applying both grasp and manipulation forces. The gripper must have the dexterity and sensing capabilities to evaluate and control the deformation behaviour of the products and enable the implementation of in-gripper manipulation.

![Diagram

Figure 1.2 Conceptual framework for a robotic handling system suitable for non-rigid products

1.5 SUMMARY

This chapter has introduced the subject of robotic handling systems and has identified research opportunities in this area. It has focused on the extension of handling applications in dealing with products presenting non-rigid behaviour. A classification for this type of products and a reference architecture suitable for robotic handling systems was proposed. Such a system must be able to implement three main tasks - perception, grasping and manipulation. It requires a robotic gripper embodying sensing capabilities and dexterity necessary to accomplish these tasks.
A NEW GRIPPER FOR NON-RIGID PRODUCTS

This chapter starts with a review of available robotic grippers and current trends in their development. It goes on to present general guidelines for the development of grippers suitable for dealing with non-rigid products. Based on these guidelines, the concept of a new modular gripper is proposed.

2.1 INTRODUCTION

In a robotic handling system the gripper is an essential component. Current industrial grippers are often custom engineered for particular products, performing a single function, with limited sensing capabilities and lacking dexterity (Kato and Sadamoto, 1987). For non-rigid products the capabilities of grippers need to be much greater. The gripper must be able to cope with the variation of characteristics that the same product can present, such as shape or size. It must also sense and control the deformation behaviour of products. This implies the development of robotic grippers with force control systems making extensive use of sensors, capable of implementing different grasp configurations to provide the necessary dexterity to cope with non-rigid products. There is also the need to provide the gripper with the capability of changing the position of the grasped product through the manipulation from within the gripper. This in-gripper manipulation offers the possibility of dealing with discrete or continuous products, transferring the manipulation requirements from the robot arm to the gripper. Some robotic grippers are available and offer some of these requirements (Jacobsen et al., 1984; Doll and Schneebeli, 1988; Schwarzinger et al., 1992; Bonivento et al., 1988) but their complex mechanical structures, control and cost render them unsuitable for industrial applications. There is still a window of opportunity in the development of general purpose robotic grippers suitable for industrial applications but still incorporating the sensing and manipulation capabilities required for dealing with non-rigid products.
2.2 ROBOTIC GRIPPERS REVIEW

At an industrial level, grippers are often designed for a specific product and a single task. Typically the gripper grasps and holds the product while the robot arm performs the manipulation. Very often products are considered rigid and no gripper force control is available. The sensing devices incorporated in the grippers are kept to a minimum, normally being used to detect the presence of the product. The review will begin by looking at the development of industrial grippers.

Schneider and Servis (1988) put the emphasis on the process of developing special grippers for particular applications. Taking into consideration the handling parameters, the workpiece characteristics and environmental conditions, three particular grippers are described; two of which are developed to pick up rough workpieces heated in a furnace at high temperatures (1200°C) and handle them through several press operations, being able to cope with the high temperatures and to accommodate the change in shape of the parts during the forging process; the third gripper was specially built to load/unload small parts (3 gr each) to a particular grinding machine. Taylor and Koudis (1988) refer to the development of an electrostatic gripper that is able to pick up a panel of fabric from a ply and handle it during transport with minimum distortion. Parker et al. (1986) proposes the use of adhesive tapes or intrusive pins for the same type of task. Another mechanical gripper also intended for the same automatic acquisition of fabric plies from a stack is presented by Kemp et al. (1986). It is an air-jet finger separation device with rudimentary sensing capabilities. The technique consists of blowing on the top of the stack to loosen out the uppermost piece of fabric so it can easily be gripped. Another gripper to deal with fabrics, using two driven rollers, is referred to by Taylor et al. (1988). Tur-Kaspa and Lenz (1986) report the use of a specific gripper designed to handle tubes with wall thickness as small as 0.01 mm. This gripper has two fingers made out of two strips of photo-elastic material and incorporates a measurement of the gripping force so that the handled part is not damaged. These are all examples of specially built grippers for particular tasks and products and as such are confined to the use within the specific applications.
There are ready available grippers, normally mechanical fingered grippers (pinch-like) and suction grippers, that are widely deployed and can be adapted to a range of product shapes and sizes (Lundstrom et al., 1973). The pinch-like grippers are normally simple mechanical devices with two fingers operated through a mechanical transmission linkage powered in most cases by a pneumatic cylinder or small electric motor (Chen, 1982). These grippers employ simple control systems and may incorporate sensing devices for simple functions such as the detection of the product between the fingers. Although these single function grippers offer some flexibility, the low sensing capabilities, simple control systems and low number of degrees of freedom, limit manipulation capabilities and restrict the range of products, making them unsuitable for non-rigid products.

At the other extreme there are grippers that mimic the human hand - dexterous hands - the Electrotechnical Laboratory (ETL) hand (Okada, 1977), the Stanford/JPL hand (Salisbury, 1982), the UTAH/MIT hand (Jacobsen et al., 1984), the Bologna hand (Bonivento et al., 1988), the Karlsruhe hand (Doll and Schneebeli, 1988), the OEDIPUS hand (Schwarzinger et al., 1992) and the Teleman-18 hand, (Holweg et al., 1993). These dexterous hands are multi-fingered grippers with complex mechanical mechanisms incorporating many degrees of freedom that emulate the human hand in dexterity. Each finger of a gripper has typically the shape of a serial link with three or four rotating joints. This results in a gripper having from nine to sixteen degrees of freedom, DoF, without considering the possible DoF of the palm of the gripper. The resulting performance is impressive, with these systems capable of grasping and manipulating objects, but requiring complex control and actuation systems. Most of these hands are tendon driven systems (the ETL hand, the UTAH/MIT hand, the Stanford/JPL, the Bologna hand) and as such the capability to exert force is limited and problems like friction, elongation and routing with the use of cables or tendons may give rise to reliability problems. To overcome these problems, some of the designs (the Karlsruhe hand and the OEDIPUS hand) use miniature DC motors and reduction gears at a cost of a bulky solution. The Teleman-18 hand proposes the use of miniaturized electric-hydraulic actuators, combining a higher capacity to exert forces with a small size (Brunt and Jongkind, 1994). These complex mechanical devices have the potential to deal with non-rigid products, but the need of sophisticated control
systems, the problems of contamination of the mechanical systems and high costs, render them unsuitable for industrial applications involving many non-rigid products.

There is a need for grippers of a simple form combining some of the versatility of the dexterous hands with the easy control characteristics of the simple grippers. Such general purpose grippers would need to sense position, force, torque or slip for which suitable techniques would have to be developed. Some research has recognized these needs (Ulrich et al., 1988) and different grippers offering some of the benefits of the anthropomorphic type grippers that are flexible in application and not specific to a particular task and product have been proposed. Skinner (1974) presents a gripper with three fingers capable of achieving different prehension patterns with all fingers being bent by motor-driven cross-four-bar link mechanisms. Each finger uses one electric motor and there is a fourth to displace each of the fingers at their base and change the direction of the bending of the fingers. In a simplified version of this gripper each finger is a rigid lever with a single revolute joint. The three fingers are actuated simultaneously by a single drive and a second drive is used to displace only one of the fingers. Hanafusa and Asada (1978) use a three fingered planar gripper to present the development of a gripping theory in the plane. Each finger has a single degree of freedom and is powered by a stepper motor. The only sensed signal was position (measured at the stepper motor), but as the fingers were assembled on springs, it was possible to measure the grasp force at the fingertip. Taking a non-anthropomorphic approach, Datseris and Palm (1985) and Palm (1987) describe the design and control of a hand for the manipulation of cylindrical workpieces. The hand has six independent motions and is capable of reorientation of a product while keeping it grasped. The hand has an interesting design for dealing with the intended type of rigid products, but the omission of force control and low sensory perception capability reduces the potential application for non-rigid products.

Other researchers have used simple parallel-plate type grippers as a basis for incorporating sensing devices and active force control. Luo and Henderson (1986) propose a changeable set of gripper fingers equipped with multiple sensors, including a tactile force sensor, a slip sensor and a proximity sensor. The gripper is powered by an air-servo system and embodies position and force control. Masory et al. (1989) built a parallel-plate finger type gripper incorporating force sensors in
the fingers. Electric motors are used to drive the fingers and digital control of position and force is implemented. Using the techniques described it is possible to control the grasp force and provide active compliance in insertion tasks. Bao and Van Brussel (1990) use a parallel two-jaw gripper incorporating position and force sensors and driven by a pneumatic controller. They discuss and demonstrate the use of tactile information for control purposes and for product perception. Evans et al. (1994) proposes a parallel-plate gripper mechanism incorporating a novel tactile sensor and automated selection of gripping control strategy suitable for handling compact shaped products presenting plastic and viscoelastic behaviour. An interesting feature of this system is the identification of the properties of the material.

Although some of these grippers provide sensing capabilities that enable the control of grasp forces and perform some manipulation tasks, the mechanical solutions adopted are not suited to the form of a variety of non-rigid products, particularly if the products are presented in a continuous form. Nevertheless some of the designs provide interesting solutions that can be incorporated in the design of new grippers. Examples include the design solution proposed by Hanafusa and Asada (1978) where a finger of a gripper is driven on a fixed spring to enable a simple form of sensing and controlling force. The stiffness of the spring limits the range of applicable forces but the use of springs with variable or controllable stiffness could minimize that limitation. Another interesting approach is to provide the gripper with interchangeable fingers (Luo and Henderson, 1986) which can be provided with specific sensors and be of different shapes to adapt to the tasks and products.

### 2.3 GRIPPER REQUIREMENTS

While dexterous gripper solutions are necessary to handle a broad range of non-rigid products it is also recognized that the level of dexterity needs to be cost effective. The development of a gripper will focus on the requirements emerging from the complexities of handling non-rigid products and applying them to the development of a gripper suitable for coping with one of the
classes of non-rigid products identified in chapter 1. In this case discrete or continuous bar-shaped products are considered.

Expanding and adapting the work of Heilala and Ropponen (1990) it is possible to establish a general framework for the development of robotic grippers suitable for non-rigid products (see Figure 2.1). The four basic aspects that must be addressed relate to the operational functions which the gripper must perform, to the design aspects, to the characteristics of products and to the task type.

Figure 2.1 Framework for the development of a gripper suitable for non-rigid products

Operating the gripper and implementing the operational functions requires closed loop control of actuators and the use of adequate sensing systems. Controlling grasp forces, assessing contact characteristics, detecting slip and contact, are essential for evaluation and control of the deformation of non-rigid products and identifying their material properties and physical attributes. Minimizing product deformation at contact locations requires low contact pressures. This implies controlling the contact force and using large contact areas. To provide large contact surface area with a product, the use of multiple and compliant fingertips is an option. Another possibility includes the use of a gripper with few but large contact areas able to deform and mould to the shape of the
product. The need to constrain must be balanced with the need to manipulate the product within the gripper. This is particularly important when dealing with continuous products. Other requirements point to the need to apply grip forces in multiple and arbitrary directions as a way to impose particular handling behaviour: holding a bar or sheet product under tension imposes rigid behaviour. The need to minimize the deformation of the products during handling leads to the use of manipulation forces with a magnitude comparable to the weight of the product and to maintain gripping forces just high enough to prevent the workpiece from slipping.

Taking into consideration the above general requirements, the new design of a gripper must fulfil the following objectives:

- must deal with a class of non-rigid products, discrete or continuous bar-shape products; among the bar shaped-products are prismatic and cylindrical products; when presented in a continuous form, the gripper must act as a feeder, implementing simultaneously the actions of grasping and moving the product.

- must perform the basic tasks of perception of product attributes, grasping and performing in-gripper manipulation; the perception tasks must include the identification of physical and mechanical characteristics of the grasped products, such as product size, shape and product compliance.

- must lead to a solution where costs and complexity of the mechanical and control systems are acceptable for industrial application.

Considering the above requirements, the custom specification for the design of a new gripper is presented in Table 2.1.
Table 2.1 Custom specifications for a new gripper

| Mechanical requirements | • gripper opening: 100 mm  
|                         | • gripping force: 100 N  
|                         | • gripper weight: less than 5 kg |
| Driving system          | • electric or pneumatic |
| Sensing requirements    | • Position, velocity and force/torque  
|                         | • Tactile sensing |
| Control requirements    | • real time computer control system implementing force control, position and velocity control. |
| Product characteristics | • bar-shaped non-rigid products with thickness up to 100 mm  
|                         | • prismatic and cylindrical bar products  
|                         | • spherical products up to Ø100 mm  
|                         | • product weight: up to 5 kg |
| Gripper tasks           | • identification of physical and mechanical characteristic of grasped products such as product size, shape and compliance.  
|                         | • performance of grasp actions with controlled grip force  
|                         | • performance of in-gripper manipulation of products |

2.4 GRIPPER CONCEPT

2.4.1 Conceptual designs

Trying to meet the requirements for a gripper suitable for dealing with non-rigid products, taking into consideration the custom specification presented in Table 2.1, it is proposed that a finger-type gripper is used to enable a flexible configuration. The fingers should be independently
driven. The fingers should provide adequate contact locations and enable the manipulation of the product within the gripper. Two possible configurations for a finger that enable the implementation of in-gripper manipulation are identified: in the first, the finger has a shape of a roller and in the second, the finger is in the form of a belt conveyor (see Figure 2.2).

![Figure 2.2 Concept configurations for a finger of a gripper](image)

Based on these configurations for a finger, two concept designs for a gripper making use of three fingers are proposed: design A and design B (see Figure 2.3). Design A is a modular gripper with a basic configuration of three equal cylindrical rollers. The fingers are configured as the jaws of a chuck of a lathe but have independent motions. Design B uses three fingers configured as conveyor belts; each finger has a translational movement apart from the movement of the conveyor belt; two of the fingers define a grasp plane and it is the displacement of the third finger that enables to grasp a product. Table 2.2 presents the results of the comparison between these two designs.

![Figure 2.3 Concept configurations for three-fingered grippers](image)
Table 2.2 Comparison between conceptual designs

<table>
<thead>
<tr>
<th></th>
<th>Design A</th>
<th>Design B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gripper</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Configuration</td>
<td>planar</td>
<td>spatial</td>
</tr>
<tr>
<td>• Modularity</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td><strong>Fingers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• shape</td>
<td>roller</td>
<td>conveyor belt</td>
</tr>
<tr>
<td>• number</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>• number of independent movements</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>• type of movement</td>
<td>rotation &amp; translation</td>
<td>rotation &amp; translation</td>
</tr>
<tr>
<td><strong>Grasping capabilities</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• shape of product:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bar type (prismatic and cylindrical)</td>
<td>possible</td>
<td>possible</td>
</tr>
<tr>
<td>sheet type</td>
<td>possible</td>
<td>possible</td>
</tr>
<tr>
<td>bulk: spherical</td>
<td>possible</td>
<td>-</td>
</tr>
<tr>
<td>• grasp forces:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>compressive</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>tension</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Manipulation capabilities</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• rotation</td>
<td>possible</td>
<td>possible</td>
</tr>
<tr>
<td>• translation</td>
<td>possible</td>
<td>possible</td>
</tr>
<tr>
<td>• feeder mechanism</td>
<td>possible</td>
<td>limited</td>
</tr>
</tbody>
</table>

Both conceptual designs meet the custom requirements for the gripper. They both require the implementation of linear displacements of the fingers. To implement this type of movement, linear actuators are required. If position control is to be implemented in these movements, the use of pneumatic cylinders should be avoided. An option is using rotary actuators coupled with mechanical transmission mechanisms such as ball screw systems. This type of solution can lead to heavy and bulky systems. The design of the gripper should thus avoid the need for linear movements. Taking this into consideration, the conceptual design A can be modified to accommodate this requirement. The planar characteristic of this design enables the replacement of the linear movements of the fingers by circular translations, as shown in Figure 2.4.
Appropriate computer control applied to a gripper such the one presented in Figure 2.4 allows the gripper to operate in three modes: grasp, manipulation and perception modes. In the operational grasp mode, the gripper can be set to different configurations (Figure 2.5). The grasp can be achieved by both moving and rotating the fingers. The gripper can grasp a product from the exterior or interior. By rotating the fingers while grasping the product between them it is possible to keep the product under tension. In this way the gripper can be used as a feeder for a continuous product.

The manipulation mode corresponds to the implementation of product manipulation within the gripper. It is achieved by a combination of grasp action with controlled movement of the two possible motions of each finger (Figure 2.6). It includes passive and active manipulation. Passive manipulation is defined as an approach that minimizes the deformation of the product. Active manipulation imposes controlled deformation of the product.
The perception mode uses the data from the sensing systems together with the manipulation to extract both physical and mechanical characteristics of products. Examples of possible tasks include the determination of product size, shape, compliance and yield characteristics.

2.4.2 Chosen design

2.4.2.1 Mechanical Design

The chosen conceptual design for a gripper is the one that was presented in Figure 2.4. It has a modular design as additional fingers can be used. The fingers are equipped with a range of sensors to measure finger position, force and distribution of contact force. Electric motors are used to directly drive the fingers, achieving a compact solution. The use of electric actuators also allows the implementation of fine position control required for in-gripper manipulation tasks. A more detailed description of the mechanical concept will now be given.

The gripper comprises a support frame that carries the fingers which can be moved independently to grip a product. At least one of the fingers can be driven in rotation relative to the support frame in order to move a gripped product relative to the support. The axis of rotation of the
finger relative to the support frame is preferably transverse to the direction of displacement of the finger. In a preferred embodiment, all the fingers are displaceable and rotatable relative to the support frame. Each finger may be mounted with eccentricity on a carrier which is provided through a revolute joint at the support frame, so that rotation of the carrier effects displacement of the finger. The carrier is in the form of an arm which can be rotated by a respective actuator mounted on the support frame. Each finger is preferable cylindrical and can be rotated about an axis perpendicular to the support frame. To drive this movement the carrier can be provided with a second actuator. The fingers can be provided with sensors to measure contact characteristics and for assisting the control of the fingers in position, velocity and force. There was a patent application for this gripper. It was filed (British patent application Nº 9221016.0) but for financial reasons it was not followed up.

For a better understanding of the present concept of the gripper and to show how it may be implemented, an example of a gripper having a three-fingered and planar configuration is now presented (Figure 2.7). Each cylindrical shaped finger has two degrees of freedom. One is the rotation of the finger around its longitudinal axis and the other is the displacement motion perpendicular to that axis that provides the movement relative to the other fingers. The joint motions are independently powered. Joint sensors for position, velocity and torque can be employed. Other sensing systems to measure forces and torques applied by the fingers can also be used. The gripper can be configured to accommodate a different number of fingers and configurations with four and five fingers being possible.
2.4.2.2 Sensing Systems

Sensing systems are required for controlling the motion of the fingers and for perception tasks. The needs for sensing include position, velocity, force, slip and tactile sensing for contact characteristics such as force distribution and contact location. The common characteristic of these sensors is that they are all built into the gripper, although other sensors such as distance and vision systems could be employed and integrated with the control of the gripper if necessary.

2.4.2.3 Control System

The control system for the gripper has to deal with the control of individual fingers and with the coordination control of all the fingers to achieve the desired operation modes (Figure 2.8). At a low-level there is a requirement to implement position, velocity and force control for each motion of a finger and to support the sensing devices. The high-level supervisory control system supports the operator in programming and executing the tasks within each operating mode. It also plans the coordination of the motions of the fingers, processes the data from the multiple sensors and presents a set of reference commands to the lower-level controller that operates directly on the manipulator hardware.
2.5 SUMMARY

This chapter has reviewed the current state of the art in robotic grippers and has established the essential design requirements for the development of robotic grippers. It has concluded that grippers for handling non-rigid products have special requirements that currently available grippers do not fulfil. In meeting these requirements, the concept for a novel modular gripper has been proposed. It is a finger-type gripper, equipped with multiple sensors, suitable for implementing different grasping configurations and performing in-gripper manipulation. The gripper is suitable for dealing with classes of non-rigid products having bar shaped, with the products presented in discrete or continuous form.
3 THE KINEMATICS OF THE GRIPPER

This chapter provides the background on current kinematic tools for the design and analysis of performance of robotic systems (single and multiple arm systems) that can be applied to the design of robotic grippers. The kinematic model of the gripper is presented and used for the design of the gripper and planning the manipulation of products.

3.1 BACKGROUND

A multi-fingered gripper can be seen as set of single-arm manipulators acting together. The interaction of the fingers with a product enables grasping and manipulation of the product within the gripper. The areas of single-arm and multi-arm robotic systems and the areas of grasping and manipulation are then related topics in the design and characterization of a gripper. The analysis of the grasp and manipulation actions through a kinematic point of view is examined.

3.1.1 PERFORMANCE MEASUREMENTS FOR DESIGN AND EVALUATION OF ROBOTIC SYSTEMS

Many aspects affect the performance of a robotic system such as the kinematics of the mechanisms, the dynamic characteristics of the actuators and control systems. Performance analysis involves the behaviour and interaction of individual system components regarding the desired tasks. Among task related aspects, the qualification and quantification of aspects such as workspace characteristics, force capacity, position capability, velocity and acceleration capabilities, play an important role in the design and evaluation of robotic systems. It is well known that the performance of a robotic system is not uniform over its workspace. The evaluation of these aspects can make use of performance tests such as repeatability, accuracy and load carrying tests or can be evaluated at an
analytical level. The analytical approach is a powerful tool for the design, evaluation and simulation of robotics systems. The kinematics and the kinstatic analysis have an essential role. The kinematic analysis addresses the geometric and motion aspects - the parameters of interest are position, displacement, velocity, acceleration and time. The kinstatic analysis uses the kinematics and includes the effect of forces on the motion of the masses of the system components (Sandor, 1983). Different performance measurements have been proposed using the kinematics and kinstatic analysis for single-arm and multi-arm robotic systems (Buckingham, 1992, Lee et al., 1993).

When evaluating the performance of robotic systems, the geometric aspects of the workspace such as size and shape, maximum reach and its continuity, are examples of important performance measures. Any task to be performed must be conducted inside the workspace of the robotic system and so there is a need to be able to define that workspace. In a multi-fingered gripper the overall workspace and the common workspace of the fingers will depend on the individual workspace of the fingers and on the relative finger locations. The gripper configuration can then be optimized for the individual workspace of a finger and their interaction in space (Salisbury and Craig, 1982). The payload capacity of a robotic system is another performance measure. A robot arm or a gripper does not have a uniform load capacity (or uniform capacity to apply a force) over the whole workspace. To represent that variable load capacity, Yap (1985) proposes the use of constant force contours over the workspace of a single robot arm.

Associated with the workspace definition, Kumar and Waldron (1981) refer, for single-arm systems, the concept of dexterous workspace - a space in which the manipulator's end-effector can rotate fully about all axes through any point. To describe these geometric aspects of the reachable and the dexterous workspace various techniques have been used. Kumar and Waldron (1981) and Lai and Menq (1988) developed algorithms to define the boundaries of the workspace for single-arms. Yang and Lee (1983) used recursive equations. Tsai and Soni (1983) employed a linear programming technique. Freudenstein and Primrose (1984) used algebraic equations. Gupta and Roth (1982) considered the effect of hand size on the dexterous workspace.
The concept of the dexterous workspace corresponds to all possible arm configurations where singularities do not occur. A singularity point in a robot arm corresponds to a particular configuration in which the robot end-effector cannot move in a particular direction. If the motion is not possible in that direction, then it is not possible to control and exert force in that direction. Using the Jacobian transform, $\mathbf{J}$, to represent the kinematics of a robotic system, a singularity point can be mathematically defined when the rank of the Jacobian matrix becomes less than full (i.e., det $\mathbf{J} = 0$). A finger for a gripper should not have singularity points inside the workspace so that controlled forces on the grasped product can be exerted at any point of the workspace (Salisbury and Craig, 1982, McAree et al., 1991). This clearly shows the use of the Jacobian as a tool for the design and evaluation of a finger at a point in the workspace.

The use of the Jacobian has been further applied to establish different performance measures over the whole workspace, applied to single-arm and multi-arm systems, with or without kinematic redundancy. Uchiyama et al. (1984) uses the determinant of the Jacobian as a performance measure (the performance is high for large values of $|\text{det } \mathbf{J}|$) for non-redundant, single-arm systems. The distribution of the performance measure in different planes and the use of a colour display is used to visualize the performance over the whole workspace. For some arm geometry the determinant of the Jacobian can be expressed analytically as a function of the joint angles and therefore be used for control purposes. Salisbury and Craig (1982) use the condition number of the transpose of the Jacobian matrix for measuring the quality of points in the workspace and for kinematics design optimization. The condition number is defined as the product of the norm of a matrix and the norm of the inverse of the same matrix (condition number of matrix $\mathbf{A} = \| \mathbf{A} \| \| \mathbf{A}^{-1} \|$). Points in the workspace that minimize the condition number of the Jacobian transpose are best conditioned to minimize error propagation from input torques to output forces. This also applies when finding the joint velocities given the end-effector velocities. The minimum value that is possible to obtain for the condition number is 1. The respective points are referred as isotropic points (Salisbury and Craig, 1982). These concepts relate to the performance at single points in the workspace, as the Jacobian is a local transform but they can be extended to the whole workspace (Gosselin and Angeles, 1988, Klein and Miklos, 1991).
To establish other performance measurement that can be applied to single-arm kinematically redundant manipulators the Jacobian transform is formulated based on the singular value decomposition (SVD) theorem. This is a powerful approach as it enables its application both to the design optimization and control implementation (Maciejewski and Klein, 1989). Yoshikawa (1985a) proposes a kinematic manipulability measure defined by the product of the singular values of the Jacobian matrix. This measure relates to the ability to position and orientate the end-effector of a single-arm. Klein and Blaho (1987) propose the use of the minimum singular value of the Jacobian matrix as a "measure of the upper bound of the magnitude of the velocity at which the end-effector can be moved in any direction". This measure ignores the fact that the arm may just be required to move in particular directions to accomplish a certain task. The condition number of the Jacobian transpose matrix proposed by Salisbury and Craig (1982) can be redefined in terms of the singular values of JT (given by the ratio of the largest to the smallest singular value) and a new performance measure using the modified inverse of the condition number is proposed by Homsup and Anderson (1986).

To extend, represent and visualize these performance measures, Yoshikawa (1985b) and Chiu (1988) use the concept of force and velocity ellipsoids. The force ellipsoid, first referred to by Asada (1983), describes the force transmission characteristics of a manipulator at a given posture. In an analogous way, the velocity ellipsoid, (Yoshikawa, 1985b, calls it the manipulability ellipsoid) describes the velocity transmission characteristics. The optimal direction for effecting velocity is along the major axis of the velocity ellipsoid, where the transmission ratio is at a maximum. Conversely, the minor axis of the ellipsoid has the direction where the velocity is most accurately controlled, where the transmission ratio is at a minimum (Chiu, 1988). The properties of these ellipsoids in terms of volume, directions of its principal axis, directional uniformity and the mathematical formulation based on the single value decomposition permits the definition of different measures of performance, static and dynamic, for single-arms (Homsup and Anderson, 1986). One performance measure relates to the volume of the velocity ellipsoid. The volume can be regarded as a distance from singularity points (the ellipsoid volume is zero at a singular point). To maximize the ellipsoid volume, Yoshikawa (1985b) proposes the use of kinematic redundancy. The performance measure proposed by Homsup and Anderson (1986), based on the modified inverse of the condition number of the Jacobian, can then be interpreted as the directional uniformity of the velocity ellipsoid.
The use of these performance measures and the mathematical formulation are particularly useful for control purposes and task optimization (Klein and Blaho, 1987, Chang, 1989, Chiu, 1988, Dubey and Luh, 1988) as they give indication of preferable workspaces, of how to choose between different configurations and of what the preferable directions are for exerting force control and velocity control. The concept of ellipsoids (force, velocity and task ellipsoids) has been further applied to multi-arm robotic system (Buckingham, 1991, 1992, Chiachio et al., 1991, Bouffard et al., 1991). Buckingham (1992) developed a simulation package for multi-arm robot systems to be used for trajectory planning and task planning. The quality measure of the workspace is based on the condition number of the Jacobian. The continuous characteristic of the condition number is used with advantage to visualize the whole workspace through colour regions with similar condition number when manipulating rigid objects.

3.1.2 GRASPING AND MANIPULATION BY MULTI-FINGERED GRIPPERS

Grasping involves the application of a set of constraints to a product. The constraints must restrain the six degrees of freedom the product has in free space so that the grasp holds the product securely. The grasp constraints must also cope with any disturbance forces acting on the product to maintain a stable grasp. The constraints can be partial or total. In the case of grasping a compliant product, there is the added problem resulting from the possible deformation of the product during the grasp. This may imply the need for a continuous adaptation of the grasp’s constraints in response to deformation of the product.

A grasp can be characterized by the type of contacts that are established between the gripping device and the object and by the forces applied. The geometric figure formed by the contact locations define the grasp configuration. The set of forces exerted on the object by the device define the grasp forces. Planning a good grasp configuration and applying the correct grasping forces is essential for a robust grasp and successful manipulation (Ji and Roth, 1988a). The approach to the grasp and manipulation problems has thus been focused on the grasp configurations and on the analytical
modelling of the interaction between the gripper and the product along with the development of various multi-fingered robot grippers.

3.1.2.1 Grasp configurations and classification

The classification of grasping actions normally involves the use of grasping taxonomies and the use of geometric modelling describing products and gripping devices. The analysis of human grasping is well documented and well established. Many studies are reported with emphasis in hand surgery and in the development of prosthetic devices (Napier, 1956, Becker, 1988). Taxonomies associating the grasping configuration with the geometrical shape of the object are described by Taylor and Schwartz (1955). As the same object may be grasped in different ways depending on the task that is going to be performed, other authors have considered that grasps should be categorized on the task function instead of geometrical appearance (Cutkosky, 1989).

Iberall (1987, 1988) presents a set of grasping taxonomies not based on the human hand emulation. He introduces the concept of "virtual fingers" and proposes a grasping classification considering the type of opposition between fingers.

A grasping taxonomy itself presents some limitations. It is always possible to find particular types of grasp that are difficult to be incorporated in the generic topology defined. Although, the proposed classifications inherent in a taxonomy are helpful for comparing different types of grasps and useful for grasp planning by expert systems.

The geometric modelling of the object and consideration of the constraints and compatibility between the gripper, task and object geometry can be used to define and plan grasp configurations. Dunn and Segen (1988) use a two dimensional model of the object obtained from digitized image using a vision camera system. Ji and Roth (1988b) discuss the planning of grasp-configurations for three-finger tip-prehension grasps based on geometric considerations of the objects and on compatibility constraints between the task and the geometry of the object. Rao et al. (1988) uses a
volumetric shape description of the product in an expert system to define possible configurations for grasps.

3.1.2.2 **Grasp modelling**

The analytical modelling of the interaction between a particular mechanical device and a product, as was pointed out by Cutkosky (1989), needs to address several issues: the geometry, the kinematics, the dynamics and the constitutive relations. To reduce the complexity of the required models, several assumptions are made. The most complex models involve the following assumptions (Cutkosky, 1989):

- rigid products having regular shapes and smooth surfaces
- idealized models for fingertip contacts (for example point-contact or soft finger models with linear elastic deformation)
- idealized models for friction (for example, Coulomb friction) ignoring the dynamic effects of sliding velocity, materials properties and surface conditions
- idealized actuators and drive mechanisms, ignoring backlash and friction

Asada (1979) uses a grasping model without friction, without sliding or rolling on the fingertips, treating the object as a rigid body. He also considers contact points between the fingertips and the object, quasi static analysis (no inertia or viscous terms), no cases with redundant degrees of freedom and no over constrained grasp, linearized (instantaneous) kinematics. On the basis of this model he forms a function indicating a relative stability of different finger configurations, using it to select a grasp.

Cutkosky and Wright (1987) present the use of compliant materials in robotic fingers and the use of a shearing model to describe the contact between the finger and an object. Other models of fingertip/object contact conditions are referred and their influence on the overall strength and controllability of the grasp action is evaluated.
Li and Sastry (1988) use screw theory and elementary differential geometry to define quality measures for evaluating a grasp by a multi-fingered robot hand. One of the quality measures is task oriented, which implies the modelling of the task. Point contacts (without friction, with friction and soft contacts) and rigid products are considered.

The contact modelling between a finger and the product has also received considerable attention. Early work of contact characteristics on grasping took an approach in terms of kinematics of the contact (Cutkosky, 1985). Purely kinematic models do not give information on the pressure distribution across the contact, and therefore cannot deal with the relative magnitudes of linear and torsional friction. For soft fingertips, this leads to inaccurate results. Improved models account for finite contact areas and combined compressive and torsional loads, but these results make unrealistic assumptions in modelling fingertip material properties, friction and pressure distribution (Cutkosky and Wright, 1987). When considering the dynamics of the contact early sliding models used the Coulomb friction model, in which friction is strictly proportional to normal force. This works well for contacts between rigid materials, but is not accurate for viscoelastic materials such as rubbers. Most literature assumes that the coefficient of friction is independent of sliding speed, although the value of elastomeric friction is a strong function of speed. This has lead to other contact models. Howe and Cutkosky (1988) describe an improved friction model for elastomers in contact with smooth, dry surfaces which predicts that friction is proportional to the normal force to the 2/3 power, proved by experimental trials. This result is then used on the calculation of the beginning of sliding as a function of the load, using a model that combines the effects of torsion and shear loading. The results are verified experimentally.

3.1.2.3 Grasp quality measures

Considering the various analytical models, different quality measures to describe a grasp have been developed. They are well summarized in Cutkosky (1989) and include:

- compliance: use of a grasp compliance matrix (see Cutkosky and Kao, 1989)
connectivity: number of degrees of freedom between the grasped product and gripping device necessary to fully specify the location of the product (see Mason and Salisbury, 1985)

force closure: the grasp can only resist disturbance forces that act to maintain the contact between gripper device and product (see Salisbury, 1982)

form closure (or complete kinematic restraint): the grasp can resist any disturbance forces (see Mason and Salisbury, 1985, Ohwovoriole, 1987)

grasp isotropy: related to the capability of controlling forces and motion in a gripping configuration; defined as a function of the condition number of the grasp Jacobian matrix (see Mason and Salisbury, 1985, Kerr and Roth, 1986)

internal forces: the contact forces and friction forces applied to an object without disturbing its equilibrium when the object is completely restrained by the grasp constraints; formally, the internal grasp forces are the homogeneous grasp solution to the equilibrium equations of the object; the internal force from each contact is cancelled out by internal forces at other contacts (see Salisbury and Roth, 1983, Mason and Salisbury, 1985, Yoshikawa and Nagai, 1991)

manipulability: relating to the capability of the grasping constraints imposing arbitrary motion to the grasped product (see Kobayashi, 1985, Kerr and Roth, 1986, Li et al., 1989)

resistance to slipping: related to the scope of forces and moments the object can withstand before starting to slip at the contact locations (see Kerr and Roth, 1986, Cutkosky and Wright, 1987, Jameson and Leifer, 1987)

stability: the effects of disturbance forces on the grasp; with static conditions, the grasp is stable if the overall stiffness matrix is positive definite (see Cutkosky and Kao, 1989, Fearing, 1986, Nguyen, 1989); for consideration of dynamic stability, see Nakamura et al. (1989);

These parameters can be used to describe a grasp, to access the suitability of a grasp for a given task and to implement the control of grasp. The geometrical considerations, already referred to, must also be considered to select and characterize a grasp.
3.1.3 AN ANALYTICAL MODEL FOR A MULTI-FINGERED GRIPPER

The representation and modelling of the interaction between a multi-fingered robotic gripper and an object requires the determination of the force and the velocity relationship between the fingers of the gripper and the object. This area has received considerable attention by many researchers and has been discussed in greater depth by Salisbury (1982), Kerr (1984), Cai and Roth (1986), Kerr and Roth (1986), Montana (1988), Li et al. (1988,1989), Cutkosky and Kao (1989). The following review follows the work by Li et al. (1989).

First assume that the robotic gripper has $n$ fingers and that each finger can be considered a serial link arm with $k_i$ joints with $i = 1, ..., n$. Assume that the contact between the fingers and the product occurs at the last link assigned to each finger; this location will be referred to as the fingertip. Next, assign a contact type for the contact between each fingertip and the object. Assuming that the product is rigid, the formulation starts by establishing the equations of motion and forces for the gripper only. Depending on the contact constraints, the motion of the fingertips and the forces that can be exerted at these locations can be related to the motion of the object. This approach provides the means to consider the case where the object may slide or rotate at the contact locations.

Let each joint of a finger $i$ ($i = 1, ..., n$) be characterized by the joint angle and the joint torque. Let $\mathbf{q}_i \in \mathbb{R}^{k_i}$ and $\mathbf{p}_i \in \mathbb{R}^3$ represent the position vector of the tip of the finger $i$ expressed respectively in the joint coordinate space and in the task coordinate space. Also define $\mathbf{\tau}_i \in \mathbb{R}^{k_i}$ and $\mathbf{h}_i \in \mathbb{R}^6$ as the generalized force vector of the finger $i$ ($i = 1, ..., n$) expressed in joint coordinate space and in task coordinate space, respectively.

For each finger, the Jacobian transform maps the joint velocity into the task space velocity; it is the locally linearized transformation matrix $\mathbf{J}_i \in \mathbb{R}^{6 \times k_i}$ that is defined by the equation:

$$\mathbf{v}_i = \mathbf{J}_i(\mathbf{q}_i)\dot{\mathbf{q}}_i$$  \hspace{1cm} (Eq. 3.1)
where $V_t = [v_t \ \omega_t]^T \in \mathbb{R}^{6}$ and $\dot{q}_i \in \mathbb{R}^{k_i}$ are the fingertip velocity expressed in task and joint coordinate systems, respectively. Considering the duality between velocity and force, the joint driving torque is related to the force exerted at the fingertip by:

$$\tau_t = J_t^T(q_t) h_t \quad (Eq. 3.2)$$

Consider now the $n$ fingers of the gripper. The kinematic equation for the gripper corresponds with (Eq. 3.1) and is given by:

$$V_g = J(q) \dot{q} \quad (Eq. 3.3)$$

where

$$V_g = [V_1 \ \cdots \ V_n]^T \in \mathbb{R}^{6n}$$

$$\dot{q} = [\dot{q}_1 \ \cdots \ \dot{q}_n]^T \in \mathbb{R}^{k^*} \quad \text{with} \quad k^* = \sum_{i=1}^{n} k_i$$

$$J(q) = \text{diag}\{J_1 \ \cdots \ J_n\} \in \mathbb{R}^{6nxk^*}$$

The forces that the $n$ fingers can apply, and how they relate to the torques of the joints of the fingers, may be described by an equation, corresponding to (Eq. 3.2), given by:

$$\tau_g = J^T(q) h_g \quad (Eq. 3.4)$$

where

$$\tau_g = [\tau_1 \ \cdots \ \tau_n]^T \in \mathbb{R}^{k^*}$$

$$h_g = [h_1 \ \cdots \ h_n]^T \in \mathbb{R}^{6n}$$

These two equations (Eq. 3.3) and (Eq. 3.4) relate to the velocities and forces at the fingertips expressed in task and joint coordinate systems adopted for each finger of the gripper. To consider the effect of the action of the fingers on the product and to describe the kinematic and force relations
between the fingers and the product, the following set of coordinate systems will be defined (refer to Figure 3.1):

- \( \{C_a\} \) absolute coordinate reference frame
- \( \{C_t\} \) task coordinate frame (to be considered coincident with \( \{C_b\} \))
- \( \{C_b\} \) object coordinate frame, fixed at the mass centre of the object
- \( \{C_{bi}\} \) object local coordinate frame, relative to \( \{C_b\} \), fixed at the \( i^{th} \) point of contact with finger \( i \); the \( z \)-axis of this frame coincides with the outward pointing normal to the object surface
- \( \{C_{fi}\} \) finger coordinate frame, fixed to the last link of finger \( i \); the \( z \)-axis of this frame coincides with the outward pointing normal to the finger surface
- \( \{C_{li}\} \) finger local coordinate frame, relative to \( \{C_{fi}\} \), fixed at the \( i^{th} \) point of contact with finger \( i \); the \( z \)-axis of this frame coincides with the outward pointing normal to the finger surface

![Coordinate frames for a multi-fingered gripper holding an object](image)

*Figure 3.1* Coordinate frames for a multi-fingered gripper holding an object
Other parameters to be defined are:

- $\epsilon_i$ contact angle, defined by the angle between the x-axes of $\{C_{bi}\}$ and $\{C_{fi}\}$; the sign of $\epsilon_i$ is chosen so that a rotation of $\{C_{bi}\}$ through $-\epsilon_i$ around its z-axis aligns its x-axis with the x-axis of $\{C_{fi}\}$

- $a_{r_b} \in \mathbb{R}^3$ position vector, from the origin of the coordinate frame $\{C_a\}$ to the origin of the coordinate frame $\{C_b\}$, expressed in $\{C_a\}$

- $a_{R_b} \in \text{SO}(3)$ rotation matrix (3×3) giving the orientation of origin of the coordinate frame $\{C_b\}$ relative to the coordinate frame $\{C_a\}$, expressed in $\{C_a\}$

A brief review relating the relative motion of coordinate frames is presented below.

For any two coordinate frames $\{C_\alpha\}$ and $\{C_\beta\}$ the position and orientation of the origin of frame $\{C_\beta\}$ relative to $\{C_\alpha\}$ is given by:

- $a_{r_\beta} \in \mathbb{R}^3$ the position vector

- $a_{R_\beta} \in \text{SO}(3)$ the orientation (rotational) matrix

If frame $\{C_\beta\}$ moves relative to frame $\{C_\alpha\}$, $a_{r_\beta}$ and $a_{R_\beta}$ are functions of time. Furthermore, if $(a_{r_\beta}(t), a_{R_\beta}(t))$ is a curve describing the trajectory of the origin of frame $\{C_\beta\}$ relative to $\{C_\alpha\}$, then the velocity of the origin of $\{C_\beta\}$ relative to $\{C_\alpha\}$ is given by:

$$
\begin{bmatrix}
    a_{v_\beta} \\
    a_{\omega_\beta}
\end{bmatrix}
= 
\begin{bmatrix}
    a_{R_\beta}^T & a_{\dot{r}_\beta} \\
    a_{\omega_\beta} & S^{-1}(a_{R_\beta}^T a_{\dot{R}_\beta})
\end{bmatrix}
\quad (Eq. 3.5)
$$

where $a_{v_\beta}, a_{\omega_\beta} \in \mathbb{R}^3$ are the translational and rotational components of the velocity and $S$ is an operator defined by:

$$
S(\omega) =
\begin{bmatrix}
0 & -\omega_3 & \omega_2 \\
\omega_3 & 0 & -\omega_1 \\
-\omega_2 & \omega_1 & 0
\end{bmatrix}
$$

and

$$
\omega =
\begin{bmatrix}
\omega_1 \\
\omega_2 \\
\omega_3
\end{bmatrix}
$$
that satisfies:

\[ S(\omega)\mathbf{p} = \omega \times \mathbf{p} \quad \text{and} \quad RS(\omega)R^T = S(R\omega) \quad \text{for all} \quad R \in SO(3), \omega, \mathbf{p} \in \mathbb{R}^3 \]

The vector \( \alpha \mathbf{v}_\beta = [\alpha \mathbf{v}_\beta \quad \alpha \omega_\beta] ^T \in \mathbb{R}^6 \) is called the generalized velocity (or twist) of \( \{ C_\beta \} \) relative to \( \{ C_\alpha \} \).

For any three coordinate frames, \( \{ C_\alpha \} \), \( \{ C_\beta \} \) and \( \{ C_\rho \} \), their relative velocities are given by:

\[ \alpha \mathbf{v}_\rho = \beta R^T_\rho \left( \alpha \mathbf{v}_\beta + \alpha \omega_\beta \times \beta \mathbf{r}_\rho \right) + \beta \mathbf{v}_\rho \]  
\( (Eq. 3.6) \)

\[ \alpha \omega_\rho = \beta R^T_\rho \alpha \omega_\beta + \beta \omega_\rho \]  
\( (Eq. 3.7) \)

or, written in another way

\[
\begin{bmatrix}
\alpha \mathbf{v}_\rho \\
\alpha \omega_\rho
\end{bmatrix} = 
\begin{bmatrix}
\beta R^T_\rho & -\beta R^T_\rho S(\beta \mathbf{r}_\rho) \\
0 & \beta R^T_\rho
\end{bmatrix}
\begin{bmatrix}
\alpha \mathbf{v}_\beta \\
\alpha \omega_\beta
\end{bmatrix} + 
\begin{bmatrix}
\beta \mathbf{v}_\rho \\
\beta \omega_\rho
\end{bmatrix} = \beta \Delta_\rho
\begin{bmatrix}
\alpha \mathbf{v}_\beta \\
\alpha \omega_\beta
\end{bmatrix} + 
\begin{bmatrix}
\beta \mathbf{v}_\rho \\
\beta \omega_\rho
\end{bmatrix}
\]  
\( (Eq. 3.8) \)

where

\[ \beta \Delta_\rho = 
\begin{bmatrix}
\beta R^T_\rho & -\beta R^T_\rho S(\beta \mathbf{r}_\rho) \\
0 & \beta R^T_\rho
\end{bmatrix}
\]  
\( (Eq. 3.9) \)

If frame \( \{ C_\rho \} \) is fixed to frame \( \{ C_\beta \} \), \( \beta \mathbf{v}_\rho = \beta \omega_\rho = 0 \), and (Eq. 3.8) simplifies to:

\[
\begin{bmatrix}
\alpha \mathbf{v}_\rho \\
\alpha \omega_\rho
\end{bmatrix} = \beta \Delta_\rho
\begin{bmatrix}
\alpha \mathbf{v}_\beta \\
\alpha \omega_\beta
\end{bmatrix}
\]  
\( (Eq. 3.10) \)

The relationship between moving frames expressed in (Eq. 3.10) can be applied to the object and the gripper. It shows the existence of a constant transformation for the velocity of the object when expressed in the absolute and local frames. As the local frame is fixed at the point of contact, that transformation is a function of the contact geometry of the object (Li et al., 1989).
Applying now the previous results to the case of an object being grasped by a fingered gripper, the relative velocities between the object and the fingers can be expressed by making use of the coordinate frames defined. Consider the velocity of the object relative to finger \( i \) expressed in the local frames. Denote the translational and rotational velocity of the origin of \( \{C_{bi}\} \) relative to \( \{C_i\} \) by:

\[
\begin{bmatrix}
\dot{v}^i_{bi} \\
\dot{\omega}^i_{bi}
\end{bmatrix}
= \begin{bmatrix}
v^i_x & v^i_y & v^i_z
\end{bmatrix}^T \quad \text{and}
\]

\[
\begin{bmatrix}
\dot{\omega}^i_{bi}
\end{bmatrix}
= \begin{bmatrix}
\omega^i_x & \omega^i_y & \omega^i_z
\end{bmatrix}^T
\]

The velocity of the point of contact relative to the absolute reference frame is given by the velocity of \( \{C_{bi}\} \) relative to \( \{C_a\} \), expressed in \( \{C_a\} \). Using equations (Eq. 3.6) and (Eq. 3.7) this becomes:

\[
\begin{bmatrix}
\dot{a}v^i_{bi} \\
\dot{a}\omega^i_{bi}
\end{bmatrix}
= \begin{bmatrix}
\dot{a}R^i_{bi} & 0 \\
0 & \dot{a}R^i_{bi}
\end{bmatrix}
\begin{bmatrix}
\dot{v}^i_{bi} \\
\dot{\omega}^i_{bi}
\end{bmatrix}
+ \begin{bmatrix}
\dot{a}v^i_{bi} \\
\dot{a}\omega^i_{bi}
\end{bmatrix}
\]

\[
\text{as } \dot{a}r^i_{bi} = 0
\]

(Eq. 3.11)

where

\[
\dot{a}R^i_{bi} = \begin{bmatrix}
\cos \varepsilon_i & -\sin \varepsilon_i & 0 \\
\sin \varepsilon_i & \cos \varepsilon_i & 0 \\
0 & 0 & -1
\end{bmatrix}
\]

The velocity of \( \{C_{bi}\} \) relative to \( \{C_b\} \) can also be expressed as:

\[
\begin{bmatrix}
\dot{a}v^i_{bi} \\
\dot{a}\omega^i_{bi}
\end{bmatrix}
= \begin{bmatrix}
\dot{b}R^i_{bi} & 0 \\
0 & \dot{b}R^i_{bi}
\end{bmatrix}
\begin{bmatrix}
\dot{v}^i_{bi} \\
\dot{\omega}^i_{bi}
\end{bmatrix}
+ \begin{bmatrix}
\dot{a}v^i_{bi} \\
\dot{a}\omega^i_{bi}
\end{bmatrix}
\]

(Eq. 3.12)

This is the velocity of the contact point relative to the object frame, expressed in the absolute reference frame. In a similar way, the velocity of the contact point relative to the finger frame, expressed in the absolute reference frame is given by:
\[
\begin{bmatrix}
^a \mathbf{v}_{li} \\
^a \mathbf{\omega}_{li}
\end{bmatrix} = 
\begin{bmatrix}
^\beta \mathbf{R}_{hi}^T & -^\beta \mathbf{R}_{hi}^T S(^\beta \mathbf{r}_{hi}) \\
0 & ^\beta \mathbf{R}_{hi}^T
\end{bmatrix}
\begin{bmatrix}
^a \mathbf{v}_{fi} \\
^a \mathbf{\omega}_{fi}
\end{bmatrix} = ^\beta \Delta_{hi} 
\begin{bmatrix}
^a \mathbf{v}_{fi} \\
^a \mathbf{\omega}_{fi}
\end{bmatrix}
\quad (Eq. 3.13)
\]

Substituting equations (Eq. 3.12) and (Eq. 3.13) in (Eq. 3.11) yields:

\[
^b \Delta_{bi} 
\begin{bmatrix}
^a \mathbf{v}_{bi} \\
^a \mathbf{\omega}_{bi}
\end{bmatrix} = 
\begin{bmatrix}
^\mu \mathbf{R}_{bi}^T & 0 \\
0 & ^\mu \mathbf{R}_{bi}^T
\end{bmatrix} 
^b \Delta_{bi} 
\begin{bmatrix}
^a \mathbf{v}_{fi} \\
^a \mathbf{\omega}_{fi}
\end{bmatrix} + 
\begin{bmatrix}
^\mu \mathbf{V}_{bi} \\
^\mu \mathbf{\omega}_{bi}
\end{bmatrix}
\quad (Eq. 3.14)
\]

Using the finger Jacobian, \( J_f \in \mathbb{R}^{6 \times k_f} \), this relates the velocity of the finger frame \( \{C_{fi}\} \) to the velocity of the finger joints \( \dot{q}_i \) by:

\[
\begin{bmatrix}
^a \mathbf{v}_{fi} \\
^a \mathbf{\omega}_{fi}
\end{bmatrix} = J_f(q_i) \dot{q}_i \quad (Eq. 3.15)
\]

and then, using equation (Eq. 3.15), (Eq. 3.14) gives:

\[
^b \Delta_{bi} 
\begin{bmatrix}
^a \mathbf{v}_{bi} \\
^a \mathbf{\omega}_{bi}
\end{bmatrix} = 
\begin{bmatrix}
^\mu \mathbf{R}_{bi}^T & 0 \\
0 & ^\mu \mathbf{R}_{bi}^T
\end{bmatrix} 
^b \Delta_{bi} J_f \dot{q}_i + 
\begin{bmatrix}
^\mu \mathbf{V}_{bi} \\
^\mu \mathbf{\omega}_{bi}
\end{bmatrix}
\]

or, written in a compact form:

\[
^b \Delta_{bi} ^a \mathbf{v}_{bi} = J_f \dot{q}_i + ^\mu \mathbf{V}_{bi} \quad (Eq. 3.16)
\]

where:

\[
^a \mathbf{v}_{bi} = 
\begin{bmatrix}
^a \mathbf{v}_{bi} \\
^a \mathbf{\omega}_{bi}
\end{bmatrix}, \quad ^\mu \mathbf{V}_{bi} = 
\begin{bmatrix}
^\mu \mathbf{V}_{bi} \\
^\mu \mathbf{\omega}_{bi}
\end{bmatrix} \quad \text{and} \quad J_f = 
\begin{bmatrix}
^\mu \mathbf{R}_{bi}^T & 0 \\
0 & ^\mu \mathbf{R}_{bi}^T
\end{bmatrix} \quad ^b \Delta_{bi} J_f
\]

Expression (Eq. 3.16) relates the velocity of the object to the joint velocity of the finger considering the contact constraints defined in terms of the relative velocities at the contact location.

For example, for a point contact with friction, \( ^\mu \mathbf{v}_{bi} = [0 \ 0 \ 0]^T \); for a rigid contact, \( ^\mu \mathbf{v}_{bi} = [0 \ 0 \ 0]^T \) and \( ^\mu \mathbf{\omega}_{bi} = [0 \ 0 \ 0]^T \). Considering now that at each contact the force and velocity constraints can be represented by a matrix \( B_i \in \mathbb{R}^{p \times 6} \), as defined by Kerr and Roth (1986) and Cutkosky and Kao (1989), expression in (Eq. 3.16) can be rewritten as:

\[
B_i ^b \Delta_{bi} ^a \mathbf{v}_{bi} = B_i J_f \dot{q}_i \quad (Eq. 3.17)
\]
The expression in (Eq. 3.17) is called the velocity constraint equation between the object and finger \( i \). As an example, for a soft point contact (\( p=4 \)) and for a point contact with friction (\( p=3 \)), \( B_i \) is given, respectively, by:

\[
B_i = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\quad \text{and} \quad
B_i = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0
\end{bmatrix}
\]

To describe the force that a finger can exert on the object at the fingertip start by defining a generalized force acting on the object, relative to the object coordinate frame \( \{C_b\} \), by:

\[
\lambda_b = [ f_b \ u_b ]^T \quad \text{(Eq. 3.18)}
\]

where

- \( u_b \in \mathbb{R}^3 \) is the torque about the origin of \( \{C_b\} \)
- \( f_b \in \mathbb{R}^3 \) is a linear force

The force seen by the object (\( \lambda_b \in \mathbb{R}^6 \)) results from the force (\( h_i \in \mathbb{R}^6 \)) exerted by the finger transformed by the contact constraints. For a finger \( i \) it will be:

\[
\lambda_i^e = \Delta_h^e B_i^T h_i \quad \text{(Eq. 3.19)}
\]

and, by the principle of virtual work, the finger joint torque is

\[
\tau_i = J_f^T B_i^T h_i \quad \text{(Eq. 3.20)}
\]

The velocity and force equations for each finger can be expanded to consider the \( n \) fingers of the gripper giving:

\[
G \ a V_b = J_a \dot{q} \quad \text{(Eq. 3.21)}
\]

where:
\( \mathbf{G} = \mathbf{B}\begin{bmatrix} \Delta_{b_1} & \cdots & \Delta_{b_n} \end{bmatrix}^T \) is the grasp matrix,

\( \mathbf{J}_k = \mathbf{B} \text{diag}[\mathbf{J}_{f_1} \cdots \mathbf{J}_{f_n}] \) is the gripper Jacobian

\[
\dot{\mathbf{q}} = \begin{bmatrix} \dot{q}_1 & \cdots & \dot{q}_n \end{bmatrix}^T \\
\mathbf{a}_k = \begin{bmatrix} a_{b_1} \mathbf{V}_{b_1} & \cdots & a_{b_n} \mathbf{V}_{b_n} \end{bmatrix}^T
\]

with \( k = \sum_{i=1}^n k_i \) and \( \mathbf{B} = \text{diag}[\mathbf{B}_1 \cdots \mathbf{B}_n] \)

The grasp matrix will be time dependent if the fingertips roll or slide over the object.

The force relations for the gripper are:

\[ \lambda_b = \mathbf{G}^T \mathbf{h} \tag{Eq. 3.22} \]

\[ \mathbf{\tau} = \mathbf{J}_k^T \mathbf{h} \tag{Eq. 3.23} \]

The first of these two expressions, (Eq. 3.22), relates the resultant force acting on the object (\( \lambda_b \)) to the force (\( \mathbf{h} \)) applied at the contact locations. The second expression (Eq. 3.23) shows the relationship between the joint torques (\( \mathbf{\tau} \)) and the exerted forces (\( \mathbf{h} \)).

The force and velocity relations are summarized in Table 3.1, where \( \mathbf{v} \) represents the contact velocity.

**Table 3.1 Force and velocity relations for a multi-fingered gripper**

<table>
<thead>
<tr>
<th></th>
<th>Joints to fingertips</th>
<th>Object to fingertips</th>
</tr>
</thead>
<tbody>
<tr>
<td>velocity</td>
<td>( \mathbf{v} = \mathbf{J}_k \dot{\mathbf{q}} )</td>
<td>( \mathbf{G} \mathbf{a}_b = \mathbf{v} )</td>
</tr>
<tr>
<td>force</td>
<td>( \mathbf{\tau} = \mathbf{J}_k^T \mathbf{h} )</td>
<td>( \lambda_b = \mathbf{G}^T \mathbf{h} )</td>
</tr>
</tbody>
</table>

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This formulation can be applied to grasp planning and control, considering different contact cases both in terms of transmission of forces and relative contact velocities; it is then possible to consider roll and slip at the fingertips.

Cole et al. (1988) derives the kinematic equations of rolling contact for two surfaces of arbitrary shape rolling on each other by considering the contact between the two surfaces to be of a point contact type with Coulomb friction. Using these equations he proposes a control scheme for a planar two-fingered hand manipulating a rigid object. Slipping contacts are considered by Cole et al. (1992) and the kinematic and dynamic equations for a fingered gripper are obtained for a rigid product. Then a dynamic coordinated control scheme is derived for a gripper manipulating a product in the plane. This has particular interest for regrasping operations, where the manipulation of the product can be achieved by controlling the slip between the fingers and the product.

Li et al. (1989) based on the assumption of point contact models and rigid grasps, developed a control scheme using a computed torque methodology, taking in account the dynamics of the rigid object and of the fingers of the gripper. This control scheme is similar to that in Cole et al. (1988). The control scheme enables the desired trajectory for the object to be implemented and the desired internal grasp forces applied. This formulation does not take into consideration environmental constraints imposed on the motion of the product during manipulation. To include these constraints a new formulation is proposed by Yoshikawa and Zheng (1993). A dynamic hybrid position/force control assuming point contacts and no slip at the fingertips is considered.

3.2 THE KINEMATIC MODEL OF THE GRIPPER

The gripper can be viewed as a group of $n$ equal fingers fixed to a support frame (see Figure 3.2) due to its configuration and modularity. Each finger can be considered as a revolute and planar arm having three links and three joints; the first link and joint are fixed to the support frame; the
second link corresponds to the carrier of the finger; the second joint implements the carrier movement - the grasp movement of a finger; the third link corresponds to a virtual arm defined by the radius of the roller that is established in the direction of contact between finger and product; the third joint, enabling the rotation of the finger, implements the roller movement.

![Figure 3.2 Grippe configuration](image)

For each finger the relevant coordinate frames and variables are shown in Figure 3.3.

![Figure 3.3 Coordinate frames for a finger](image)

- \{C_a\} Absolute base frame
- \{C_{1n}\} Frame at carrier joint of finger \(n\)
- \{C_{2n}\} Frame at roller joint of finger \(n\)
- \{C_{3n}\} Frame at tip point of finger \(n\)
- \(b_n\) radius of roller of finger \(n\)
- \(\beta_n\) angle of rotation of carrier of finger \(n\)
- \(a_n\) radius of carrier of finger \(n\)
- \(\alpha_n\) angle of rotation of carrier of finger \(n\)
- \(e_n\) reference distance of location of carrier
- \(\xi_n\) reference angle of location of carrier
- \(P_n\) Contact point on finger \(n\)
The geometric configuration of the gripper is then described by the following parameters:

\[ n \] - number of fingers

and for each finger \( n \)

\( (e_n, \zeta_n) \) - location of the centre of rotation of the carrier

\( a_n \) - carrier radius

\( b_n \) - roller radius

where the variables of the joints are:

\( \alpha_n \) - angle of rotation of the carrier

\( \beta_n \) - angle of rotation of the roller

3.2.1 ANALYSIS OF A FINGER OF THE GRIPPER

3.2.1.1 Forward and inverse Kinematics

The position of the finger in the workspace is given by the angle of rotation of the carrier. When it is considered a contact point in the surface of the roller of the finger, the location of that contact is given by the angle of rotation of the roller. In such a situation, a finger of the gripper can be seen as a two-link, revolute and planar manipulator. The forward and inverse kinematics for that case are well known (see Lewis et al., 1993).

In order to obtain the forward kinematics of a finger it is required to write the position vector, \( r_n \), for the point of contact expressed in the coordinate frame of the carrier joint \( \{C_{1n}\} \) (refer to Figure 3.3). That kinematic transformation is given by:

\[
\hat{r}_n \|_{\{C_{1n}\}} = ^{1n}R_{3n}^r r_n \|_{\{C_{3n}\}} + ^{1n}R_{2n}^r P_{C_{3n}} \|_{\{C_{2n}\}} \quad (Eq. 3.24)
\]

where \(^{1n}R_{3n}\) and \(^{1n}R_{2n}\) are the rotation matrices (3x3) of the coordinate system \( \{C_{3n}\} \) and \( \{C_{2n}\} \) with respect to the coordinate system \( \{C_{1n}\} \) and are given by:
\[ \begin{bmatrix} \cos \alpha_n & -\sin \alpha_n & 0 \\ \sin \alpha_n & \cos \alpha_n & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\[ \begin{bmatrix} \cos(\alpha_n + \beta_n) & -\sin(\alpha_n + \beta_n) & 0 \\ \sin(\alpha_n + \beta_n) & \cos(\alpha_n + \beta_n) & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

To obtain the inverse kinematics different techniques are available such as dual matrices, iterative process, dual quaternion, screw algebra, inverse transform and geometric approaches (see Fu et al., 1987). Considering the simplicity of the problem, the use of the geometric approach is adopted. The inverse kinematics for a finger requires finding a solution for the joint variables \((\alpha_n, \beta_n)\) that correspond to the location of the contact point \((P_n)\). Referring to Figure 3.4 the following solution for \(\alpha_n\) and \(\beta_n\) is obtained:

\[
\begin{align*}
    r_n^2 &= x_n^2 + y_n^2 \\
    r_n^2 &= a_n^2 + b_n^2 + 2a_nb_n \cos \beta_n \\
    \cos \beta_n &= \frac{r_n^2 - a_n^2 - b_n^2}{2a_nb_n} = C \\
    \sin \beta_n &= \pm \sqrt{1 - \cos^2 \beta_n} = \pm \sqrt{1 - C^2} = D \\
    \tan \xi_n &= \frac{b_n \sin \beta_n}{a_n + b_n \cos \beta_n} \\
    \tan(\xi_n + \alpha_n) &= \frac{y_n}{x_n}
\end{align*}
\]

Then

\[
\begin{align*}
\beta_n &= \tan^{-1}(D/C) \quad \text{and} \quad \alpha_n &= \tan^{-1}\left(\frac{y_n}{x_n}\right) - \tan^{-1}\left(\frac{b_n \sin \beta_n}{a_n + b_n \cos \beta_n}\right) \quad \text{(Eq. 3.25)}
\end{align*}
\]

\[ \mathbf{r}_n = [x_n, y_n]^T \quad \text{Position vector for the contact point on finger} \ n \ \text{expressed in frame} \ \{C_{1n}\} \]

\textbf{Figure 3.4 Inverse kinematics for the finger}
In (Eq. 3.25) the use of the arctangent function rather arccosine is justified for reasons of implementation. The arctangent function, \( \tan^{-1}(y/x) \), is implemented within the Microsoft Excel by \( \text{ATAN2}(x,y) \). This function returns a unique value for the angle depending on the signs of \( x \) and \( y \), and gives the correct solution if \( x \) is zero or \( y \) is zero.

### 3.2.1.2 The Jacobian

The Jacobian of the finger, \( J \), maps the joint velocity (\( \dot{q} \)) to the cartesian velocity (\( \dot{p} \)), where:

\[
\dot{p} = J(q)\dot{q}
\]

\((\text{Eq. 3.26})\)

The Jacobian of a finger is given by (refer to Figure 3.4 and note that the Jacobian is expressed in relation to the coordinate frame \( \{C_{in}\} \):

\[
\begin{bmatrix}
\dot{x}_n \\
\dot{y}_n
\end{bmatrix} = J
\begin{bmatrix}
\dot{\alpha}_n \\
\dot{\beta}_n
\end{bmatrix}
\quad \text{and} \quad
\begin{bmatrix}
p_x \\
p_y
\end{bmatrix} =
\begin{bmatrix}
a_n \cos \alpha_n + b_n \cos(\alpha_n + \beta_n) \\
ha_n \sin \alpha_n + b_n \sin(\alpha_n + \beta_n)
\end{bmatrix}
\]

\((\text{Eq. 3.27})\)

The determinant of the Jacobian is:

\[
\det J = a_n b_n (\cos(\alpha_n) \sin(\alpha_n + \beta_n) - \sin(\alpha_n) \cos(\alpha_n \beta_n)) = a_n b_n \sin \beta_n
\]

\((\text{Eq. 3.28})\)

The inverse of the Jacobian, using an analytical approach, is obtained as follows:

\[
\begin{bmatrix}
\dot{\alpha}_n \\
\dot{\beta}_n
\end{bmatrix} = J^{-1}
\begin{bmatrix}
\dot{x}_n \\
\dot{y}_n
\end{bmatrix}
\]

and solving in order to have \( \dot{\alpha}_n \) and \( \dot{\beta}_n \):

\[
\begin{bmatrix}
\dot{x}_n \\
\dot{y}_n
\end{bmatrix} =
\begin{bmatrix}
-a_n \sin \alpha_n - b_n \sin(\alpha_n + \beta_n) \\
a_n \cos \alpha_n + b_n \cos(\alpha_n + \beta_n)
\end{bmatrix}
\begin{bmatrix}
\dot{\alpha}_n \\
\dot{\beta}_n
\end{bmatrix}
\]

\[
\begin{bmatrix}
\dot{\alpha}_n = \cos(\alpha_n \beta_n) \dot{x}_n + \frac{\sin(\alpha_n + \beta_n)}{a_n \sin \beta_n} \dot{y}_n \\
\dot{\beta}_n = \frac{a_n \cos(\alpha_n) + b_n \cos(\alpha_n + \beta_n)}{a_n b_n \sin \beta_n} \dot{x}_n - \frac{a_n \sin \alpha_n + b_n \sin(\alpha_n + \beta_n)}{a_n b_n \sin \beta_n} \dot{y}_n
\end{bmatrix}
\]
\[
J^{-1} = \begin{bmatrix}
\frac{\cos(\alpha_n + \beta_n)}{a_n \sin \beta_n} & \frac{\sin(\alpha_n + \beta_n)}{a_n \sin \beta_n} \\
-\frac{a_n \cos \alpha_n - b_n \cos(\alpha_n + \beta_n)}{a_n b_n \sin \beta_n} & -\frac{a_n \sin \alpha_n - b_n \sin(\alpha_n + \beta_n)}{a_n b_n \sin \beta_n}
\end{bmatrix}
\]

(Eq. 3.29)

### 3.2.1.3 Kinematic optimization of the design of a finger

The kinematic tools reviewed in the beginning of this chapter will now be used to optimize the design of a finger.

The analysis of the determinant of the Jacobian enables the determination of the configurations for which the finger reaches a singular point. From expression given in (Eq. 3.28) it is possible to conclude that these configurations occur when the direction of the virtual link of the roller is aligned with the carrier. This occurs independently of the radius of the carrier and of the radius of the roller. This conclusion just points out that when operating a gripper, with a given number of fingers, to hold or manipulate a product, the relative positions of the fingers should be selected so as to avoid the individual singular locations of each finger.

The concept of velocity and force ellipsoids (Asada, 1983, Yoshikawa, 1985b), where the volume of the ellipsoid is used as a performance measure, can also be applied to the design of a finger. Configurations that maximize the volume of the ellipsoid correspond to position the finger away from singular points. Uchiyama et al. (1984) and Yoshikawa (1985b) showed that the volume of the velocity ellipsoid for non redundant manipulators, is directly proportional to the modulus of the det \( J \). The plot presented in Figure 3.5 shows the variation of this performance measure with the rotation angle of the roller. As the Jacobean is a function of the length of the links, as it can be seen by (Eq. 3.27), this lead to consider different configurations of a finger. The ratio between the radius of carrier \((a)\) and the radius of the roller \((b)\) defines the configuration of the finger. For comparison purposes of different configurations the sum of these two parameters is kept constant \((a+b=1)\) and different ratios of \(a/b\) are considered. The results that maximize the measure of performance point to a finger configuration with the radius of the carrier equal to the radius of the roller.
Figure 3.5 The determinant of the Jacobian and the configuration of the finger

Another important measure of performance as an optimization criterion in link design is the condition number of the transpose of the Jacobian (Salisbury and Craig, 1982). Configurations that minimize the condition number of $J^T$ improve the force application accuracy. The minimum possible value for the condition number is unity. The correspondent locations are called isotropic points. These locations are suitable for implementation of fine velocity and force control equally in any direction. The plot shown in Figure 3.6 presents the variation of the condition number of $J^T$ with the rotation angle of the roller, considering different configurations of the finger, as the Jacobean is a function of the length of the links of the finger. Therefore the condition number of $J^T$ is also a function of the lengths of the links. The configuration that minimizes the condition number corresponds to a finger having a carrier radius ($a$) larger than the roller radius ($b$), by a multiplication factor of square root of two. A continuous set of isotropic points exists for this configuration. These points are on a circle of radius ($b$) and centre on the joint of the carrier, as shown in Figure 3.7. For other configurations, the path of points that minimize the condition number is also circular and centred on the joint of the carrier.
The use of the condition number points to a different finger configuration when compared with the previous method for maximization of the ellipsoid of velocity. Other design criteria are required to be investigated, such as the shape and size of the work area of a finger. This is important since the finger has the particularity of having a link - the roller radius - occupying a circular area. As each finger moves on a planar and circular path, the work envelope for each finger is an annular region bounded by two concentric circles. The radii of these two concentric circles depend on the configuration of the finger, i.e., on the length of the carrier \( a \) and on the radius of the roller \( b \). The radius of the outer boundary circle is given by \( a+b \) and the radius of the inner boundary circle is
given by $|a-b|$. The size of the work area is then given by $4\pi ab$. The shape of the work area reflects the relative sizes of the carrier and the roller. Three possible configurations for a finger, corresponding to the cases of $a < b$, $a = b$, $a > b$ and a fourth particular configuration with $a = 2b$, are presented in Figure 3.8.

![Figure 3.8 Work area and configurations of the finger](image)

For each configuration, it is possible to define a ratio of areas between the area used by the finger and the total work area. This parameter, given by $b/(4a)$, measures the occupation of the available work area. The smaller the ratio, the better, i.e., a small part of the work area is occupied by the finger and so there is more space available to place a product. Fixing the work area of a finger, $a+b=const.$, the configuration having $a > b$ gives the best result.

The configuration of a finger is also important for the implementation of manipulation and perception tasks. When using the gripper for identification of a profile of a product, the finger has the behaviour of a typical oscillating roller that follows the profile. The values of the radius of the roller and of the carrier restrict the capability of identifying product features in terms of resolution (Figure 3.9). A smaller radius follows smaller features.

![Figure 3.9 Size of roller of a finger and profile identification](image)
Considering the above three criteria (shown in Figure 3.5, Figure 3.6 and Figure 3.8) the chosen design sizes of the finger were a compromise. The adopted value for the radius of the carrier is larger than the radius of the roller, by a factor of two \((a=2b)\).

3.2.2 ANALYSIS OF SPECIFIC CONFIGURATIONS OF THE GRIPPER

The modularity of the gripper allows for setting up a gripper with a different number of fingers. Configurations using one, two and three fingers will now be examined.

3.2.2.1 Gripper with one finger

A gripper with only one finger requires the use of a base frame to enable the product to be grasped and manipulated between the base frame and the finger. Three different configurations of such a gripper using a planar and fixed base frame are presented in Figure 3.10.

![Figure 3.10 Configurations for a one-fingered gripper](image)

The selection of a configuration for this type of gripper will use the considerations established in the design of a finger. It was seen in the previous section (section 3.2.1.3) that the best position to exert force and velocity control equally is defined by the configuration of the finger that minimizes the condition number of the Jacobian transpose. This position can be selected for the initial contact point between the finger and the product. For the adopted configuration of a finger (the radius of the carrier with the double size of the radius of the roller, \(a=2b\)) this point occurs when the angle between the
carrier and the grasp direction, $\varphi_{cn_{min}}$, is equal to 132 degrees (refer to Figure 3.11). The location of the joint of the carrier relative to the base frame can then be chosen as a function of a reference distance. This reference distance is defined from the contact point (the fingertip) to the fixed frame, measured in the orthogonal direction to the fixed frame and will be referred to as the grasp gap. If the nominal value of the grasp gap is $l_{gn}$ (refer to Figure 3.11), the ideal location for the centre of the joint of the carrier, $d_r$, is given by:

$$d_r = l_{gn} - \left( a \cos(\varphi_{cn_{min}}) - b \right)$$  \hspace{1cm} (Eq. 3.30)

Note that this grasp gap can be regarded as the nominal size of a product.

![Diagram](image)

*Figure 3.11 Particular configuration for a one-fingered gripper*

The force that the finger can exert in the grasp direction is a function of the value of the angle between the carrier and the grasp direction. Considering that the grasp direction remains orthogonal to the fixed frame, the variation of the grasp force with the grasp gap can be plotted for different configurations of the gripper. The plot shown in Figure 3.12 considers that the finger has a configuration given by $a=2b$ and the nominal grasp gap corresponds to a gripper configuration that minimizes the condition number of the Jacobian transpose of the finger. With the plot shown in Figure 3.12 it is possible to identify, for different configurations of the gripper, what is the admissible variation in the grasp gap if the grasp force is to be kept within a given interval. For example, if it is considered that the grasp force should be kept within the range 50 % to 100 %, the gripper
configuration with $d_f=a$ is able to cope with changes in the grasp gap, from zero up to 117% of the nominal grasp gap.

$$F = \frac{T_m}{a} \eta \sin \varphi$$

$$l_g = d_f - b - a \cos \varphi$$

*Figure 3.12 Grasp force for configurations of a one-fingered gripper*

### 3.2.2.2 Gripper with two fingers

A gripper making use of two fingers enables different configurations defined by the relative location of the fingers. These configurations define the pattern of the interaction between the work area of each finger. Figure 3.13 presents three possible configurations and work areas for a two-fingered gripper.
The choice of a configuration for this type of gripper will use the findings of previous configurations of a finger and one-fingered gripper.

The relative location of the two fingers should be chosen such that, when a gripper holds a reference product, each contact point between the finger and product (the fingertip) should correspond to the configuration of the finger that minimize the condition number of the Jacobian transpose. As for each finger there are an unlimited number of points that verify this condition (the points that belong to a circle concentric with the joint of the carrier) an infinite number of possible configurations for the gripper exists. To chose a configuration, a nominal distance between the two contact points is selected and the alignment of the grasp direction with the direction defined by the centres of the rollers of the two fingers is imposed, as shown in Figure 3.14. The distance between the contact points on each finger will be referred to as the grasp gap. This grasp gap can be regarded as the nominal size of a product in the grasp direction. If the nominal value of the grasp gap is \( l_{gn} \) (refer to Figure 3.14), the ideal relative location for the centres of the joints of the fingers, \( d \), is given by:

\[
d = l_{gn} - 2a \| \cos(\phi_{cm}) \| - b
\]

(Eq. 3.31)
Considering that the grasp direction is kept fixed, the variation of the grasp force with the grasp gap can be plotted for different configurations of a gripper. The plot shown in Figure 3.15 considers that each finger has a configuration given by $a=2b$ and the nominal grasp gap corresponds to a gripper configuration that minimizes the condition number of the Jacobian transpose of each finger. The plot shown in Figure 3.15 can be used to find what the admissible variation in the grasp gap is if the grasp force is to be kept within a given interval when considering different configurations of a gripper. For example, the configuration of the gripper having $d=2a$ is able to cope with grasp gaps, ranging from 0 to 117% of the nominal grasp gap, while maintaining the grasp force within the range of 50% to 100%.

\[
F = \frac{T_m}{a} \eta \sin \varphi \\
l_g = d + 2a \left[ \cos(\pi - \varphi) \right] - 2b
\]
3.2.2.3  

**Gripper with three fingers**

The choice of a configuration for a gripper with three fingers follows the approach used for the design of a gripper with one and two fingers. The relative location of the fingers is chosen such that the initial contact between a reference product and each roller corresponds to an arrangement of the three fingers that minimizes the condition number of the Jacobian transpose of each finger. It was seen in section 3.2.1.3 that each finger has an infinite set of points, lying on a circular path, that verify that condition. This would lead to multiple possible configurations for a gripper. To select a configuration for a gripper it is considered that, for a reference product of circular shape, the geometric centre of the product should be located at the centre of the gripper. This leads to a configuration of the gripper with the joint of the carrier of each finger equally spaced on a circle, as shown in Figure 3.16. This circle is concentric with the product. For this configuration and for the reference product with a circular shape, the grasp forces exerted by the fingers converge to the centre of the product and the contact angles have the same value. The gripper that was built uses a configuration as the one shown in Figure 3.16. The size of the reference circular product was chosen to be 52.6 mm to give a separation between the fingers such that:

\[ d = 2a = 4b = 100 \text{ mm} \]  

(Eq. 3.32)

\[ \text{Figure 3.16  Configuration for a three-fingered gripper} \]
For a configuration of the gripper as the one shown in Figure 3.16, the relation between the nominal size of the reference product ($\rho_{pn}$) and the separation of the joints of the carriers ($d$) is given by:

$$d = \sqrt{a^2 + \left(\frac{x_{pm} + b}{2}\right)^2 + 2a \left(\frac{x_{pm} + b}{2}\right) \cos(\phi_{\text{cm}})}$$  

(Eq. 3.33)

To choose a configuration for the gripper, as a function of the nominal size of the circular product, the plot that results from the use of (Eq. 3.33), is shown in Figure 3.17. It is considered that, for each finger, the size of the radius of the carrier has the double size of the radius of the roller ($a=2b$). The nominal size of the circular product is normalized with reference to the radius of the carrier. The separation of the carriers of the fingers, which define the configuration of the gripper, is also normalized with reference to the radius of the carrier.

![Figure 3.17 Separation of centres of joints of carriers and size of reference product for a three-fingered gripper](image)

For each configuration of a gripper, the force each finger exerts in the direction of contact changes if the nominal size of the product is modified. The force a finger exerts in the grasp direction
is given by (Eq. 3.34). The contact angle, expressed as a function of the nominal size of the product, is given by (Eq. 3.35).

\[
F = \frac{T_m}{a} \eta \sin \varphi
\]  
(Eq. 3.34)

\[
\varphi = \cos^{-1}\left(\frac{d^2 - 3a^2 - 3\left(\frac{\rho_{pn}}{2} + b\right)^2}{6a\left(\frac{\rho_{pn}}{2} + b\right)}\right)
\]  
(Eq. 3.35)

The plot shown in Figure 3.18 uses equations (Eq. 3.34) and (Eq. 3.35) to present, for different configurations of the gripper, the variation of the force exerted by one finger when the nominal size of the product changes. That plot can be used to select a configuration for a gripper. Considering that the size of the product is within a given range, a configuration for a three-fingered gripper that enables the application of grasp forces within a given range, can be chosen. As an example, the configuration of the gripper having \(d=2a\) is able to cope with products sizes ranging from 50% up to 150% of the nominal reference product size while maintaining the grasp force within the range of 95% down to 22%.

![Figure 3.18](image)

*Figure 3.18  Force applied by a finger in the direction of contact and the variation in the size of a reference product, for configurations of three-fingered grippers*
3.3 MANIPULATION OF PRODUCTS WITHIN THE GRIPPER

3.3.1 KINEMATIC ANALYSIS

The analytical model of a gripper presented in section 3.1.3 is now used as a planning tool for the manipulation of a product within the gripper. The strategy used to implement the manipulation of a product requires the establishment of the equations that govern the relation between the velocities of the joints of the fingers and the velocity of the product. The mapping of this relation can be obtained with the Jacobian transform. Then, using the algorithm presented in Figure 3.19, the desired trajectory of the product is used to compute the reference position signal that drives the joints of each finger. The implementation of this algorithm involves the computation of the inverse of the Jacobian and the use of the direct kinematics of the gripper.

![Diagram](image.png)

*Figure 3.19* Algorithm for implementing the manipulation of a product within the gripper
To view the implementation of this approach, the manipulation of two products using the model of the developed gripper is simulated. The simulation was performed using the Microsoft Excel spreadsheet. This computer program was also used to plot the results of the simulation. The products considered are a rectangular shaped product and a circular product. The first step to implement the algorithm is to obtain the Jacobian transform that relates the velocity of each finger with the velocity of the product.

For a finger contacting a rectangular product, the Jacobian can be obtained expressing the velocity of the product as a function of the velocity of the contact point. The coordinate frames and parameters presented in Figure 3.20 are considered to obtain the equation, (Eq. 3.36), that expresses the velocity of the product.

![Coordinate frames for a finger contacting a rectangular product](image)

Figure 3.20 Coordinate frames for a finger contacting a rectangular product
\[
\begin{bmatrix}
\dot{^1v}_{p1} \\
\dot{^1\omega}_{p1}
\end{bmatrix} = \begin{bmatrix}
\dot{^1v}_{r1} + {^1\omega}_{r1} \times ^1r_{Pc1} - {^1\omega}_{p1} \times ^1r_{Pc1} + t^1r_{Pc1} - ^1r_{p1} \\
\dot{^1\omega}_{c1} + c^1t_1 \omega_{r1} + c^1r_1 \omega_{r1}
\end{bmatrix}
\]  
(Eq. 3.36)

where

\(^1v_{p1}\) and \(^1\omega_{p1}\) are the linear and angular velocities of frame \(\{C_{p1}\}\) relative to frame \(\{C_1\}\)

\(^1v_{r1}\) and \(^1\omega_{r1}\) are the linear and angular velocities of frame \(\{C_{r1}\}\) relative to frame \(\{C_1\}\)

\(^1t_{Pc1}\) is the position vector of the contact point relative to frame \(\{C_{r1}\}\)

\(^1r_{Pc1} = \begin{bmatrix} 0 & r_{p1} \end{bmatrix}^T\) is the position vector of the contact point relative to frame \(\{C_{p1}\}\) and is expressed in frame \(\{C_{p1}\}\)

\(^1t_{Pc1}\) is the relative linear velocity of the contact point relative to frame \(\{C_{r1}\}\)

\(^1v_{Pc1}\) is the relative linear velocity of the contact point relative to frame \(\{C_{p1}\}\)

\(^1\omega_{c1} = \begin{bmatrix} 0 & 0 & \dot{\alpha}_{1} \end{bmatrix}^T\) is the angular velocity of frame \(\{C_{c1}\}\) relative to frame \(\{C_1\}\)

\(^1\omega_{r1} = \begin{bmatrix} 0 & 0 & \dot{\beta}_{1} \end{bmatrix}^T\) is the angular velocity of frame \(\{C_{r1}\}\) relative to frame \(\{C_{c1}\}\)

\(^1t_{r1} = \begin{bmatrix} 0 & 0 & \dot{\phi}_{1} \end{bmatrix}^T\) is the angular velocity of frame \(\{C_{r1}\}\) relative to frame \(\{C_{c1}\}\)

Expanding (Eq. 3.36) the following result is obtained:

\[
\begin{bmatrix}
\dot{x}_{p1} \\
\dot{y}_{p1} \\
\dot{\theta}_{p1}
\end{bmatrix} = \begin{bmatrix}
-a\dot{\alpha}_{1} \sin \alpha_{1} \\
a \dot{\alpha}_{1} \cos \alpha_{1} + b(\dot{\alpha}_{1} + \dot{\beta}_{1}) \sin \theta_{p1} \\
\dot{\alpha}_{1} + \dot{\beta}_{1} + \dot{\phi}_{1}
\end{bmatrix} \begin{bmatrix}
b(\dot{\alpha}_{1} + \dot{\beta}_{1}) \cos \theta_{p1} \\
r_{p1} \dot{\theta}_{p1} \cos \theta_{p1} \\
r_{p1} \dot{\theta}_{p1} \sin \theta_{p1}
\end{bmatrix} + \begin{bmatrix}
\sin \theta_{p1} (b\dot{\phi}_{1} - \dot{r}_{p1}) \\
\cos \theta_{p1} (b\dot{\phi}_{1} - \dot{r}_{p1}) \\
0
\end{bmatrix}
\]  
(Eq. 3.37)

Considering that the product rolls without slip, \(b\dot{\phi}_{1} - \dot{r}_{p1} = 0\) and (Eq. 3.37) can be written in a compact form as:

\[
\begin{bmatrix}
\dot{x}_{p1} \\
\dot{y}_{p1} \\
\dot{\theta}_{p1}
\end{bmatrix} = J \begin{bmatrix}
\dot{\alpha}_{1} \\
\dot{\beta}_{1} \\
\dot{\phi}_{1}
\end{bmatrix}
\]  
(Eq. 3.38)

where:
\[
J_1 = \begin{bmatrix}
-a \sin \alpha_i - b \sin \theta_{pl} + r_{pl} \cos \theta_{pl} & -b \sin \theta_{pl} + r_{pl} \cos \theta_{pl} & r_{pl} \cos \theta_{pl} \\
-a \cos \alpha_i + b \cos \theta_{pl} + r_{pl} \sin \theta_{pl} & b \cos \theta_{pl} + r_{pl} \sin \theta_{pl} & r_{pl} \sin \theta_{pl} \\
1 & 1 & 1
\end{bmatrix}
\] (Eq. 3.39)

The equation (Eq. 3.38) establishes the relation between the velocity of the product and the joint velocities of finger one. The same equation can be applied to the other fingers of the gripper.

The settings adopted for the simulation using the rectangular product are presented in Table 3.2. The planned manipulation implies the rotation of the product while keeping the geometric centre of the product fixed. The initial location of the product relative to the fingers is as shown in Figure 3.21. The centre of the product is placed at the centre of the gripper and the initial orientation of the product, relative to the fixed frame, is 20 deg. The location of the product defines the initial location of the fingers. Figure 3.21 also shows, for each finger, the adopted coordinate frames and the directions used in the measurement of the rotation angle of the carrier and the roller. The plot shown in Figure 3.22 presents the results of the simulation, where a sequence of the location of the product is shown. The position signal to drive each joint of the fingers, that was required to implement the manipulation of the product, is presented in the plots shown in Figure 3.23, for the rotation of the carriers, and in Figure 3.24, for the rotation of the rollers.

**Table 3.2** Settings for the manipulation of a rectangular product

| Configuration of gripper | three-fingered configuration, with 
| | a = 50 mm; b = 25 mm; d = 100 mm |
| Initial location of fingers | \( \alpha_1 = 125 \text{ deg} \) \( \alpha_2 = 118 \text{ deg} \) \( \alpha_3 = -107 \text{ deg} \) |
| Product shape | rectangular |
| Product dimension | 50x300 mm |
| Initial location of product | Geometric centre of product placed at centre of gripper |
| Product orientation: \( \theta_p = 20 \text{ deg} \) |
| Product manipulation rotation | 25 deg, around the geometric centre of the product, with a rotation velocity of \( \dot{\theta}_p = 0.313 \text{ deg/s} \) |
Figure 3.21  Initial location of product and coordinate frames adopted to simulate the manipulation of a rectangular product

Figure 3.22  Simulation results of the manipulation of a rectangular product
Figure 3.23  Manipulation of rectangular product - angle of rotation of the carriers

Figure 3.24  Manipulation of rectangular product - angle of rotation of the rollers
To obtain the Jacobian of a finger that contacts a circular product, the coordinate frames and parameters presented in Figure 3.25 are adopted.

\[
\begin{align*}
\{ C_1 \} & \quad \text{Reference frame fixed at joint of carrier of finger 1} \\
\{ C_{c1} \} & \quad \text{Frame associated to carrier of finger 1} \\
\{ C_{r1} \} & \quad \text{Frame associated to roller of finger 1} \\
\{ C_{pl} \} & \quad \text{Frame fixed to product} \\
\{ C_{1} \} & \quad \text{Product local frame, at contact point, relative to } \{ C_{r1} \} \\
\{ C_{ul} \} & \quad \text{Product local frame, at contact point, relative to } \{ C_{pl} \} \\
P_{ci} & \quad \text{Contact point between roller 1 and product}
\end{align*}
\]

**Figure 3.25 Coordinate frames for a finger contacting a circular product**

The velocity of the product, written as a function of the velocity of the contact point, is expressed by:

\[
\begin{bmatrix}
1v_{pl} \\
1\omega_{pl}
\end{bmatrix}
= \begin{bmatrix}
1v_{pl} + 1\omega_{pl} \times r_{pc1} - 1\omega_{pl} \times r_{pc1} + r_{pc1} \times 1v_{pc1} - 1\omega_{pl} \times r_{pc1} + r_{pc1} \times 1v_{pc1} \\
1\omega_{pl} + 1\omega_{pl} \times r_{pc1} - 1\omega_{pl} \times r_{pc1} + r_{pc1} \times 1v_{pc1} - 1\omega_{pl} \times r_{pc1} + r_{pc1} \times 1v_{pc1}
\end{bmatrix}
\] (Eq. 3.40)

where:

1. $1v_{pl}$ and $1\omega_{pl}$ are the linear and angular velocities of frame $\{ C_{pl} \}$ relative to frame $\{ C_1 \}$
2. $1v_{pl}$ and $1\omega_{pl}$ are the linear and angular velocities of frame $\{ C_{pl} \}$ relative to frame $\{ C_1 \}$
3. $r_{pc1}$ is the position vector of the contact point relative to frame $\{ C_{r1} \}$
\( p_l r_{pl} = [-r_{pl} \ 0 \ 0]^T \) is the position vector of the contact point relative to frame \( \{C_{pl}\} \) and is expressed in frame \( \{C_{ul}\} \).

\( v_{pl} \) is the relative linear velocity of the contact point relative to frame \( \{C_{pl}\} \).

\( v_{pl} \) is the relative linear velocity of the contact point relative to frame \( \{C_{pl}\} \).

\( \omega_{cl} = [0 \ 0 \dot{\alpha}]^T \) is the angular velocity of frame \( \{C_{cl}\} \) relative to frame \( \{C_1\} \).

\( \omega_{pl} = [0 \ 0 \dot{\beta}]^T \) is the angular velocity of frame \( \{C_{pl}\} \) relative to frame \( \{C_{cl}\} \).

\( \omega_{pl} = [0 \ 0 \dot{\phi}]^T \) is the angular velocity of frame \( \{C_{pl}\} \) relative to frame \( \{C_{cl}\} \).

\( \omega_{pl} = [0 \ 0 \dot{\psi}]^T \) is the angular velocity of frame \( \{C_{pl}\} \) relative to frame \( \{C_{pl}\} \).

Expanding (Eq. 3.40) the following result is obtained:

\[
\begin{bmatrix}
\dot{x}_{pl} \\
\dot{y}_{pl} \\
\dot{\theta}_{pl}
\end{bmatrix} =
\begin{bmatrix}
-a \alpha_1 \sin \alpha_1 \\
a \alpha_1 \cos \alpha_1 \\
\alpha_1 + \beta_1 + \phi_1 - \psi_1
\end{bmatrix}
+ \begin{bmatrix}
-b(\alpha_1 + \beta_1) \sin(\alpha_1 + \beta_1 + \phi_1) \\
-b(\alpha_1 + \beta_1) \cos(\alpha_1 + \beta_1 + \phi_1) \\
0
\end{bmatrix}
+ \begin{bmatrix}
-r_{pl} \dot{\theta}_{pl} \sin(\alpha_1 + \beta_1 + \phi_1) \\
r_{pl} \dot{\theta}_{pl} \cos(\alpha_1 + \beta_1 + \phi_1) \\
0
\end{bmatrix}
+ \begin{bmatrix}
-sin(\alpha_1 + \beta_1 + \phi_1)(b\dot{\phi}_1 + r_{pl}\dot{\psi}_1) \\
cos(\alpha_1 + \beta_1 + \phi_1)(b\dot{\phi}_1 + r_{pl}\dot{\psi}_1) \\
0
\end{bmatrix}
\]  
(Eq. 3.41)

Considering that the product rolls without slip, \((b\dot{\phi}_1 + r_{pl}\dot{\psi}_1) = 0\) and (Eq. 3.41) can be written, in a compact form, as:

\[
\begin{bmatrix}
\dot{x}_{pl} \\
\dot{y}_{pl} \\
\dot{\theta}_{pl}
\end{bmatrix} = J_1 \begin{bmatrix}
\dot{\alpha}_1 \\
\dot{\beta}_1 \\
\dot{\phi}_1
\end{bmatrix}
\]  
(Eq. 3.42)

where

\[
J_1 =
\begin{bmatrix}
-a \sin \alpha_1 - b \sin \gamma - r_{pl} \sin \gamma \\
a \cos \alpha_1 + b \cos \gamma + r_{pl} \cos \gamma \\
1
\end{bmatrix}
\begin{bmatrix}
-b \sin \gamma - r_{pl} \sin \gamma \\
-b \cos \gamma + r_{pl} \cos \gamma \\
1 + \frac{b}{r_{pl}}
\end{bmatrix}
\]  
(Eq. 3.43)

with \( \gamma = \alpha_1 + \beta_1 + \phi_1 \)
The (Eq. 3.42) establishes the relation between the joint velocities of one finger and the velocity of the product. The same equation can be applied to the other fingers. The settings adopted for the simulation using the circular product are presented in Table 3.3. The planned manipulation implies the displacement within the fingers of the circular product while keeping fixed the orientation of the product. The product is initially placed at the geometric centre of the gripper. The size of the product was chosen to enable the minimization of the condition number of the Jacobian transpose of each finger at the initial grasp configuration, as seen previously in section 4.2.2.3. The initial location of the product and the coordinate frames adopted in the implementation of the simulation are shown in Figure 3.26. The plot shown in Figure 3.27 presents the results of the simulation, where a sequence of the location of the product is presented. The position signal to drive each joint of the fingers, that was required to implement the manipulation of the product, is presented in the plots shown in Figure 3.28, for the rotation of the carriers, and in Figure 3.29, for the rotation of the rollers.

<table>
<thead>
<tr>
<th>Configuration of gripper</th>
<th>three-fingered configuration, with a = 50 mm; b = 25 mm; d = 100 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial location of fingers</td>
<td>$\alpha_1 = -62 \text{ deg} \quad \alpha_2 = 58 \text{ deg} \quad \alpha_3 = 178 \text{ deg}$</td>
</tr>
<tr>
<td>Product</td>
<td>shape: circular</td>
</tr>
<tr>
<td></td>
<td>dimension: $\varnothing 52.6 \text{ mm}$</td>
</tr>
<tr>
<td>Initial location of product</td>
<td>Geometric centre of product placed at centre of gripper</td>
</tr>
<tr>
<td></td>
<td>Product orientation: $\theta_p = 0 \text{ deg}$</td>
</tr>
<tr>
<td>Product manipulation</td>
<td>20 mm in 45 deg direction, with a velocity of 0.25 mm/s</td>
</tr>
<tr>
<td>linear displacement</td>
<td></td>
</tr>
<tr>
<td>rotation</td>
<td>$\theta_p = 0 \text{ deg}$.</td>
</tr>
</tbody>
</table>
Figure 3.26  Initial location of product and coordinate frames adopted to simulate the manipulation of a circular product

Figure 3.27  Simulation results of the manipulation of circular product
Figure 3.28 Manipulation of circular product - angle of rotation of the carriers

Figure 3.29 Manipulation of circular product - angle of rotation of the rollers
3.3.2 ANALYSIS OF STATIC EQUILIBRIUM

The previous section examined the kinematic aspects of the manipulation of a product. It was shown how to compute the reference position signals used to drive the joints of the fingers leading to the desired motion of the product. The implementation of the manipulation of the product can only be done if it is possible to keep the product in equilibrium at each grasp configuration. To verify the equilibrium of the product at each grasp configuration, a static analysis of the forces exerted by the fingers on the product is made.

The force equilibrium requires that the resultant of the forces and moments applied on the product is null:

\[
\sum_{i=0}^{n} f_i = 0 \tag{Eq. 3.44}
\]

\[
\sum_{i=0}^{n} r_i \times f_i = 0
\]

where

\( f_i \) is the force vector applied at the contact point by finger \( i \)

\( r_i \) is the position vector of the contact point \( i \) relative to the centre of mass of the product

Applying the condition of force equilibrium to the manipulation of the rectangular product (refer to Figure 3.31) the following relations are obtained:

\[
\begin{align*}
\{ f_1 + f_2 + f_3 & = 0 \\
r_1 \times f_1 + r_2 \times f_2 + r_3 \times f_3 & = 0
\end{align*} \tag{Eq. 3.45}
\]

Setting a value for \( f_1 \), the values of \( f_2 \) and \( f_3 \) that verify this system of equations are given by:
\[ \| r_2 \| = \| r_3 \| \sin(\theta_3 - \theta_p) - \| r_1 \| \sin(\theta_1 - \theta_p) \\
\| r_3 \| = \| r_2 \| \sin(\theta_2 - \theta_p) - \| r_1 \| \sin(\theta_1 - \theta_p) \]  

(Eq. 3.46)

where

\( \theta_1, \theta_2 \) and \( \theta_3 \) are the orientation angles of \( r_1, r_2 \) and \( r_3 \) relative to the reference frame \( \{C_a\} \)

\( \theta_p \) is the orientation angle of the product, relative to the reference frame \( \{C_a\} \)

It can be concluded that the values \( \| r_2 \| \) and \( \| r_3 \| \) in (Eq. 3.46) must be positive so that exists a solution for \( f_1, f_2 \) and \( f_3 \) satisfying the conditions of force equilibrium. This leads to the following relation between the location of the contact points and the orientation of the product:

\[ \| r_3 \| \sin(\theta_3 - \theta_p) - \| r_1 \| \sin(\theta_1 - \theta_p) > \| r_2 \| \sin(\theta_2 - \theta_p) - \| r_3 \| \sin(\theta_3 - \theta_p) \]  

(Eq. 3.47)

\[ -\| r_2 \| \sin(\theta_2 - \theta_p) - \| r_1 \| \sin(\theta_1 - \theta_p) > \| r_3 \| \sin(\theta_2 - \theta_p) - \| r_3 \| \sin(\theta_3 - \theta_p) \]

The conditions expressed in (Eq. 3.47) were verified during the simulation of the manipulation of the rectangular product, presented in the previous section.

The kinematic constraints expressed by (Eq. 3.47) are better interpreted through the examples of the grasp configurations presented in Figure 3.30: a stable grasp can be achieved with the configurations (i) and (ii) but with the grasp configuration (iii) that is impossible.

![Diagram](image)

*Figure 3.30 Kinematic constraints in the manipulation of a rectangular product*
Figure 3.31  Manipulation of rectangular product - force analysis

Applying the condition of force equilibrium to the manipulation of the circular product (refer to Figure 3.32) it can be verified that the forces applied by each finger converge to the geometric centre of the product. Thus, the equations of static equilibrium reduce to:

\[ f_1 + f_2 + f_3 = 0 \]  \hspace{1cm} (Eq. 3.48)

Expanding (Eq. 3.48) gives:

\[
\|f_1\|\cos(\theta_1) + \|f_2\|\cos(\theta_2) + \|f_3\|\cos(\theta_3) = 0 \\
\|f_1\|\sin(\theta_1) + \|f_2\|\sin(\theta_2) + \|f_3\|\sin(\theta_3) = 0 \]  \hspace{1cm} (Eq. 3.49)

where

\[ \theta_1, \theta_2 \text{ and } \theta_3 \text{ are the orientation angles of } f_1, f_2 \text{ and } f_3 \text{ relative to the reference frame } \{C_a\} \]
Figure 3.32 Manipulation of circular product - force analysis

Expressing \( f_2 \) and \( f_3 \) in (Eq. 3.49) as function of \( f_1 \) it is obtained:

\[
\|f_2\| = \|f_1\| \frac{\sin(\theta_2 - \theta_1)}{\sin(\theta_2 - \theta_3)} \\
\|f_3\| = \|f_1\| \frac{\sin(\theta_2 - \theta_1)}{\sin(\theta_2 - \theta_3)}
\]  
(Eq. 3.50)

In order to find a solution for the system of equations (Eq. 3.50) the following conditions must be verified:

\[
\sin(\theta_3 - \theta_1) > \sin(\theta_2 - \theta_3) \\
\sin(\theta_2 - \theta_1) > \sin(\theta_2 - \theta_3)
\]  
(Eq. 3.51)

The conditions expressed in (Eq. 3.51) can be used for planning and accessing the implementation of the manipulation of a product. These conditions were verified during the manipulation of the circular product presented in the previous section.
The kinematic constraints expressed by (Eq. 3.51) imply that, in order to grasp a circular product securely, the three contact points cannot be located in the same half sector of the product, as shown in Figure 3.33.

![Grasp Stability Diagram](image)

**Figure 3.33 Kinematic constraints in the manipulation of circular product**

### 3.3.3 CONCLUSIONS

This section presents the simulation of the manipulation of products making use of the model of the developed gripper. Although the manipulation of rigid products is considered and point contact types between the fingers and the product are assumed, this analysis can be used as a reference approach to the manipulation of non-rigid products. For a non-rigid product, at discrete time intervals, the shape of the product may be assumed to remain constant. The shape and the location of the product within the gripper at each instant may be accessed and used to update the model of the planned manipulation and to control the manipulation of the product.
3.4 SUMMARY

In this chapter different kinematic tools available for the design and optimization of robotic manipulators were reviewed. These tools were then used for the design and analysis of the gripper. Different configurations of the gripper making use of one, two and three fingers, were presented and discussed. The kinematic model of the gripper developed was presented and used for simulating the manipulation of products. It was shown how to plan and implement the manipulation of rectangular and circular shaped products within the gripper. An analysis of the static equilibrium of possible grasp configurations was performed to access the feasibility of the implementation of the manipulation of the products.
4  THE EXPERIMENTAL APPARATUS

From custom specifications and basic concepts described in chapter 2 and using the kinematic
tools and the findings presented in chapter 3, the experimental rig is now defined. This chapter
presents the physical and operational characteristics of the prototype of the gripper that has been built.
It focuses on the mechanical design of the gripper and on the sensing systems employed and
developed. It discusses different methods for the control of the fingers of the gripper and presents the
control architecture adopted.

4.1  THE GRIPPER

The concept of a gripper for non-rigid products presented in chapter 2 was used to build a
particular configuration of the gripper (Abreu and Brett, 1992, 1993). This prototype is a research
tool for the testing and demonstration of procedures and techniques for operation and development of
robotic handling systems suitable for non-rigid products. Ultimately it is intended for industrial use
together with available industrial robot arms. One possible application is in the manipulation of
explosive materials. In the process of producing explosive cord, there is a requirement to hold and
handle that product immediately after an extrusion process. The product is bar-shaped, continuous and
discrete situations are possible, and the material properties are viscoelastic in nature.
4.2 MECHANICAL DESIGN

The mechanical design follows the concept of the gripper that was presented in chapter 2.4 making use of three fingers. The photograph of Figure 4.1 shows a global view of the apparatus with the gripper and the control equipment. The three identical fingers are configured as shown in Figure 4.2. Each finger is assembled as an autonomous functioning unit. The two degrees of freedom - DoF - of each finger are the roller movement and the carrier movement. These two movements of rotation are independently driven by DC servo motors and reduction gears. Figure 4.3 shows the design of a finger in detail. Table 4.1 presents a summary of the specifications of the gripper. Detailed information on the specification of components and sensing systems used in the gripper can be found in Appendix A.

Figure 4.1 Photograph of global view of the gripper and control equipment
Figure 4.2 Configuration and dimensions of gripper

Figure 4.3 Configuration of a finger
Table 4.1 Summary of specifications of the gripper

<table>
<thead>
<tr>
<th>GRIPPER</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fingers</td>
<td>3</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>2 per finger</td>
</tr>
<tr>
<td>Size of a finger</td>
<td>roller radius: (a = 25) mm; roller length: (l_r = 110) mm</td>
</tr>
<tr>
<td></td>
<td>carrier radius: (b = 50) mm</td>
</tr>
<tr>
<td>Location of fingers</td>
<td>joint of carrier of each finger equally spaced on a circle, with distance between joints, (d = 100) mm</td>
</tr>
<tr>
<td>Gripper overall size</td>
<td>enclosed in a cylinder of (\varnothing 250 \times 335) mm</td>
</tr>
<tr>
<td>Working volume of gripper</td>
<td>enclosed in a cylinder of (\varnothing 250 \times 110) mm</td>
</tr>
<tr>
<td>Gripper opening</td>
<td>cylindrical product “inside” fingers: (\varnothing 8) up to (\varnothing 136) mm</td>
</tr>
<tr>
<td></td>
<td>cylindrical product “outside” fingers: (\varnothing 108) up to (\varnothing 236) mm</td>
</tr>
<tr>
<td></td>
<td>spherical product: (\varnothing 8) up to (\varnothing 100) mm</td>
</tr>
<tr>
<td></td>
<td>prismatic product thickness: 0 up to 111 mm</td>
</tr>
<tr>
<td>Drive system</td>
<td>DC servo motors and planetary gearboxes</td>
</tr>
<tr>
<td>Motion of fingers</td>
<td>carrier movement: 0 to 300 degrees; max. velocity 17 rpm</td>
</tr>
<tr>
<td></td>
<td>roller movement: free to rotate; max. velocity 64 rpm</td>
</tr>
<tr>
<td>Max. gripping force/torque</td>
<td>carrier movement: 118 N</td>
</tr>
<tr>
<td></td>
<td>roller movement: 1.8 Nm</td>
</tr>
<tr>
<td>Sensors</td>
<td>position: incremental encoder</td>
</tr>
<tr>
<td></td>
<td>velocity: tachogenerator</td>
</tr>
<tr>
<td></td>
<td>torque: measurement of current of motor</td>
</tr>
<tr>
<td></td>
<td>contact and force:</td>
</tr>
<tr>
<td></td>
<td>tactile sensor</td>
</tr>
<tr>
<td></td>
<td>deflection of finger (finger set as position/force sensor)</td>
</tr>
</tbody>
</table>

The roller of the finger is assembled with a replaceable and flexible finger wall (see Figure 4.4). This type of construction provides the gripper with deformable fingertips that are advantageous as they reduce the contact pressure and increase grip stability. The wall of the roller can be made of different materials to select stiffness appropriate to the material being handled. The level of flexibility offered can ease the control task and adjust the sensitivity of the tactile sensor incorporated in the
finger construction. The driving mechanism shown in Figure 4.4 provides the rotation motion of the finger along its longitudinal axis - the roller movement. In this configuration the inner part of the finger remains motionless and is used to provide a base for the tactile sensor. This construction avoids the problem of having to cross the cables for the sensor. The drawback is that it prevents the movement of the roller when the roller wall contacts the tactile sensor.

![Diagram of finger construction](image)

*Figure 4.4 Finger construction using a flexible wall*

4.3 SENSING SYSTEMS

Each joint of the fingers is provided with sensing systems to measure position, velocity, torque and force.

The measurement of the position uses an incremental encoder. The measurement of the velocity uses a tachogenerator. The encoder and the tacho are assembled into the motor providing a
compact unit, as shown in Figure 4.3. The signals from these sensors are connected to a computer through standard data acquisition boards (see Appendix A.2 for specification of interface boards).

The torque is measured indirectly from the value of the current of the motor. For a DC motor the torque generated by the motor is proportional to the value of the current of the armature, considering a steady situation. Thus, to measure the torque, the current is monitored differentially across a small resistance placed in series with one of the motor leads. The signal is fed to an interface circuit (see Appendix A.3) before being connected to a standard data acquisition board fitted to the computer.

The measurement of the torque of the driving motor is used to evaluate the force applied by a finger. Considering the geometric configuration of the gripper, knowing the torque the motor is using, the position of the finger and the local of contact within the finger (see Figure 4.5), the force exerted in the grasp direction is given by:

\[ F = \frac{T_m \eta}{a} \sin \varphi \]  

(Eq. 4.1)

where

\[ T_m = K_t \cdot I_a \]  

(Eq. 4.2)

\[ \text{DC motor and gearbox} \]

\[ \text{Finger} \]

\[ a \]

\[ T_m \]

\[ \phi \]

\[ \text{Contact} \]

\[ \text{point} \]

\[ \text{Grasp force} \]

\[ F \]

\[ \text{Grasp direction} \]

\[ \text{Figure 4.5 Grasp force and torque of motor} \]
There are some obvious problems with this technique for sensing force. In particular, friction, gravity and inertial loads can influence the measurement of force. Any alteration in these loads that can occur throughout the grasp and manipulation operation changes the relationship between the torque developed by the motor and the force the finger can exert. Thus, the measurement of force is limited by the accuracy and availability of control systems that take account of the change in the load conditions. Other sources of problems are the motor brush noise and the variation in brush resistance, both of which make accurate monitoring of the armature current difficult. The use of brushless dc servo motors can significantly reduce or even eliminate this problem, but at a higher cost. Within the limitations associated with this technique of measurement of force it is still possible to use it with advantage. The detection of the contact between the finger and product and the control of force can be implemented using the signal of current. This will be referred to and applied in chapter 5, where different techniques for using the gripper in perception tasks are discussed.

The implementation of the measurement of the deflection of a finger adopted in the experimental rig - finger as a position/force sensor - uses a special hardware arrangement. In that arrangement, the finger is mounted on a spring that substitutes for the motor of the finger carrier, as shown in Figure 4.6. The actuation of the spring corresponds to an exerted force on the finger. This construction enables the finger to offer deflection in reaction to a gripping force and enables the measurement of that force. The stiffness characteristic of this measurement system can be selected by choosing the spring and the location where the extension of the carrier connects to the spring (see Appendix A.4 for a detailed description and specification of the configuration of a finger as a position/force sensor). If a motor for driving the finger is available, this hardware system can be replaced by software control. Stiffness can be modified by adjusting the gain for the position control of the finger.
The other sensing system of force is a specially built tactile sensor mounted inside the finger. It uses a piezo resistive material placed between conducting material, forming an array of sensing elements. The sensor provides the system with information regarding the contact force, the spatial distribution of the contact force and the contact location. See Appendix A.5 for a description of the design of the tactile sensor and experimental results.

4.4 CONTROL SYSTEMS

Position and force control are of primary importance to control the deformation of the products and for the implementation of grasping and manipulation actions. This problem of controlling the motion of an actuator that contacts with an object - compliant motion control - has been widely studied, and among the various control methods suggested, active stiffness (Salisbury, 1980), impedance control (Hogan, 1980, 1985), and hybrid position/force control (Raibert and Craig, 1981) are the most used.
The impedance and stiffness control methods provide an intuitive process for simultaneous control of motion and force, as position and force are not controllable independently in the same direction. The controller is used to regulate the dynamic behaviour between the manipulator position and the force exerted on the object, rather than considering the position and force problems separately.

Stiffness control is based on the formulation of the force-displacement relationship for a linear spring \( F = K_s \delta x \), where \( K_s \) is the spring stiffness and \( \delta x \) is the displacement about an equilibrium point) applied to the interaction between the manipulator and the object. When the manipulator contacts the object, force is created by an infinitesimal displacement of the end-effector within the object. If the manipulator moves from \( \delta x \) against a contact surface, the reaction force exerted by the object on the manipulator is proportional to the object stiffness and to the displacement \( \delta x \). Thus by controlling the stiffness of the manipulator when moving to a given reference position, it is possible to control, in an integrated way, motion and force. That involves setting a stiffness matrix \( K_F \) at an arbitrary point in the space and obtain the joint torque command to move to the reference position through a control law of the type:

\[
\tau = -K_q \delta q \quad (Eq. 4.3)
\]

where \( \tau \) is the joint torque vector, \( K_q = J^T K_F J \) is the joint stiffness matrix, with \( J \) as the Jacobian, and \( \delta q \) is the joint displacement vector. Normally the stiffness matrix is defined at the centre of compliance and is a diagonal matrix. The centre of compliance is not necessarily coincident with the reference position. This stiffness matrix may be modified under program control to match varying task requirements. The problem of designing this controller is establishing the matrix \( K_F \). The simplest implementation would be to estimate that matrix without using any force sensing, but that approach would not account for any change in the object stiffness as perceived by the manipulator. In fact, that would correspond to an open loop implicit force control where the manipulator is set to have a pre-defined stiffness. Additional implementations (see Figure 4.7) make use of sensors to provide the information on the stiffness of the object as perceived by the manipulator and then choose an appropriate stiffness matrix \( K_F \).
Impedance control, as pointed out by Asada and Slotine (1986), is an extension of the methodology of stiffness control. The object is now modelled as an impedance requiring the implementation of a control law of the type of a computed torque PD plus gravity controller:

$$\tau = \hat{g}(q) - J^T(q) \left[ K_p \ddot{x} + K_d \dot{x} \right]$$ (Eq. 4.4)

where $\hat{g}(q)$ is the estimated gravitational torque, $\ddot{x}$ is the position error, with $\ddot{x} = \dot{x} - x_d$ where $x_d$ is the reference position. Matrices $K_p$ and $K_d$ can be interpreted as the desired apparent stiffness and damping of the manipulator, as seen from the object. Controlling the manipulator requires now the choice of appropriate $K_p$ and $K_d$ matrices so that the manipulator will have a given impedance when moving to the desired reference position, $x_d$. Normally, $K_p$ and $K_d$ are diagonal matrices if defined at the centre of compliance. As in stiffness control, force sensors can be used to provide information for choosing the stiffness and damping matrices. In Figure 4.8 a control architecture for implementing impedance control is presented.
The hybrid position force control (Raibert and Craig, 1981) based on the analysis of Mason (1981), uses a parallel architecture, where the control is decoupled in two complementary sets of feedback loops, a force control loop for controlling forces in some directions, and a position control loop for controlling positions in the other directions (see Figure 4.9). The important aspect of this approach is the division of the task space in these two orthogonal subspaces, where in one force is controlled and in the other position is controlled. The force control loop and the position control loop both contribute to the driving torque of each joint of the manipulator. This can be a problem as each control loop sees each other as a source of disturbance. This issue and the problem of the control of the contact between the manipulator and the constraint surface of the object have been identified by An and Hollerbach (1989) as the most essential problem in the application of hybrid position/force control schemes.
Salisbury and Craig (1985) using stiffness and hybrid position/force schemes developed a control scheme for multi-fingered hands. The proposed control scheme is based on the grip matrix concept - which relates the force and velocity of the grasped object to the forces and velocity of the whole hand. This assumes that the product and contact locations are known and the point type contacts remain fixed. Considering these assumptions, a control law can be implemented to achieve the manipulation of a product. The inputs are the desired position of the fingertips that will yield the new location of the product and the desired stiffness behaviour between the fingers and the product. The new fingertip locations can be obtained by straightforward cartesian frame transformations of the desired location of the product. This approach, requiring a prior knowledge of the product, does not account for the problems associated with the occurrence of slip or rolling at the contact locations and, in many cases, the contact cannot be considered of the point type.

The work of De Schutter and Van Brussel (1988) and Perdereau and Drouin (1993) incorporate some ideas from the stiffness control approach but uses explicit force control loops (see Figure 4.10). This avoids the parallel architecture characteristic of the hybrid position force control and the associated problems of implementation. Adopting this approach and integrating the need to implement control of position, velocity and force for each finger of the gripper, the control architecture shown in Figure 4.11 is now proposed.

![Figure 4.10 Force and position control](image.png)
Figure 4.11 Architecture of control for each joint of a finger

The architecture of control uses a hierarchical structure with a nest of control loops as shown in Figure 4.11 having the velocity control as the innermost loop. The force controller generates a position reference that the position controller uses to generate a velocity reference. The velocity controller generates a torque reference that drives the amplifier of the motor. As it is a DC motor driven through a current driver amplifier, there is an inherent hardware controller of torque. Thus it is possible to implement the control of velocity with a programmable control of the torque. In the same way, the position control is implemented using programmable values for the velocity and the torque that the motor can use during the control of position. The force control is implemented using programmable values for the position, velocity and torque. With this control architecture the implementation of the different modes of control requires only the selection of the required control loops by setting the values of the control input references. In this way the integration of the different control modes is made possible, and a smooth easy switch between the position, velocity and force control can be achieved. In Appendix C experimental results of the implementation of the different control modes and of the switch between control modes are presented.
4.5 SUMMARY

This chapter has presented the prototype of the gripper that was built. It has described the physical features and specifications of the main components of the gripper, focusing on the sensing and control systems. The built gripper uses electric DC motors to drive the movements of the fingers. The sensing systems employed include the use of incremental encoders and tachos for measurement of position and velocity, respectively. Three systems were used to measure force. One measures the force indirectly, through the measurement of the current at the armature of the DC motors. The second force sensing system is a tactile sensor that was built to be fitted inside a finger. The third system uses a mechanical arrangement fitted with a spring that enables a finger to be set as a position/force sensing system. The control architecture adopted uses a hierarchical structure with a nest of control loops, enabling the integration of torque, velocity, position, and explicit force control.
5 IMPLEMENTATION OF THE OPERATIONAL FUNCTIONS OF THE GRIPPER

This chapter describes the operational functions and procedures implemented to operate the gripper for the handling of non-rigid products. To support the implementation of the procedures, common techniques are used and described. Finally, results of tests are presented to show the feasibility and performance of the techniques and procedures.

The techniques presented are the detection of contact, the determination of contact location and the application of different types of control. The tested procedures refer to the identification of product size, product compliance and product profile.

5.1 OPERATIONAL FUNCTIONS AND PROCEDURES

The successful implementation of robotic handling systems capable of dealing with products presenting a non-rigid behaviour requires the perception of the physical behaviour of the products. The information on the characteristics and behaviour of the products is then used in the implementation of grasp and manipulation tasks.

The perception and analysis of characteristics of products and environment as individual tests have existed for a long time. The mechanical tests on material properties, the physical and optical tests on products and materials are common procedures in mechanical and civil engineering.
However the integration of the perception with robotics is more recent. Stansfield (1992) recognizes perception as an important function which a robotic system must implement, both for extracting information about the environment and in acquiring information for grasp and manipulation implementation. The relevance of such a perception capability has also been highlighted by other researchers in the field of robotic locomotion and all-terrain vehicles (Sinha et al., 1993; Krotov, 1990).

The use of vision systems has been the main means for perception in the field of industrial robotics. This is due not only to the natural development and fast progress that has been occurring in the field of vision, but also as an answer to the typical problem of locating a well-known product. The vision systems are just a part of a perception system and the non-contact nature of that sensing system limits the information that can be acquired. Other sensing systems capable of detecting and evaluating the contact between the robotic system and the product or environment are thus required. The cooperative use of sensing systems with robotic mechanical systems is the key issue to the implementation of perception activities. Lederman and Klatzky (1987) studies on human haptic perception showed the extraction of object attributes by the manipulation of objects by the human hand. They compiled a set of exploratory procedures, or EPs, in which each EP extracts a particular object attribute through the implementation of purposeful hand movements. The concept of exploratory procedures can be adopted in the identification and characterization of product attributes by robotic systems. The advantage of such approach is that each exploratory procedure can be made independent of particular sensing devices or robotic hand and used as a building block in the construction of perception systems (Stansfield, 1992, Sinha et al., 1993).

Making use of this concept of exploratory procedures, the reference architecture introduced in chapter 1 is now expanded (see Figure 5.1). For each operational function defined - perception, grasp and manipulation - different procedures can be implemented.
The perception operational function requires the conjunction of grasp and manipulation procedures with the processing of the information from the sensing systems. This leads to the choice of the following perception procedures to be implemented and tested:

- identification of product size
- identification of product compliance
- identification of product shape (profile)

The implementation of these procedures uses a set of common techniques: detection of contact, measurement of the relative location of contact points and control of the fingers. The following sections review these techniques and present the implementation of the referred procedures.

5.2 TECHNIQUES

5.2.1 CONTROL OF FINGERS

The control architecture discussed in chapter 4 involves the use of four control modes for each joint of a finger: force, position, velocity and torque. A typical operation of grasping a product between two fingers involves different stages with different control modes. The approach movement of the fingers towards the product can use velocity control. When contact occurs in one finger, the control of the finger switches to position control and the finger is kept at the contact location. When the other finger contacts the product, the grasp begins. The control of this second finger switches from velocity to force control while the other can remain under position control.

The use of the different control modes and the capability to switch between them is a fundamental technique to the implementation of the operational procedures. In Appendix C, experimental results of the implementation of the control modes and the demonstration of the capability to switch between them are presented.
5.2.2 DETECTION OF CONTACT

Detection of contact between a finger of the gripper and the product plays an important role in the implementation of perception procedures. Detecting the contact locates the boundaries of the product through the location of the fingers at the instant of contact. Furthermore, the detection of contact can be associated with the control system to implement different control strategies. This allows a finger to move at high velocity with high stiffness before contacting the product and then switch to low velocity and low stiffness. In this way the force exerted on the product and the possible deformation of the product can be minimized and controlled.

The detection of contact between a finger of the gripper and a product, relying on the measurement of the contact characteristics, can make use of different sensing systems:

- Current of motor
- Tactile sensor
- Position/force sensor

The current technique uses the current of the driving motor as a measure of the force that the finger can exert. The detection of contact relies on a modification in the value of the current when a finger, moving towards the product, makes contact.

The tactile sensor technique uses a sensor mounted on the finger able to react to the contact pressure. The detection of contact relies on the actuation of the sensor.

The position/force sensor technique can be employed when using two fingers of the gripper as in a grasp action. One finger, configured as a position/force sensor, is used to detect the contact between the other moving finger and the product, which is then grasped between the two fingers.
DETECTION OF CONTACT WITH CURRENT OF MOTOR

This technique uses the evaluation of the current at the driving motor to detect the contact between the finger and the product. Through the employment of a permanent magnet DC motor the current in the armature can be taken as a measure of the torque (in a steady situation, the current is directly proportional to the torque). If the finger is set to move towards a product and to push against it, an increase in the current will occur if the contact can affect the movement of the finger. The driving motor sees the contact between the finger and the product as an added load. The control system, to maintain the movement of the finger, reacts by increasing the torque supplied to the motor. It is then possible to detect contact through the current.

To implement this technique the finger is set to move under velocity control. During the approach movement, the value of the current at the motor relates to the torque necessary to keep the finger moving at the desired reference velocity. The torque that the motor uses at this stage must be smaller than the maximum torque it can use. In this way, when contact occurs there is scope for a rise in the current being used by the motor. The contact must introduce a larger load when compared to the other loads the motor has to cope with during its movement - finger’s own weight, gearbox and coupling systems. In occurring this, the current at the motor increases after the contact. On the other hand, if any of these loads change, as they could if the gravity forces acting on the finger do not remain fixed, then the variation in the value of the current is not necessarily associated with the contact. Other situations that can limit the application of this technique occur when the finger contacts and pushes the product out of reach.

Two products presenting different stiffness characteristic, specimen A and specimen B (refer to Appendix B), were used to test the implementation of this technique. The products, placed in known locations, cannot move when touched by the finger (see Figure 5.2). The finger of the gripper was driven towards the product under velocity control using a fixed and low reference velocity and the torque of the motor was limited to a small value. The small torque limits the force the finger can exert on the product. The low velocity minimizes the impact when contact occurs and ensures that the
motor is not using the maximum torque before contact occurs. The experimental conditions used in
these tests are presented in Appendix D, Table D.1.

The compliance at the finger is due to the flexible nature of the finger wall, that was deformed, and so
the compliance of the gearbox and driving shaft is presented in Figure 5.4. The two contact
points are presented in Figure 5.2. The finger is subject to the same contact
and load conditions. After contact, the behaviour is different due to the lower stiffness characteristics
of specimen B. The finger continues in movement accomplished by a decrease in the velocity and an
increase in the current. That movement relates to the deformation of the product and the deformation
of the specimen B. The plots shown in Figure 5.3 and Figure 5.4 present the results of the tests. For each test
four plots are presented. Plot (i) shows the position of the finger during the test; the instant of contact
can be obtained from this plot because the test arrangement imposes that contact occurs when the
finger reaches zero degrees. The plot (ii) shows the variation of the current of the motor during the
test; consideration of contact used the instant when the current reached the double of the value during
the approach movement. The plot (iii) shows the velocity of the finger during the test. Finally, plot
(iv) presents all the previous data.

The analysis of the test with specimen A (Figure 5.3) reveals two distinct phases in the
movement of the finger, before and after contact. The contact is associated with a sharp increase in
the current at the motor. The detection of contact can then make use of the value of the current. A
detailed analysis of the plots reveals that before contact, the finger moves at a steady velocity with a
fairly constant current (except for a current peak at the start moment). After contact, as the presence
of the product restricts the movement of the finger, the control system increases the torque, trying to
keep the reference velocity. The current starts to increase, first at a slower rate and then sharply until
it reaches a maximum and steady value, at which point the finger stops its movement.
Simultaneously, the velocity decreases, first at a slower rate and then with a sharp fall to zero. The
small angular displacement of the finger, that occurs from contact until the movement of the finger is halted, is due to the compliance at the finger, since the product cannot move and it is not deformed. The compliance at the finger is due to the flexible nature of the finger wall, that was deformed, and to the compliance of the gearbox and driving mechanism.

The analysis of the test involving specimen B (Figure 5.4) also reveals the two distinct phases in the movement of the finger, before and after contact. The contact is still associated with an increase in the current, but that increase is less sharp than in the previous test. The phase before contact is similar to the case of the test with specimen A, as the finger is subject to the same control and load conditions. After contact, the behaviour is different due to the lower stiffness characteristic of specimen B. The finger continues its movement accomplished by a decrease in the velocity and an increase in the current. That movement relates to the deformation of the product and the deformation of the wall of the finger. When the current reaches the maximum value a steady situation develops, at which point the finger is kept halted.

Both of these tests show the feasibility of detecting contact through the evaluation of the current used by the motor. If the product is rigid the rise in the current is sharper and the detection time is shorter in comparison to the case of the deformed product. Thus it is also possible to determine surface hardness by this technique.
(i) position of finger

(ii) current of motor

(iii) velocity of finger

(iv) contact start and contact detection

Figure 5.3 Contact detection when pushing against specimen A

(technique using the current of motor)
Figure 5.4  Contact detection when pushing against specimen B

(technique using the current of motor)
DETECTION OF CONTACT WITH THE TACTILE SENSOR

The implementation of this technique to detect contact uses the developed tactile sensor (see Appendix A.5 for a description of the tactile sensor). Consideration of contact occurs when the contact area measured by the sensor becomes non-zero.

To test this technique an experimental arrangement (Figure 5.2) identical to the one used for the current technique was adopted. A finger of the gripper was driven against two products, specimen A and specimen B (refer to Appendix B for properties of tested products). The control of the movement of the finger and the type of products used were identical to the test of the current technique. The finger was driven under velocity control, with a constant reference velocity. The contact area measured with the tactile sensor was used for the detection of contact. The experimental conditions used in these tests are presented in Appendix D, Table D.2.

The plots shown in Figure 5.5 and Figure 5.6 present the results of the tests. For each test three plots are presented. Plot (i) shows the position of the driven finger during the test; the instant of contact can be obtained from this plot because the test arrangement imposes that contact occurs when the finger reaches zero degrees. The plot (ii) gives the contact area measured by the tactile sensor; consideration of contact used the instant when the contact area became non-zero. The plot (iii) presents the previous data in only one plot, showing the instant when contact occurred and when contact was detected.

The results of the test with specimen A (see Figure 5.5) show that between the start of contact and the detection of contact, there was a small displacement of the finger. That displacement relates to the deformation of the wall of the finger, that must occur, before the actuation of the tactile sensor is possible. After contact, and before the movement of the finger had stopped, there was a further displacement of the finger which is due to a further deformation of the wall of the finger and to the compliance of the gearbox and driving mechanism. Note that the measurement of the position
of the finger is done on the side of the driving motor. Thus, the build up of the mechanical backlash of the gearbox appears in the measurement of the position.

The results of the test with specimen B (Figure 5.6) show that between the contact and the detection of contact, a larger displacement of the finger occurred, when compared to the test using specimen A. This happened because the contact force necessary to actuate the sensor implied a previous deformation of the product. The use of this technique is thus affected by the compliance of the finger wall, that requires a minimum contact force to make possible the actuation of the tactile sensor. A tactile sensor incorporated in the wall of the finger would avoid this limitation.
Figure 5.5 Contact detection when pushing against specimen A

*(technique using the tactile sensor)*
(i) position of finger

(ii) contact area at tactile sensor

(iii) contact start and contact detection

Figure 5.6 Contact detection when pushing against specimen B
(technique using the tactile sensor)
DETECTION OF CONTACT WITH THE POSITION/FORCE SENSOR

This technique of detection of contact arises from the use of a finger configured as a position/force sensor (see Appendix A.4 for a description and performance of a finger configured as a position force sensor). When a finger pushes a product against the other finger, configured as a position/force sensor, the contact between the pushing finger and the product can be detected by the actuation of the position/force sensor. To engage the actuation of the sensor when the pushing finger contacts the product, the finger configured as a sensor must be located close to the product. This is a critical aspect with the implementation of this technique because it needs to locate the sensor close to the product without modifying its position. If that is not achieved, and the product has to be pushed before it contacts the sensor, the contact will occur even before it can be detected. The movement of the product and the development of the reaction forces to that movement can also affect the actuation of the sensor. These aspects prompt the use of a finger, configured as a position/force sensor, as a means to measure and control the grasp force, rather than to detect the instant of contact.

To test the implementation of this technique the experimental arrangement shown in Figure 5.7 was used. The finger configured as a position/force sensor was placed manually near the product. That finger was set up with a rigid wall instead of using a flexible wall. This avoids the deformation of the finger wall before the displacement of the finger. The product was hung from an external support through a cable. That arrangement minimizes the friction forces when the product is pushed by the finger. The finger pushing against the product was under velocity control, with a fixed reference velocity. As in the previous tests of detection of contact, two products with different stiffness were used, specimen A and specimen B (refer to Appendix B). The experimental conditions used in these tests are presented in Table D.3, in Appendix D.
Figure 5.7 Test arrangement for detection of contact using a finger configured as a position/force sensor

The plots shown in Figure 5.8 and Figure 5.9 present the results of the tests. For each test, four plots are presented. Plot (i) shows the position of the pushing finger during the test and the instant when contact occurs (the test arrangement imposes the start of contact when the finger reaches the position of zero degrees). Plot (ii) shows the position of the sensing finger and the instant when the sensor is actuated and contact detected. Plot (iii) shows the velocity of the pushing finger and finally plot (iv) shows all the data from plots (i) to (iv) and indicates the instant when contact started and when contact was detected.

For both products, the instant of start of contact matched the instant of detection of contact (see plots (iv) in Figure 5.8 and Figure 5.9). These results must be seen in the context of the tests that were performed. It was possible to locate the sensor close to the product and the friction forces in the displacement of the product were minimized. The test with specimen A showed that immediately after contact the displacement of the pushing finger was identical to the displacement of the sensing finger. Then, the displacement of the pushing finger became larger than the one of the sensing finger. That difference related to the fact that the wall of the pushing finger started to deform due to the build up of the contact force and as such that finger had a larger displacement. In the test with specimen B the displacement of the pushing finger after contact was always larger than the one of the sensing finger. This occurred due to the deformation of the product that begun immediately after contact.
(i) position of pushing finger

(ii) Position of sensing finger

(iii) velocity of pushing finger

(iv) contact start and contact detection

*Figure 5.8  Contact detection when pushing against specimen A*  
*technique using finger as a position/force sensor*
Figure 5.9 Contact detection when pushing against specimen B

(technique using finger as a position/force sensor)
5.2.3 LOCATION OF THE CONTACT POINTS

When the gripper holds a product the direction between the contact point of each finger defines the grasp direction. The relative location between contact points permits the identification of the size of a product in the grasp direction. The orientation of the grasp direction and the knowledge of the torque being supplied by the motor that drives the carrier, allows the calculation of the force that a finger applies in the grasp direction. Any displacement of the finger from the location where the contact starts indicates the occurrence of a deformation or the movement of the product.

Considering the kinematic model of the gripper, the location of each contact point can be obtained by knowing the position of the contact on the roller and the position of the finger. The location of the contact point on the roller is given by the centre of application of the contact force that can be identified with the tactile sensor. The location of the finger is given by the angular position of the carrier. It is then possible to measure the distance between the contact points and their relative orientation. Using the kinematic model of the gripper, presented in chapter 3, the distance between any two contact points and their relative orientation can be obtained. Referring to Figure 5.10, the distance between the contact points of finger $n$ and finger $m$, is given by the norm of the position vector $\mathbf{p}_{mn}$ and is expressed in (Eq. 5.1).

![Figure 5.10 Distance and orientation between fingers of the gripper](image)

108
\[ \|p_{mn}\| = \|p_n - p_m\| \]  \hspace{1cm} (Eq. 5.1)

where:

\[
p_n = \alpha c_n + \beta R_{1n} \alpha c_{2n} + \beta R_{2n} \alpha c_n p_n
\]

\[
e_n \cos \zeta_n \hspace{1cm} \beta_n \cos \beta_n
\]

\[
e_n \sin \zeta_n \hspace{1cm} \beta_n \sin \beta_n
\]

\[
= \begin{bmatrix}
e_n \cos \zeta_n \\
e_n \sin \zeta_n \\
0
\end{bmatrix} + \begin{bmatrix}
a_n \cos \alpha_n \\
a_n \sin \alpha_n \\
0
\end{bmatrix} + \begin{bmatrix}
\beta_n \cos \beta_n \\
\beta_n \sin \beta_n \\
0
\end{bmatrix}
\]  \hspace{1cm} (Eq. 5.2)

with

\[
\alpha R_{1n} = \begin{bmatrix}
\cos \zeta_n & -\sin \zeta_n & 0 \\
\sin \zeta_n & \cos \zeta_n & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

and

\[
\beta R_{2n} = \alpha R_{1n} \beta R_{2n} = \begin{bmatrix}
\cos(\zeta_n + \alpha_n) & -\sin(\zeta_n + \alpha_n) & 0 \\
\sin(\zeta_n + \alpha_n) & \cos(\zeta_n + \alpha_n) & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  \hspace{1cm} (Eq. 5.3)

Substituting (Eq. 5.3) in (Eq. 5.2) gives:

\[
p_n = \begin{bmatrix}
e_n \cos \zeta_n \\
e_n \sin \zeta_n \\
0
\end{bmatrix} + \begin{bmatrix}
\cos \zeta_n & -\sin \zeta_n & 0 \\
\sin \zeta_n & \cos \zeta_n & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
a_n \cos \alpha_n \\
a_n \sin \alpha_n \\
\beta_n \cos \beta_n \\
\beta_n \sin \beta_n
\end{bmatrix}
\]  \hspace{1cm} (Eq. 5.4)

Solving (Eq. 5.4) gives:

\[
p_n = \begin{bmatrix}
e_n \cos \zeta_n + a_n \cos(\zeta_n + \alpha_n) + b_n \cos(\zeta_n + \alpha_n + \beta_n) \\
e_n \sin \zeta_n + a_n \cos(\zeta_n + \alpha_n) + b_n \cos(\zeta_n + \alpha_n + \beta_n) \\
0
\end{bmatrix}
\]  \hspace{1cm} (Eq. 5.5)

The position vector of the contact point at finger \( n \) is thus given by (Eq. 5.5). For the contact point of finger \( m \), the position vector is given by a similar equation (Eq. 5.6).

\[
p_m = \begin{bmatrix}
e_m \cos \zeta_m + a_m \cos(\zeta_m + \alpha_m) + b_m \cos(\zeta_m + \alpha_m + \beta_m) \\
e_m \sin \zeta_m + a_m \cos(\zeta_m + \alpha_m) + b_m \cos(\zeta_m + \alpha_m + \beta_m) \\
0
\end{bmatrix}
\]  \hspace{1cm} (Eq. 5.6)
Substituting (Eq. 5.5) and (Eq. 5.6) in (Eq. 5.1) the distance between the two contact points can be obtained. The orientation angle of the grasp direction relative to the absolute coordinate frame, \( \theta_{mn} \), is given by (Eq. 5.7).

\[
\theta_{mn} = \cos^{-1} \left( \frac{p_{mn} \cdot \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T}{\|p_{mn}\|} \right)
\] (Eq. 5.7)

The angle \( \varphi_{mn} \), defined by the relative orientation of the carrier of finger \( m \) with the position vector \( p_{mn} \), is given by (Eq. 5.8).

\[
\varphi_{mn} = \cos^{-1} \left( \frac{r_{2m} \cdot p_{mn}}{\|r_{2m}\|\|p_{mn}\|} \right)
\] (Eq. 5.8)

where

\[
r_{2m} = \begin{bmatrix}
    e_m \cos \zeta_m + a_m \cos(\zeta_m + \alpha_m) \\
    e_m \sin \zeta_m + a_m \cos(\zeta_m + \alpha_m) \\
    0
\end{bmatrix}
\]

### 5.3 TESTS OF PERCEPTION PROCEDURES

Perception procedures provide a solid framework for exploration and identification of features of products with a view to implement grasp and manipulation actions. For each feature of a product to be identified, each procedure will be designed around a generic operation with the gripper, making use of common techniques (referred to in the previous section, 5.2) and of particular conditions. The framework of these procedures is designed to be executed independently of a particular design of a gripper or of particular sensing systems. They are sufficiently generic to be implemented on different hardware systems. The requirements are, that hardware systems must be able to provide and implement the execution of the required movements and to acquire the relevant
sensing information. For example, the procedures that require sensing the contact force, are independent from the technical implementations used for measuring force.

The following identification procedures are examples of generic procedures that were implemented with the developed gripper and making use of the available sensing systems.

5.3.1 IDENTIFICATION OF SIZE AND DEFORMATION OF A PRODUCT

Procedure

The identification of the size of a product has relevant applications in planning grasps and in the identification of the deformation of the product as a result of grasp or manipulation tasks. The procedure for identification of the size of a product is designed to be executed in the following manner:

- the gripper is set to grasp a product
- the location of the contact between the fingers of the gripper and the product are recorded when contact occurs
- the size of the product in the grasp direction is calculated from the location of the contact points at the initial contact
- at the end of the grasp action, the distance between the contact points is again calculated and the deformation of the product in the grasp direction identified

This procedure involves controlling and sensing the forces each finger exerts on the product, detecting the contact between the finger and product and monitoring the location of each contact point. It is similar to the procedure of identification of compliance that will be described in the next section. However, it is through the interpretation of the sensed data - contact, force and position - that the features of interest are actually identified.
The implementation of this procedure for the cases where it is not possible to grasp the product, can make use of a single finger of the gripper. In that case, the finger is set to move towards the product and to apply a given force. The position of the finger is then monitored and recorded when contact occurs and when the applied force reaches the desired value. From the position of the finger when contact occurs, a point in the boundary of the product can be identified. Then, using the end position of the finger, the local deformation of the product can also be found. This procedure can be repeated to enable the identification of different contact locations. It is then possible to build a map of the boundaries of the product and of the deformations at the local contacts.

The identification of the size of a product through a grasp action gives only the size of the product in the grasp direction. Although, if different grasp directions are used, an extensive identification of the size of the product can be performed. This procedure requires the detection of the contact between the finger and the product and as such is dependant on the accuracy of the detection of contact. Any deformation of the product before contact is detected introduces an error in the identification of the size and local deformation.

**Tests**

To test the implementation of this procedure, the configuration of the gripper making use of two fingers was adopted. The product was grasped between the fingers. One finger was configured as a position/force sensor (refer to Appendix A.5 for configuration of the finger) - the passive finger. The other finger was under control - the active finger - to allow the control of the applied grasp force. The effect of the gravity on the motion of the fingers was avoided by placing the gripper in a vertical configuration. The position of the product relative to the fingers was chosen to ensure that when the product is grasped, the fingers are in a symmetric configuration (see Figure 5.11). With this arrangement, the size of the product was obtained by measuring the separation between the fingers. This arrangement also ensures that the detection of contact, using the passive finger, can be made with minimal displacement of the product. Contact is considered when the position of the passive finger changes. The control of the active finger used implicit force control, with the velocity and torque
limited to low values (refer to Appendix C for control experiments with implicit force control). Through the use of force control, the grasp force can be controlled and limit the deformation the product can endure when the finger contacts and moves against it. These tests made use of three products, with different stiffness characteristics: specimen A, specimen B and specimen C (refer to Appendix B for properties of tested products). Table D.4, in Appendix D, presents the test conditions adopted.

![Figure 5.11 Test arrangement for identification of product size](image)

### Results

The plots shown in Figure 5.12, Figure 5.13 and Figure 5.14 present the results of the identification of the size and deformation for the three specimens. Each plot shows the separation of the two fingers and the angular position of the passive finger during the test. The separation of the fingers is used to measure the deformation of the tested specimens during the grasp. Each plot also shows the instant when contact was detected. At that instant the separation of the fingers gives the size of the specimen, measured on the grasp direction. The values obtained agree with the real size of the product in that direction.
The separation of the fingers after contact can be used as a measure of the deformation of a product. The relative deformation of the product can then be obtained. The initial size of the product is given by the separation of the fingers when contact first occurs. The plot in Figure 5.15 shows the relative variation of the separation of the fingers for the three specimens tested. That plot also includes the instant when contact was considered for each specimen. The results show that the magnitude of the deformation of each specimen was different, although the specimens were subjected to the same grasp force. Specimen B suffered the larger deformation, as it would be to expect, since it is the specimen that presents the lowest stiffness. These results also point to the possible identification of the rigidity of each specimen, but that feature will be left for the specific procedure of identification of compliance.
Figure 5.12 Identification of size and deformation of specimen B

Figure 5.13 Identification of size and deformation of specimen C
Figure 5.14 Identification of size and deformation of specimen A

Figure 5.15 Grasp action and deformation of tested specimens
5.3.2 IDENTIFICATION OF PRODUCT COMPLIANCE

Procedure

The identification of compliance of a product with the gripper can be used to predict the deformation behaviour of a product during grasp and manipulation actions. It can also be used for classification and comparison of products. Compliance can be interpreted as a measure of the deformation behaviour of a product when subjected to a load. Typically, compliance is defined as the inverse of the stiffness. The stiffness \( K \) is the constant of proportionality of an elastic material that can be expressed by the relation \( K = \delta F/\delta x \) where \( \delta F \) is the change in the applied force and \( \delta x \) the deformation. Thus, the procedure for identification of the compliance of a product is designed to be executed in the following manner:

- Apply a load against the surface of the product
- Measure the contact force during the application of the load
- Measure the displacement of the surface during application of the load

The procedure for identification of compliance remains invariant independently of the systems adopted to apply force and sensing the contact force and deformation of the product. The application of the load on the product can be made using a finger of the gripper pushing against the product or with the product being grasped between the fingers.

The adopted procedure uses a gripper configuration with two fingers. One finger is configured as a position/force sensor - the passive finger- and the other is set to apply the grasp force - the active finger (Figure 5.16). The passive finger detects the contact and measures the applied force. The measurement of the deformation of the product uses the relative location of the fingers. The active finger moves towards the product under velocity control.
Figure 5.16 Test arrangement for identification of product compliance

To examine the implementation of this procedure, the action of gripping a product between the two fingers is now represented by the model shown in Figure 5.17.

Figure 5.17 Model of the system for identification of compliance

It is assumed that the product is adequate modelled by a second order dynamic model, represented by a mass $m_p$ and an impedance (with an elastic constant $K_p$ and damping constant $D_p$). The finger that applies the force on the product - the active finger - is modelled as a rigid body, with a mass and damper connecting to the ground. The mass represents the effective moving mass of the
finger. The viscous damper $D_{df}$ gives the appropriate rigid body mode of the finger. The model of the finger also includes an impedance, representing the flexible wall of the finger. The mass of this wall is included in the mass of the active finger, $m_{af}$. The passive finger, that behaves as the position/force sensor, is modelled as an elastic body with a stiffness $K_p$ and mass $m_p$. The force the active finger exerts is represented by the input force $F$. The equations that describe this system are:

\[
F = m_{af} \ddot{x}_{af} + D_{af} \dot{x}_{af} + K_w \delta x_w + D_w \dot{x}_w \\
\dot{m}_p \ddot{x}_p + D_p \dot{x}_p + K_p \delta x_p = D_w x_w + K_w \delta x_w \\
m_f \ddot{x}_f + D_f \dot{x}_f + K_f \delta x_f = D_p \dot{x}_p + K_p \delta x_p
\]  
\text{(Eq. 5.9)}

Considering that the execution of this procedure is performed at slow velocity so that the dynamics of the system are not excited, it is possible to assume the static situation as representing the current procedure. The reduced equations are:

\[
F = K_w \cdot \delta x_w \\
K_p \cdot \delta x_p - K_w \cdot \delta x_w = 0 \\
K_f \cdot \delta x_f - K_p \cdot \delta x_p = 0
\]  
\text{(Eq. 5.10)}

Considering that the spring and damper elements are ideal and transmit the forces applied to them, the contact force $F_c$ and the deformation on the passive finger $\delta x_f$ are related by:

\[
F_c = K_f \cdot \delta x_f
\]  
\text{(Eq. 5.11)}

Therefore, (Eq. 5.10) can be written as:

\[
F = F_c \\
K_p = \frac{F_c}{\delta x_p}
\]  
\text{(Eq. 5.12)}

These results show that to measure the compliance of the product $- 1/K_p$ - requires the measurement of the contact force $F_c$ and the deformation of the product $\delta x_p$. Considering now that the deformation of the product can be expressed in terms of the displacement of the active finger, (Eq. 5.12) can be written as:
$$K_p = \frac{K_f \delta x_f}{\delta x_{of} - \delta x_f - \delta x_w} \quad (Eq. \ 5.13)$$

The result expressed in (Eq. 5.13) shows that to measure the compliance of a product with such an arrangement it requires the knowledge of:

- the stiffness of the passive finger
- the displacement of both fingers, $\delta x_{of}$ and $\delta x_f$
- the deformation of the wall of the finger, $\delta x_w$

The use of fingers fitted with a rigid wall eliminates the variable $\delta x_w$; considering that the position of the active finger is the control variable and known, reduces the determination of the compliance of the product to the measurement of the position of the passive finger.

**TESTS**

This procedure was implemented to identify the compliance of the three products, specimen B, specimen C and specimen D, presenting different stiffness (refer to Appendix B for properties of tested products). The implementation of this procedure requires the adequate choice of the stiffness of the passive finger. Ideally, the passive finger should have a stiffness lower than the product so that the deformation of the product is minimized. At the same time, the displacement of the passive finger should be kept small to limit the displacement of the product. This led to configure the passive finger with a stiffness compatible with each tested specimen (refer to Appendix A.4 for the process of selection and calibration of the stiffness of the finger). The test conditions are presented in table D.5, in Appendix D.

**Results**

The plots shown in Figure 5.18, Figure 5.19 and Figure 5.20 present the results for the identification of the compliance of the three tested specimens. Each plot shows the product strain versus the contact force. The contact force was measured through the position of the passive finger,
taking into account the contact angle and the stiffness of the configuration adopted. The identification of the size of the specimens with the gripper is used to compute the strain. The initial size of the specimen was obtained at the instant of contact between the finger and the specimen. For all tests, the size of the specimen computed at the instant of contact was identical to the actual size of the specimen. The plot shown in Figure 5.21 groups the results obtained for the three specimens. In this plot it is perceptible the difference in the force resolution of the passive finger. The difference is due to the use of a passive finger configured to have a high stiffness that was required to test specimen C. The modification in the stiffness of the passive finger was achieved using a stiffer spring, spring S2 (see Appendix A.4).

For the analysis of the results obtained with the gripper, the stiffness behaviour of the tested specimens is presented in the plots shown in (Figure 5.22). These results were acquired during a compression test performed on a tensile test machine (refer to Appendix B). The results obtained with the gripper are in accordance with the properties of the tested specimens as seen when comparing the plots shown in Figure 5.21 and Figure 5.22. The procedure of identification of compliance can distinguish and identify the three tested specimens. The values of forces measured in the tests using the gripper are in the same range of the values of the forces measured with the tensile test machine. They are used to obtain an effective compliance behaviour of the products under a grasp action. It should be noted that the implementation of the procedure of compliance imposes a variable geometry of contact between the fingers and the products, when compared with the test in the tensile machine. While the tensile test machine uses planar test probes, the gripper has cylindrical shaped fingers contacting the products. Therefore, it is not only feasible but practical to use the gripper for identification of product compliance through a grasp action.
Figure 5.18 Identification of compliance - specimen D

Figure 5.19 Identification of compliance - specimen B
Figure 5.20  Identification of compliance - specimen C

Figure 5.21  Identification of compliance - all tested specimens
5.3.3 IDENTIFICATION OF PRODUCT PROFILE

Procedure

The identification of the profile of a product can be seen as an extension of the procedure for identification of size. While the identification of size uses a single grasp location to acquire the size of the product, the identification of profile requires multiple grasp locations. These multiple grasp locations can be implemented by successive and discrete grasp actions or by manipulation of the product within the gripper. The current implementation, adopting the manipulation approach, is thus designed to be executed in the following manner:

- the gripper is set to grasp a product
• the location of the contact points between the gripper and the product is recorded when contact first occurs
• the product is manipulated while keeping a stable grasp
• the motion of each finger is monitored during the manipulation action
• the profile of the product is obtained from the kinematic analysis of the fingers’ motion during the manipulation

This procedure involves the control of the grasp forces, the detection of the contact between the finger and product and the evaluation of the location and movement of each finger. It is necessary to maintain a secure grasp during the manipulation of the product within the fingers. The manipulation of the product requires the rotation movement of the roller of each finger. It relies on the development of friction forces between the roller and the product. Any occurrence of slip is a severe limitation on the identification of the profile of the product.

*Tests*

To test and demonstrate the implementation of this procedure, a prismatic product with a ramp shape profile, specimen E, was used (see Appendix B for properties of tested products). The gripper making use of three fingers was configured as shown in Figure 5.23. Two of the fingers were used to grasp and manipulate the product, while the third finger was used as a guidance free roller. The two grasping fingers were used in such a way that one exerted the grasp and manipulation action - the active finger - while the other was configured as a position/force sensor - the passive finger. The manipulation of the product was achieved by controlling the rotation movement of the roller of the active finger. This manipulation movement was under velocity control. The carrier movement of the active finger implemented the grasp motion. That movement was controlled under force control. Table D.6, in Appendix D, presents the test conditions used in these experiments.
Results

To obtain the profile of the product requires the measurement of the grasp motion of the active finger and the displacement of the product. The displacement of the product can be measured by the rotation of rollers of the passive fingers. Since the prototype of the gripper is not equipped with position sensors in all the rollers of the fingers, the displacement of the product was measured with an external ruler, as shown in Figure 5.23.

From the measured displacement of the product and with the monitored displacement of the active finger, the slope of the product was computed using the kinematic model of the gripper. The obtained value agrees with the real product characteristic. To verify that, the data from the test is compared with the data from the kinematic simulation of this experiment. The plots shown in Figure 5.24, Figure 5.25 and Figure 5.26 present the results. The kinematic simulation considers the
manipulation of a product identical to the one tested, placed in the same initial conditions, and considers that each finger rolls without slip on the product. The plot shown in Figure 5.24 presents the angular displacement of the grasp movement of the active finger with time. The plot shown in Figure 5.25 shows the distance between the active finger and the passive finger (the finger configured as the position/force sensor). The plot shown in Figure 5.26 shows, for the active finger, the angular displacement of the grasp movement versus the angular displacement of the rolling movement. These plots show an agreement between the experimental data and the simulation, that was to be expected since no slip between the fingers and the product occurred during the test. This proves that the profile of the product used for the simulation agrees with the profile of the product identified through the test, as was to be expected.

![Graph](image)

*Figure 5.24 Identification of profile of specimen E - grasp motion*
Figure 5.25 Identification of profile of specimen E - separation of fingers

Figure 5.26 Identification of profile of specimen E - grasp motion versus manipulation motion
5.4 SUMMARY

This chapter has described the operational functions and respective procedures implemented to operate the gripper. To support the implementation of the procedures common techniques were used and described. Finally, to show the feasibility and performance of the techniques and procedures, the results of a set of tests were presented.
6 CONCLUSIONS

This chapter reviews and presents the conclusions of the work carried out and suggests directions for further work.

6.1 REVIEW AND CONCLUSIONS

This research has been concerned with the enlargement of robotic handling applications by focusing on the development of robotic grippers capable of handling non-rigid products. The research began with the identification of broad categories of non-rigid products based on industrial handling requirements. It was found that in many industrial applications it is the shape of the product, rather than the material, that dictates the handling behaviour. This led to the identification of three classes of non-rigid products, based on their geometrical aspect: (i) bar type, (ii) sheet type and (iii) bulk type.

It was concluded that rather than concentrating on specific products and deducing the form of appropriate dedicated robotic grippers, a broad approach should be adopted. This led to the development of a dexterous robotic gripper suitable for categories of non-rigid products and of methodologies and techniques for designing and using a robotic handling system.

The analysis of the complexities of the behaviour of non-rigid products identified the need to detect and control the deformation of the products during handling operations. To implement these requirements there is a need for the integration of sensing systems with mechanical systems capable of direct interaction with the products and of continuous adaptation of the grasp to the changing conditions of the products. These requirements led to the establishment of a reference architecture for a handling system that demands the implementation of three main functions: perception, grasping and
manipulation. The perception function is required for identification of the properties and features of products, before and during the process of grasp and manipulation. The grasp function is required to select and implement grasps. The manipulation, and in particular the manipulation performed within the robotic gripper, is required not only to accomplish perception functions but also to control and minimize the deformation of the products during the handling tasks.

The implementation of a robotic handling system capable of integrating the perception functions with grasp and manipulation tasks requires the use of dexterous robotic grippers. These grippers must be able to cope with the variation of the characteristics that the non-rigid products can present, sensing and controlling their deformation, adapting to their shape and size. To fulfil these requirements, the grippers must be provided with force control systems making extensive use of sensors and having flexible mechanical solutions. The grippers must be capable of implementing different grasp configurations and performing in-gripper manipulation. A review on the availability of robotic grippers, presented in Chapter 2, identified some dexterous grippers that offer some of these requirements (the Stanford/JPL hand, Salisbury, 1982; the UTAH/MIT hand, Jacobsen et al., 1984; the Bologna hand Bonivento et al., 1988; the Karlsruhe hand, Doll and Schneebeli, 1988; the OEDIPUS hand, Schwarzinger et al., 1992). However their complex mechanical structures, control and cost, make them unsuitable for industrial applications. This led to the establishment of general guidelines for the development of industrial grippers suitable for dealing with non-rigid products. Based on these guidelines, the concept of a new modular gripper was proposed. It is a finger-type gripper, equipped with a range of sensors to measure finger position, force and contact force, capable of implementing different grasp configurations, controlling grasp forces and performing in-gripper manipulation. The gripper is suitable for dealing with classes of bar-shaped non-rigid products, being presented in discrete or continuous form.

As an application of the concept of the proposed gripper, a three-finger gripper was built. It is intended as a research tool for testing and demonstration of procedures and techniques for operation and development of robotic handling systems suitable for non-rigid products. Ultimately it is intended for industrial use in conjunction with existing robot arms.
The gripper, presented in Chapter 4, has three identical fingers, each one with two degrees of freedom and independently controllable. This has the benefit of reducing the number of different parts, making the design more economical and enables the easy replacement of the fingers and their driving systems, if desired. To drive the motion of the joints of the fingers it was decided to use electric DC motors, which fitted with a gearbox, incremental encoder and tachogenerator, are coupled directly to the joints. This avoids the use of cables for transmission of the movements that are commonly found in dexterous grippers. The reliability problems arising from the elasticity of cables and contamination that are normally associated with these systems are thus avoided.

For the development of the gripper and implementation of the control systems the use of force sensors was necessary. The lack of commercially available tactile sensors suitable for incorporating in the gripper led to the development of a tactile sensing array. The results of the development and use of the tactile sensor fitted to a finger of the gripper are presented in Appendix A.5. Problems related to the sensitivity of the sensor to the load conditions were identified in the construction of the sensor. Although these problems limit its use for accurate measurements of the contact force, it was possible to demonstrate the use of the sensor for detection of contact, identification of force distribution and contact location. Still it was concluded that the use of the sensor in its present form, and integrated with the gripper, was able to identify the stiffness characteristics of products. This is an area that deserves future research, particularly in the development and use of better performing tactile sensors.

The other force sensing system that was developed was a mechanical system that enables the configuration of a finger as a position/force sensor. The system, described in Appendix A.4, uses a finger mounted on a spring arrangement. The measurement of the displacement of the spring enables the position of the finger and the force exerted on the finger to be measured. Experimental tests were conducted to characterize this sensing system and the results obtained agree with the theoretical model of the behaviour of the sensor. This force sensing system was successfully used in the implementation of the perception procedures that involve the use of force controlled grasps. Two fingers of the gripper are used so that one finger applies the grasp force while the other, configured as a position/force sensor, measures the exerted force. This passive system proved to be an economical
replacement for the driving and control systems that would be required to operate a finger to provide similar operating conditions. Obviously it is a less flexible solution, but can still provide the gripper with a dedicated system for sensing force.

To control each joint of a finger of the gripper, the adopted control architecture has a hierarchical structure with a nest of control loops, with the force control loop as the outer loop. This is a modified version of the control architecture proposed by De Schutter and Van Brussel (1988) and Perdereau and Drouin (1993) that enables the integration of the control of position with velocity, force and torque control. This avoids the parallel architecture characteristic of the hybrid position force control (Raibert and Craig, 1981) and the associated problems of implementation. Tests have been performed on the implementation of the control architecture of the DC motors that drive each joint of a finger. From the results, presented in Appendix C, it is possible to conclude the effectiveness of this control strategy that can integrate and switch between the different modes of control - torque, velocity, position and force. Due to financial constraints that limit the availability of driving systems for all joints, current implementations involved only two joints. The coordinated control of all joints of the fingers is still required to be implemented.

The design of the gripper used the kinematic analysis that is commonly found in the development of robotic arms. A review on current kinematic tools available for kinematic design and control of robotic mechanisms was presented in chapter 3. It is concluded that the use of the Jacobian to represent the kinematics of robotics mechanisms provides an important analytical tool for the design of dexterous grippers. The design of the fingers of the gripper and the definition of possible configurations for a gripper with one, two or three fingers was presented. The design solutions are not exclusively obtained through this kinematic analysis. The workspace of the fingers and their interaction is also considered. In the current design of the gripper, the design solution is a compromise between the results obtained with the kinematic tools and the analysis of the workspace.

The kinematic analysis, using the Jacobian, for planning the manipulation of products within the gripper was shown with the simulation of the manipulation of two products. The simulation results
of the manipulation of a rectangular and circular shaped product were presented. The feasibility of the implementation of the simulation was verified through the analysis of the static forces involved in grasping and manipulation. The simulation assumed that the shape of the product remained fixed during the manipulation and that the contact between the fingers and the product was of point type. These assumptions can be a limiting factor when applied to the manipulation of non-rigid products. With NRPs deformations are expected to occur at the contact locations and the shape of the product may not remain constant. Nevertheless, the simulation can be used as a reference for the manipulation planning of non-rigid products. The shape of the product and the location of the product can be continuously accessed and used to update the model of the planned manipulation. This analysis focused on the instantaneous kinematic analysis and the force analysis was applied only to static situation. A full dynamic analysis of the manipulation is still required and is the subject of an ongoing research.

The developed gripper was used to test and demonstrate a set of techniques and procedures being examples of the operational functions that a robotic handling system suitable for non-rigid products must provide. The framework adopted for the implementation of perception procedures has the particularity of being independent from the hardware systems used. For example, the procedure for identification of product compliance requires both the identification of the deformation and the measurement of the force exerted on the product. The type of sensors used to acquire the required data is not relevant to the procedure. Different sensing systems can be used as long as the relevant information is obtained and processed by the control system.

The perception procedures implemented were the identification of product size, compliance and profile. They were chosen because their implementation involves the performance of grasp and in-gripper manipulation. They involved the control of the movements of the fingers under different modes and the integration of the position and force sensing systems with the kinematic data from the performed actions. Three products, presenting different stiffness characteristics were used in the conducted experiments, presented in Chapter 5. From the results it is possible to conclude that the gripper can be used to identify, measure and control the deformation of the products. The results of
the identification of size and compliance of the products are in accordance with the real product properties. The identification of the profile of a product through in-gripper manipulation was also successful. One of the problems foreseen in the implementation of this procedure is the possible occurrence of slip at the contact locations. The identification of the profile of the product was possible because no slip occurred during the manipulation of the product. This prompts the need of avoiding and/or detecting and controlling the occurrence of slip. Relying on friction forces and increasing the grasp forces may not always be feasible to implement, as that can cause large deformations on the products. Other solutions may include the need to adjust the grasp configuration and increase the contact area. The use of slip sensors could provide the control system with the data necessary not only to adjust the grasp conditions but also to take into account the effect of slip in the identification procedures.

The main achievements of this thesis are summarized in the following points:

- the identification of research opportunities in the field of robotic handling systems suitable for dealing with non-rigid products
- the identification of broad categories of non-rigid products based on industrial handling requirements, leading to the consideration of three classes of non-rigid products, based on their geometrical aspect: (i) bar type, (ii) sheet type and (iii) bulk type
- the proposal of a reference architecture for robotic handling systems suitable for non-rigid products where emerges the need to implement perception, grasp and in-gripper manipulation
- the design and building of a novel robotic gripper for demonstration purposes that is capable of performing perception functions through grasp and manipulation, for a range of non-rigid product types with bar shape
- the use of kinematic analysis of the gripper for design purposes and for planning in-gripper manipulation
- the demonstration of a set of techniques and procedures to be incorporated in robotic handling systems that were experimented with the developed gripper.
6.2 FURTHER DEVELOPMENTS

The field of robotic manipulation and its application to non-rigid products is still an open area with a large potential of application in industrial tasks. There is a need for the development of robotic dexterous grippers suitable for industrial use. The analytical study of the manipulation of products by a robotic gripper still offers research opportunities. Another important area, related to the implementation of robotic handling systems suitable for non-rigid products, is in the field of perception. The perception capabilities can be enhanced incorporating other sensing systems and enlarging the range of in-gripper manipulation actions as a means of identifying more features of the products. It should be taken into consideration that ultimately all of these developments and studies should lead to varied applications performing real work.

In the current work some areas for further work were identified. They are grouped in the following points:

Mechanical gripper

- full implementation of the driving systems for all joints of the fingers
- the use of pneumatic actuators, replacing the electric DC motors; it is envisaged that a pneumatic actuated version of the gripper could provide a simplified implementation of force control and be appropriated for safe use in explosive environments
- development of a gripper using a configuration with more than three fingers

Sensing systems

- the improvement on the tactile sensing systems
- the incorporation of slip sensors
- the incorporation of other sensing systems not necessarily located within the gripper; the use of vision systems which could enhance the implementation of perception functions

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Control and analytical study

- consideration of other control architectures for controlling single finger movements and for the coordinated control of all the fingers of the gripper
- extension of the analytical study of the manipulation of products within the gripper considering the dynamic aspects of the manipulation

Applications of the gripper

- implementation of procedure for detection of slip
- manipulation of sheet type products; the application is envisaged where two robotic arms, each one equipped with a gripper, are used to maintain the product under tension by the control of the rotation motion of the rollers of the fingers; the control of the manipulation of the product could be performed by the coordination of the action of the grippers, independently of the motion of the robotic arms
- implementation of dexterous manipulation tasks.
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APPENDIX A

THE EXPERIMENTAL RIG

A.1 NOMENCLATURE

a  radius of the carrier
b  radius of the roller
d  distance between centres of joints of the carriers
F_c  force at contact location
F_s  force at connection point S
F_t  force of pre-tension of the spring
K_f  stiffness of the sensing system
K_s  stiffness of the spring
l_r  length of the roller
l_s  length of the spring
l_s1  length of the spring when tensioned by force F_t
l_ab  length for assembling the spring on the V-shape holder
p_0  location of connection point, S, when the spring is not tensioned
p_1  location of connection point, S, when the spring is pre-tensioned
p_2  location of connection point, S, when the spring is pre-tensioned and loaded
      with force F_t
r_e  radius of the extension of the carrier
S  point of connection between the extension of the carrier and the spring
T_f  friction torque at the joint of the carrier
\alpha  angle of rotation of the carrier
\phi  angle between carrier and grasp direction - the angle of contact
A.2 THE GRIPPER

Figure A.1 Photograph of the gripper (top view)

Figure A.2 Photograph of the gripper (side view)
### Table A.1 Physical features of the gripper

<table>
<thead>
<tr>
<th>Number of fingers</th>
<th>3</th>
</tr>
</thead>
</table>
| Size of a finger  | carrier radius: \( a = 50 \text{ mm} \)  
roller radius: \( b = 25 \text{ mm} \)  
roller length: \( l_r = 110 \text{ mm} \) |
| Configuration of fingers | planar configuration with fingers equally spaced on a circle;  
distance between centres of the joint of each carrier: \( d = 100 \text{ mm} \) |
| Degrees of Freedom | 2 per finger |
| Gripper overall size | enclosed in a cylinder of \( \varnothing 250 \times 335 \text{ mm} \) |
| Working volume | enclosed in a cylinder of \( \varnothing 250 \times 110 \text{ mm} \) |
| Gripper weight | 4.5 Kg |
| Size of graspable products (gripper opening) | cylindrical product “inside” fingers: \( \varnothing 8 \) up to \( \varnothing 136 \text{ mm} \)  
cylindrical product “outside” fingers: \( \varnothing 108 \) up to \( \varnothing 236 \text{ mm} \)  
spherical product: \( \varnothing 8 \) up to \( \varnothing 100 \text{ mm} \)  
prismatic product (thickness): 0 up to 111 mm |

### Table A.2 Driving system of the gripper

<table>
<thead>
<tr>
<th>Driving system</th>
<th>Electric, with DC servo motors fitted with integral tachogenerator, encoder and gearhead</th>
</tr>
</thead>
</table>
| Displacement of finger (carrier movement) | motor: DC servo motor  
model: McLennan, L004 M35TCI500T  
rated torque: 0.04 Nm  
rated speed: 4200 rpm  
gearhead: planetary type, McLennan, G38/2 ratio 246:1, \( \eta = 60\% \)  
encoder: incremental type, Hewlett Packard HEDS 5500P |
| Rotation of finger (roller movement) | motor: DC servo motor  
model: McLennan, L004 M35TCI500T  
rated torque: 0.04 Nm  
rated speed: 4200 rpm  
gearhead: planetary type, McLennan, G30/1 ratio 66:1, \( \eta = 70\% \)  
encoder: incremental type, Hewlett Packard HEDS 5500P |
| Gripping force/torque | in the carrier movement: 118N  
in the roller movement: 1.8 Nm |
### Table A.3  Sensing and control systems

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position: incremental encoder</td>
<td></td>
</tr>
<tr>
<td>Velocity: tachogenerator</td>
<td></td>
</tr>
<tr>
<td>Torque: measurement of current of motor</td>
<td></td>
</tr>
<tr>
<td>Contact and force:</td>
<td></td>
</tr>
<tr>
<td>tactile sensor</td>
<td></td>
</tr>
<tr>
<td>deflection of finger (finger set as position/force sensor)</td>
<td></td>
</tr>
<tr>
<td>Control computer</td>
<td>PC 80486 @33 MHz</td>
</tr>
<tr>
<td>Interface boards</td>
<td>Multipurpose data acquisition board for PC (Fairchild, model 818)</td>
</tr>
<tr>
<td></td>
<td>Incremental encoder interface board for PC (DEVA)</td>
</tr>
<tr>
<td></td>
<td>Interface board for measurement of current of motor (see Appendix A.3)</td>
</tr>
<tr>
<td></td>
<td>Interface board for tactile sensor (see Appendix A.5)</td>
</tr>
<tr>
<td>Amplifier for motors</td>
<td>PWM switching servo amplifier (Copley Controls Corp. model 201E, supplied by McLennan)</td>
</tr>
</tbody>
</table>

### Table A.4  Specification of sensing equipment

<table>
<thead>
<tr>
<th>Data acquisition board</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 differential channels multiplexed to an A/D successive approximation converter with 12 bit resolution;</td>
<td></td>
</tr>
<tr>
<td>max. sampling rate of 50 kHz per channel;</td>
<td></td>
</tr>
<tr>
<td>2 channels of multiplying 12 bit D/A converter;</td>
<td></td>
</tr>
<tr>
<td>8 digital I/O lines, 2 programmable timers;</td>
<td></td>
</tr>
<tr>
<td>Interface board for incremental encoders</td>
<td>3 axis encoder interface with three 32 bit counters;</td>
</tr>
<tr>
<td>1 programmable timer;</td>
<td></td>
</tr>
<tr>
<td>Incremental encoder</td>
<td>resolution: 2000 pulses per rotation</td>
</tr>
<tr>
<td>Tachogenerator</td>
<td>output signal: 4.3 V/1000 rpm</td>
</tr>
<tr>
<td>Equipment</td>
<td>Supplier</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Interface card for encoders</td>
<td>DEVA Electronics Controls Ltd</td>
</tr>
<tr>
<td></td>
<td>Unit 2B, Poole Hall Industrial Estate, Ellesmere Port L66 1ST, UK</td>
</tr>
<tr>
<td></td>
<td>Fax 051-3558017</td>
</tr>
<tr>
<td>Data acquisition Board</td>
<td>Fairchild</td>
</tr>
<tr>
<td>Motors and amplifiers</td>
<td>McLennan Servo Supplies Ltd</td>
</tr>
<tr>
<td></td>
<td>Yorktown Industrial Estate, Doman Road, Camberley, Surrey, UK</td>
</tr>
<tr>
<td></td>
<td>Fax. 0276-23452</td>
</tr>
<tr>
<td>Roller material</td>
<td>Portman Products Ltd</td>
</tr>
<tr>
<td></td>
<td>P.O. Box 127, Leicester LE1 9GS, UK</td>
</tr>
<tr>
<td></td>
<td>Fax 053-7533870</td>
</tr>
<tr>
<td></td>
<td>Portman clear unreinforced PVC hose, PFP 45/51</td>
</tr>
<tr>
<td>Resistive material for tactile sensor</td>
<td>The Gates Rubber Company Limited</td>
</tr>
<tr>
<td></td>
<td>Edinburgh Road, Heathhall, Dumsfries, DG1 1QA, UK</td>
</tr>
<tr>
<td></td>
<td>Fax. 0387-68937</td>
</tr>
</tbody>
</table>
A.3 INTERFACE CIRCUIT FOR MEASUREMENT OF CURRENT OF THE MOTOR

The value of the driving torque at each joint is inferred from the measurement of the armature current at the DC motor. To connect the current signal to the data acquisition board, an interface board was built based on the circuit shown in Figure A.3. The output signal of this board has a constant characteristic of 3.2 V/A.

Figure A.3 Interface circuit for measurement of current of the motor
A.4 FINGER AS A POSITION/FORCE SENSOR

The implementation of the measurement of the deflection of a finger adopted in the experimental rig enables the use of a finger as a position/force sensor. The finger is assembled on a spring arrangement and a positional encoder replaces the driving motor of the carrier of the finger, as shown in Figure A.4 and in the photograph presented in Figure A.5. In that arrangement a V-shape holder locates the spring relative to the support frame. An extension of the carrier connects to the middle of the spring. The equilibrium of the half springs locates the finger. Measuring the position of the carrier with the encoder detects the deflection of the spring and permits the measurement of the external force applied to the finger.

Figure A.4  Finger configured as a position/force sensor
The stiffness of this sensing system can be selected by choosing the rigidity of the spring arrangement. This is achieved by assembling the spring on the V-shape holder with a pre-tension and by selecting the location where the extension of the carrier connects with the spring. Referring to Figure A.6 the stiffness of the sensing system, \( K_f \), is given by:

\[
K_f = \frac{(l_{s1} - l_s)^2}{(p_1 - p_0)(l_{s1} - l_s + p_0 - p_1)} K_s \quad \text{(Eq. A.1)}
\]

with

\[
F_s = K_f (p_2 - p_1) \quad \text{(Eq. A.2)}
\]
The influence of the location of the extension of the carrier - the connection point $S$ - on the stiffness of the sensing system can be viewed using (Eq. A.1) and is shown in the plot presented in Figure A.7. It shows that the stiffness of the system is at least four times greater than the stiffness of the spring used. This minimum increase on the stiffness occurs when the connection point is located in the middle of the spring. As the connection point is placed closer to the extremity of the spring, the stiffness of the system increases; as an example, to multiply the stiffness of the system by a factor of eleven, the connection point must be located at a distance, measured from one end of the spring, of 10% of the length of the spring.

![Stiffness and location of connection point](image-url)
Considering that for small angular displacements of the carrier the displacement of the connection point is linear, the force - $F_c$ - applied at the finger (refer to Figure A.4) is given by:

$$F_c = \frac{1}{\sin\varphi} \cdot \frac{1}{a} \left[ r_c^2 K_s \sin\alpha + T_t \right]$$  \hspace{1cm} (Eq. A.3)

The value of the angle of contact, $\varphi$, and the stiffness of the sensing system, $K_s$, affect the force resolution. Considering the configuration of the system and neglecting the friction torque at the joint of the carrier, $T_t$, the effect of the angle of contact on the force resolution is given by (Eq. A.4). The plot presented in Figure A.8 uses the (Eq. A.4) to show the influence of the angle of contact on the force resolution. It shows that the best force resolution is achieved when the force applied at the finger is aligned with the spring (angle of contact is 90 degrees). From the plot shown in Figure A.8 it is possible to conclude that for contact angles within the range of 30 to +150 degrees, the force resolution is reduced by a factor of two.

$$\frac{F_c}{K_f \left( \frac{1}{a} \right) r_c^2 \sin \alpha / \sin \varphi} = \frac{1}{\sin \varphi}$$  \hspace{1cm} (Eq. A.4)

![Figure A.8  Force resolution and angle of contact](image)
For a given stiffness of the sensing system, $K_s$, the range of measurable forces can be found using (Eq. A.3). The plot shown in Figure A.9 presents the variation of the contact force with the angular displacement of the carrier when considering the use of two different springs. The value of angle of contact, $\varphi$, is considered to remain at 90 degrees and the system that measures the angular position of the carrier is considered to have a resolution of 0.18 degrees (this is the value of the actual system employed).

![Graph showing contact force and angular displacement of the carrier]

Figure A.9  Contact force and angular displacement of the carrier

The physical and functional characteristics of the sensing system that was built to use a finger as a position/force sensor are presented in Table A.6. Two springs having different stiffness, were employed so that it was possible to cover a wide range of contact forces while keeping the displacement of the carrier small. The functional characteristics were obtained by experimentation. The value of the stiffness of each spring and of the associated stiffness of the sensing system, $K_s$, was obtained from tests performed on a tensile machine (see Appendix B for characteristics of the tensile test machine).
Table A.6  Characteristics of the finger configured as a position/force sensor

<table>
<thead>
<tr>
<th></th>
<th>Mechanical configuration</th>
<th>Position encoder resolution</th>
<th>Springs:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a = 50 mm</td>
<td>0.18 deg. (2000 pulses/rot.)</td>
<td>Spring S1</td>
</tr>
<tr>
<td></td>
<td>r&lt;sub&gt;c&lt;/sub&gt; = 100 mm</td>
<td></td>
<td>K&lt;sub&gt;s&lt;/sub&gt; = 21 N/m</td>
</tr>
<tr>
<td></td>
<td>l&lt;sub&gt;th&lt;/sub&gt; = 145 mm</td>
<td></td>
<td>l&lt;sub&gt;s&lt;/sub&gt; = 92 mm</td>
</tr>
<tr>
<td>Stiffness of sensor, K&lt;sub&gt;S&lt;/sub&gt;, when</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>assembled with connection point</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>located at p&lt;sub&gt;1&lt;/sub&gt;</td>
<td>K&lt;sub&gt;f&lt;/sub&gt; = 168 N/m</td>
<td>K&lt;sub&gt;f&lt;/sub&gt; = 2047 N/m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p&lt;sub&gt;1&lt;/sub&gt; = 20 mm</td>
<td>p&lt;sub&gt;1&lt;/sub&gt; = 64 mm</td>
<td></td>
</tr>
<tr>
<td>Range of measurable forces, F&lt;sub&gt;e&lt;/sub&gt;, for displacement of carrier, α, smaller than 4°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 to 2.6 N</td>
<td>0 to 25.4 N</td>
<td></td>
</tr>
<tr>
<td>Force resolution for 30°&lt;α&lt;150°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>better than</td>
<td>better than</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.23 N</td>
<td>2.3 N</td>
<td></td>
</tr>
</tbody>
</table>

The plots shown in Figure A.10 and Figure A.11 present the results of the tensile tests performed for the identification of the stiffness of each spring used.

Figure A.10  Tensile test of spring S1
The stiffness behaviour of the force sensing system was measured using a tensile test machine with a set up as shown in Figure A.12. The probe of the tensile machine is set to move at constant velocity contacting directly with the extension of the carrier. The spring holder is kept fixed and the carrier rotates as a result of the displacement imposed by the probe. The load cell of the test machine measures the force exerted by the probe.

![Tensile test of spring S2](image)

*Figure A.11  Tensile test of spring S2*

![Test set up for identification of the stiffness behaviour of the sensor](image)

*Figure A.12  Test set up for identification of the stiffness behaviour of the sensor*
The plots shown in Figure A.13 and Figure A.14 present the experimental results of these tests when using the spring S1 and the spring S2, respectively. The theoretical results to expect from the developed model are included in these plots. An analysis of the plots presented in Figure A.13 and Figure A.14 shows that the experimental results are within 12% of the theoretic values predicted with the model of the sensor. These results must take into consideration that the test imposed a large angle of rotation of the carrier. This introduced a displacement of the point of application of the load and the spring was subjected to bending loads. Considering these limitations, the level of agreement of the experimental results with the theoretic model can be considered to be within an acceptable range.

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**Figure A.13**  Force characteristic curve for sensor using spring S1

---

**Figure A.14**  Force characteristic curve for sensor using spring S2
A.5 TACTILE SENSOR

A.5.1 INTRODUCTION

The use of tactile sensing systems can provide information on the characteristics of contact between the gripper and the product during grasp and manipulation tasks. The information can include the detection of contact, the location of contact within the fingers of the gripper, the pattern or area of contact and the measurement of the contact force and its distribution. The data acquired with tactile sensing systems may be used not only to accomplish tasks of grasp and manipulation but also for recognition purposes. The data from tactile sensors enables the identification of product features such as shape, size, hardness and surface friction, as has been shown by Berger and Khosla (1991) and Stansfield (1992).

The development in tactile sensing systems has been focused in two main areas: the hardware side of the sensors and their use for feature-extraction and object recognition. For the development of tactile sensors a wide range of transduction techniques have been reported and used, including piezoresistive (Snyder and Clair, 1978; Hillis, 1982; Bastuscheck, 1989; Speeter, 1990), piezoelectric (Pirolo and Kolesar, 1989; Dario et al., 1991), capacitive (Fearing, 1990), electrooptical (Rebman and Morris, 1983), photoelastic (Cameron et al., 1988) and magnetoelastic (Checinski and Agrawal, 1983). Reviews of tactile systems describing the merits, limitations and performance of each sensor technology referred to can be found in the work of Hollerbach (1987), Webster (1988), Grupen et al. (1989), Nicholls and Lee (1989) and Nicholls (1992). The overall conclusion has been that none of the above techniques has emerged as the most suitable one to fulfil all the design criteria established for useful tactile sensors, nor have any proved to be suitable for all applications desired. This leads to moving the emphasis of the research on tactile hardware systems towards the design aspects and away from the issue of transduction techniques. Within the design aspects the integration of the sensor with signal conditioning and the capability to perform dynamic measurements have been the main concern (Raibert and Tanner, 1982; Howe and Cutkosky, 1989, Kobayashi et al., 1991; Koselar et al., 1992; Cutkosky et al., 1994; Yamada and Cutkosky, 1994).
The other aspect of the development of tactile sensors has come from their application to object recognition and exploration (Allen, 1992; Nicholls, 1992). This application, called *active sensing or dynamic exploration*, involves the interaction between manipulation and sensing. The information acquired from multiple sensors, where tactile sensors are of primordial importance, is used for guiding the movements of the manipulator and for identification of features and properties of the products. The identification of features of products such as local surface shape, hardness and friction have been reported by several researchers - Allen and Michelman, 1990; Stansfield, 1986, 1992. As pointed out by Allen (1992), the two main obstacles in the use and spread of these applications has been the lack of robust low level tactile sensing systems and of dexterous multi-fingered robot hands capable of performing and implementing manipulation of grasped products.

### A.5.2 SENSOR DESIGN

A tactile sensor array was built to be assembled in a finger of the gripper. The design of the sensor is based on established work on the development of piezoresistive tactile arrays (Hillis, 1982; Bao, 1990; Speeter, 1990; Fearing, 1990; Dario, 1991). The transduction technique used is based on the piezoresistivity characteristic of an elastomer - PRE. The elastomer (Bishop, 1987), supplied in a flexible sheet form, is placed between conducting material to form an array of sensing sites. For each sensing site, the electrical resistance between the conducting material through the elastomer decreases exponentially as normal force is applied. See Figure A.15 for the typical performance characteristic of the PRE material. The decrease in resistance is caused by modification in the surface interaction between the elastomer and the conducting material. As pointed out by Mokshagundam (1988), it is the variation in the contact area between the conductor and the elastomer resulting from the applied force that affects the resistance measured across the elastomer.
Figure A.15 Typical performance of PRE material (from Bishop, 1987)

The sensor array built is made of 16 x 16 sensing sites placed around a cylindrical surface (Figure A.16). The sensing points are defined at the interception between a row and a column. The rows and columns are equally spaced (3.5 mm) and are made of a Ø 0.25 mm electric wire. The tactile sensor is mounted inside the finger in an arrangement as shown in Figure A.17.

Figure A.16 Tactile sensing configuration and equivalent electric circuit
To acquire the data from the tactile sensor requires the measurement of the resistance at each sensing site. Different methods are available to isolate a single site from a resistance grid and have been addressed by several researchers (Purbrick, 1981; Hillis, 1982; Speeter, 1990). The adopted approach follows the work of Speeter (1990) and uses the circuit of Figure A.18. The array is scanned by applying a voltage to one column at a time and measuring the current flowing in each row, using feedback to eliminate unwanted current paths. When a column is selected, the voltage being supplied to that column is feedback to the other columns so that all columns are at the same voltage and no current can flow between them.

Figure A.18  Circuit for scanning the tactile sensor array
The circuit of Figure A.18 was implemented on a VERO wire-wrap board. A personal computer fitted with an interface board with digital and analogue I/O is used to acquire and process the data from the sensor. A digital image of the data acquired with the tactile sensor is obtained after digitalisation, filtering and scaling. That data is further processed providing information relating to the characteristics of contact. The following parameters are calculated:

- location and value of contact area
- average value of contact force
- maximum and minimum value of contact force
- location of maximum and minimum value of contact force

The computing time to implement the acquisition and processing of the data from a tactile sensor array with 256 sensing sites is 22 ms.

A.5.3 EXPERIMENTAL RESULTS

Few problems were detected in the assembled tactile sensor. The main one was the poor repeatability of the sensor data. It was identified as resulting from the conjugation of two factors: the high sensitivity at each sensing site and the process of scanning the sensor. The small contact area at each sensing site made the contact characteristics between the conducting material and the elastomer very sensitive to the load conditions. The inherent resistance introduced by the analogue switches and multiplexers of the scanning circuit affects the measurement of the resistance at each sensing site. An analysis of the scanning circuit (see Figure A.19, where the scanning circuit is applied to a grid of four variable resistance) shows that the measurement of the selected resistance is independent on the value of the resistance of the other sensing sites only when the resistance introduced by the switches and multiplexers is considered to be null. As the switches and multiplexers introduce a typical resistance of 200 ohm (when driven at 10 V), the measurements are affected. To view that effect the plot shown in Figure A.20 presents the influence of the value of resistances R2 and R3 (R4 is considered constant) on the measurement of resistance R1. The resolution of this problem can be achieved by solving $n$ equations in $n$ unknowns at a cost of increasing the process time. For a grid with four resistances, $n$ is
equal to twenty four. The measurement of the resistance of each site, gives a set of six equations, with
four resistances unknown and five currents unknown. This gives, for a grid with four sites, twenty
currents unknown and the four resistances unknown, totalling twenty four variables and equations.

*Figure A.19* Scanning circuit selecting resistance R1 on a grid of four resistances

![Diagram](image)

*Figure A.20* Influence of resistances R2 and R3 on the measurement of resistance R1

These aspects led to the construction of another sensor where the contact area between the
electrodes and the elastomer was enlarged and the number of independent sensing sites was reduced.
This was achieved by replacing the rows of conducting material with a sheet of aluminium foil. This
reduces the number of sensing sites of the sensor to sixteen, i.e., the number of columns of the initial
tactile sensor (Figure A.21). The same scanning circuit and software were employed and the process
time for implementation of the acquisition and processing of data was reduced to 1.4 ms.

![Tactile sensor diagram]

*Figure A.21 Tactile sensor configuration with sixteen sensing sites*

To view the performance of the sensor and its potential use in identifying the properties of a
product, experimental work was conducted. A finger of the gripper equipped with a tactile sensor was
pressed against two products of different stiffness characteristics, specimen A and specimen B (see
Appendix B for the characteristics of tested products). The products, placed in known locations,
remain still when touched by the finger. The finger of the gripper is driven towards the product under
velocity control until it stops and stays exerting a constant force.

The contact force measured with the tactile sensor is compared with the force exerted by the
finger in the plots shown in Figure A.22 and Figure A.23. The measurement of the force exerted by
the finger is obtained through the value of the current of the motor that drives the finger. The value of
the measurement at each sensing site of the sensor is scaled into 256 levels of force. The measurement
of the contact force is given by the normalized sum of the measured values at each sensing site. The
analysis of the plots presented in Figure A.22 and Figure A.23 shows that when the force being exerted
by the finger is kept constant there is a high correlation between the exerted force and the output signal
of the sensor, for both tested specimens.
Figure A.22  Sensor output and applied force during the trial with specimen A

Figure A.23  Sensor output and applied force during the trial with specimen B
To view the measured values at each sensing site of the sensor, when the finger is stationary and exerting a constant force, the plot shown in Figure A.24 is presented. The force signal of the sensor that is plotted is the normalized average value of the measurements performed at each sensing site during the last two seconds of the trial. The difference obtained between the two measurements with the sensor (Figure A.24) is as expected and shows a wider distribution of force for the specimen B that has a lower stiffness.

![Normalized output of a sensing site of the sensor](image)

*Figure A.24  Sensor output during the last two seconds of the trial*

The measurements made at the individual sensing sites close to the centre of contact during the trial are presented in Figure A.25 for specimen A and in Figure A.26 for specimen B. The output signal of each sensing site during the trial for specimen A has a sharp variation when the finger contacts the product, as shown in the plot presented in Figure A.25. For specimen B, the output signal from each sensing site has a slow response in time when the finger contacts the product, as shown in the plot presented in Figure A.26. These results can be used for inferring the stiffness properties of the tested specimens. The slower build up of contact force for specimen B when compared with specimen A reveals that specimen B is less stiff than specimen A, since the test conditions are the same.
The area of contact is determined from the measurement made at each individual sensing site of the sensor. When the measured value is above a threshold constant, contact is considered to have occurred at that site. The plot shown in Figure A.27 presents the variation of the contact area during the trial for both products (the threshold constant was considered to be 2% of the measured value of force). The modification in the value of the contact area during the trial can also be used to distinguish
the two tested specimens. The instant when the finger contacts the product can be detected from the modification of the value of the contact area.

![Graph showing variation of contact area during the trial]

*Figure A.27  Variation of contact area during the trial*

From the conducted trials and analysis performed on the data obtained with the tactile sensor, the characteristics of this sensing system are therefore summarized in Table A.7.

*Table A.7  Specification of tactile sensor system*

<table>
<thead>
<tr>
<th>Tactile sensor</th>
<th>piezo resistive sensor array</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of sensing sites: 16</td>
<td></td>
</tr>
<tr>
<td>positional resolution of sensing sites: 3.5 mm</td>
<td></td>
</tr>
<tr>
<td>Measurement parameters</td>
<td>force range (256 levels of force): 24 N to 50 N</td>
</tr>
<tr>
<td></td>
<td>force resolution: 0.2 N</td>
</tr>
<tr>
<td></td>
<td>contact area range: 1 to 16 sites</td>
</tr>
<tr>
<td></td>
<td>contact area resolution: 1 site</td>
</tr>
<tr>
<td></td>
<td>sample rate (scanning and data processing): 714 Hz</td>
</tr>
</tbody>
</table>
A.5.4 CONCLUSIONS

The review on the development of tactile sensors indicates that different transduction techniques are being employed without the predominance of a specific technique. The reduced availability in commercial tactile sensors and the growing need of sensors for the exploration and recognition of objects is still prompting the development of new tactile sensors.

A tactile sensor was built and experimental work carried out. The results showed that it was possible to use the sensor for detection of contact, contact location and identification of force distribution. The use of the sensor for accurate measurement of the contact force is limited by the sensitivity of the sensor to the load conditions. The experimental results also indicate that the integration of the sensor within the gripper provides the means to use the data acquired with the tactile sensor for identification of the stiffness characteristics of the grasped products.

A.6 OPERATING CONDITIONS

The settings adopted to operate the gripper in the different experiments conducted are presented in Table A.8, Table A.9 and Table A.10. It takes into consideration the characteristics of the different subsystems of the gripper - motors, sensing systems and control systems - and how they were configured to interact.
Table A.8 Settings of operating conditions of motors

<table>
<thead>
<tr>
<th>Operating conditions of the motors</th>
<th>Joint of the finger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>carrier movement</td>
</tr>
<tr>
<td>current/torque</td>
<td></td>
</tr>
<tr>
<td>max. current [A]</td>
<td>1</td>
</tr>
<tr>
<td>current resolution [A]</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>max. torque [Nm]</td>
<td>0.041</td>
</tr>
<tr>
<td>torque resolution [Nm]</td>
<td>$0.063 \times 10^{-3}$</td>
</tr>
<tr>
<td>velocity</td>
<td></td>
</tr>
<tr>
<td>max. velocity [rpm]</td>
<td>4200 (17 at gearbox output)</td>
</tr>
<tr>
<td>velocity resolution [rpm]</td>
<td>6.5</td>
</tr>
<tr>
<td>position</td>
<td></td>
</tr>
<tr>
<td>position range [deg]</td>
<td>0 to 73800 (0 to 300 at gearbox output)</td>
</tr>
<tr>
<td>position resolution [deg]</td>
<td>0.18 (0.73 $\times 10^{-3}$ at gearbox output)</td>
</tr>
</tbody>
</table>

Table A.9 Settings of operating conditions of a finger as a position/force sensor

<table>
<thead>
<tr>
<th>position/force sensor</th>
<th>with spring S1</th>
<th>with spring S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>position range [deg]</td>
<td>0 to 4</td>
<td>0 to 4</td>
</tr>
<tr>
<td>position resolution [deg]</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>force range [N]</td>
<td>0 to 2.6</td>
<td>0 to 25.4</td>
</tr>
<tr>
<td>force resolution [N]</td>
<td>better than 0.23</td>
<td>better than 2.3</td>
</tr>
</tbody>
</table>

Table A.10 Settings of operating conditions of the tactile sensor

<table>
<thead>
<tr>
<th>Tactile sensor variables</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>force range</td>
<td>0 to 256</td>
</tr>
<tr>
<td>resolution</td>
<td>1</td>
</tr>
<tr>
<td>contact area range</td>
<td>0 to 16</td>
</tr>
<tr>
<td>resolution</td>
<td>1</td>
</tr>
</tbody>
</table>
APPENDIX B

PROPERTIES OF THE TESTED PRODUCTS

B.1 TESTED PRODUCTS

The experiments performed with the gripper required the use of different products presenting rigid and non-rigid handling behaviour. In order to meet these requirements five products presenting different stiffness characteristics were chosen. The characteristics of the tested specimens are presented in Table B.1. To evaluate the stiffness of the material for specimens B, C and D, the products were tested on a tensile test machine (see section B.2 of this Appendix) and the stress-strain curves obtained. The test is carried out in three stages: a compression stage carried out at a fixed velocity; a wait stage, where the product is kept loaded; and the decompression stage, carried out at the same velocity as the initial compression. The velocity of the test is 15 mm/min and the wait stage lasts 90 seconds. The probes of the test machine contacting the product are planar and have a diameter of 50 mm. The plots shown in figures B.1, B.2 and B.3 present the results from the tensile tests. The plot shown in Figure B.4 summarizes the compression stage part, of the stress-strain curve of the tested specimens.
Table B.1 Properties of tested specimens

<table>
<thead>
<tr>
<th>Reference</th>
<th>Dimension [mm]</th>
<th>Material</th>
<th>Weight [Kg]</th>
<th>Stiffness [N/m²]</th>
<th>Behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen A: aluminium block</td>
<td>120 x 69 x 32</td>
<td>aluminium</td>
<td>0.7</td>
<td>15 x 10⁶</td>
<td>rigid</td>
</tr>
<tr>
<td>Specimen B: soft foam</td>
<td>85 x 75 x 32</td>
<td>foam</td>
<td>0.02</td>
<td>24 x 10³</td>
<td>elastic</td>
</tr>
<tr>
<td>Specimen C: hard foam</td>
<td>100 x 80 x 31</td>
<td>foam</td>
<td>0.03</td>
<td>130 x 10⁶</td>
<td>elastic</td>
</tr>
<tr>
<td>Specimen D: super soft foam</td>
<td>90 x 70 x 30</td>
<td>foam</td>
<td>0.018</td>
<td>45 x 10⁶</td>
<td>elastic</td>
</tr>
<tr>
<td>Specimen E: “ramp” profile</td>
<td>see Fig. B5</td>
<td>wood</td>
<td>0.3</td>
<td></td>
<td>rigid</td>
</tr>
</tbody>
</table>

Figure B.1 Specimen B
Figure B.2  Specimen C

Figure B.3  Specimen D
Figure B.4  Stress-strain curves from the compression test of the different specimens

Figure B.5  Specimen E

all dimensions in mm
B.2 TEST MACHINE

A tensile test machine was required to evaluate the stiffness behaviour of a finger configured as a position/force sensor and for the identification of the stiffness properties of the specimens used in the experiments. The test machine used was a Hounsfield H10KN tensile test machine. This is a standard worm screw machine fitted with a 1000 N load cell, laser extensometer and capable of applying loads up to 10 KN. Amplification is provided to the load cell so that full measurements' accuracy is possible over 5, 10, 20, 50 or 100 % of the 1000 N full deflection of the load cell. The most sensitive set of the machine enables loads up to 50 N to be measured with a resolution of 0.025 N.

A non-contact Hounsfield 50L laser extensometer is used for strain measurement. It requires the continuous measurement of the position of two retro-reflective strips that can be attached to the supports which hold the specimen during the test.

It is possible to control the extension rate between 0.5 mm/min up to 500 mm/min, with a 0.5 mm/min step.
APPENDIX C

CONTROL OF A JOINT OF A FINGER

This appendix presents experimental results on the control of a joint of the gripper. A set of experimental tests was conducted to evaluate the implementation and performance of different control modes: torque, velocity, position and force. The tests involved the analysis of each control mode and the implementation of the capability to switch between control modes. The experiments demonstrate the performance of the control architecture in the easy implementation of the control modes and in the capability to switch between them. The implications and potential application in the control of the movements of the fingers of the gripper are highlighted.

C.1 CONTROLLER DESIGN AND IMPLEMENTATION

The control architecture presented in chapter 3 (see Figure 3.11) was implemented using discrete time digital controllers on a personal computer. The control modes that the referred architecture can implement and the required feedback signals of each mode, are presented in Table C.1. The position signal was obtained using an incremental encoder. The velocity signal was obtained from a tachogenerator. Two force signals were available and used in the implementation of the
implicit and the explicit control of force. One signal of force was obtained using a finger configured as a position/force sensor (see Appendix A.4); this signal of force measures the force exerted on the finger through the angular deflection of the finger which is measured with an incremental encoder. The other signal of force was obtained from the measurements of force performed with the tactile sensor (see Appendix A.5).

<table>
<thead>
<tr>
<th>Control mode</th>
<th>commanded signals</th>
<th>feedback signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque control</td>
<td>torque reference</td>
<td></td>
</tr>
<tr>
<td>Velocity control</td>
<td>velocity reference, torque limit</td>
<td>velocity</td>
</tr>
<tr>
<td>Position control</td>
<td>position reference, velocity limit, torque limit</td>
<td>velocity, position</td>
</tr>
<tr>
<td>Force control</td>
<td>force reference, position limit, velocity limit, torque limit</td>
<td>force (position signal measured with finger set as position/force sensor), position, velocity</td>
</tr>
<tr>
<td>implicit</td>
<td></td>
<td>force (force signal measured with tactile sensor), position, velocity</td>
</tr>
<tr>
<td>explicit</td>
<td></td>
<td>force (force signal measured with tactile sensor), position, velocity</td>
</tr>
</tbody>
</table>

As the controllers were to be implemented digitally, the value of the sampling period had to be chosen. After some experimental trials a sampling period of 2 ms (500 Hz) was found to be adequate. This choice of sampling period is long enough for all the computer needs in sampling and processing the data of the tactile sensor, in performing the acquisition and logging of data from the sensing systems and in performing the calculations involved with the implementation of the controllers; and fast enough to provide the bandwidth needed for the desired time response.

The torque controller is implemented directly on hardware using the current amplifier of the driving card of the motor. The computer sends a voltage reference signal to the amplifier; that voltage
signal is converted, at the amplifier, into a proportional current signal that drives the motor. For the velocity, position and force control the use of simple proportional controllers proved to be adequate. The gains were adjusted individually to achieve a stable system with a critical damped response to a step signal.

The digital computer interacts with the gripper using digital inputs, analogue inputs and analogue outputs. The computer is fitted with a general purpose data acquisition board having analogue input and output capabilities. The D/A converters, used to output the control signals to the amplifiers of the motors, have a 12 bit resolution. The analogue inputs, for data logging purposes, use a multiplexed 12 bit A/D converter of the acquisition board. The torque signal is obtained through the measurement of the current used by the motor. An interface board (see Appendix A.3) is used to do the current signal conditioning before being connected to one of the analogue inputs of the data acquisition board. The encoders output the position signal in digital form. An interface board using 32 bit counters is fitted to the computer so that position can be read directly by the digital processor.

Using this input/output arrangement, sequential sampling of the torque, position, velocity and force input signals and outputting of control signals to the amplifiers is made possible. The acquired data and the generated control signals are also logged to the computer memory. The data generated was afterwards imported into a spreadsheet (Microsoft Excel). This computer program was used to perform scaling and plotting of the acquired data.
C.2 EXPERIMENTAL RESULTS

A set of experimental tests was conducted to evaluate the performance of each control mode and the performance when switching between control modes. These experiments involved the control of the finger joint that implements the carrier movement. This joint was chosen because a grasp action is usually accomplished with the carrier movement of a finger. Most of the experiments involve exciting the joint with a step reference signal and monitoring the time response of the controlled variables of the motor. The values of these measured signals are plotted for analysis. The normalized values used in the plots refer to the operating conditions of the motors and sensing systems (refer to Appendix A.6).

C.2.1 Torque control

The performance of the torque control mode was evaluated considering the response of the joint motor when its driving amplifier is excited with a step signal (see Figure C.1). This torque reference signal drives the motor moving the finger towards a fixed and rigid obstacle (the mechanical end stop of the carrier). The impact of the finger on the obstacle halts its movement. Five tests were conducted using different values for the magnitude of the reference signal (see Table C.2). The values of the current and velocity of the motor were monitored during the tests. The plot shown in Figure C.2 presents the values of the current, measured at the end of each test, when the finger is kept stationary but pressing against the obstacle.

The analysis of the results presented in Figure C.2 show that, under the torque control mode, there is a linear relationship between the commanded torque signal and the current at the motor with the joint halted. As discussed in chapter 3, the current is directly proportional to the torque of the motor at steady situations. Thus it is possible to use the torque control mode to impose a limit on the torque being supplied by the motor. The force exerted by a finger of the gripper during a grasp action can be limited using this control mode.
Figure C.1 Torque control: configuration of the control loop used in the experiments

Table C.2 Test conditions for experiments with torque control

<table>
<thead>
<tr>
<th>Test</th>
<th>Torque Reference Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test T1</td>
<td>step 100 %</td>
</tr>
<tr>
<td>Test T2</td>
<td>step 75 %</td>
</tr>
<tr>
<td>Test T3</td>
<td>step 50 %</td>
</tr>
<tr>
<td>Test T4</td>
<td>step 25 %</td>
</tr>
<tr>
<td>Test T5</td>
<td>step 12.5 %</td>
</tr>
</tbody>
</table>

Figure C.2 Torque control: current at the motor with the joint halted
The current and velocity response signals, for three of the tests performed, are presented in Figure C.3, for test T1, in Figure C.4 for test T3 and in Figure C.5 for test T4. These results are summarized in the two plots shown in Figure C.6.

The dynamic behaviour of a joint under torque control that is set to move against a fixed and rigid obstacle in response to a torque step signal (shown in the plots presented in Figure C.3, Figure C.4 and Figure C.5) reveals the existence of three distinct phases. Referring to Figure C.3, there is an initial phase, when the motor starts its movement, that is characterized by a sharp increase in the current and by the build up of the velocity. The current reaches a peak value and remains at that level for a short period. The value of the peak in the current is limited by the commanded reference signal of torque. The second phase is initiated at the end of this period where the current starts to decrease, while the velocity continues to rise. In this second phase the velocity reaches its maximum value and remains fairly constant while the current drops to a lower level. Note that the velocity that is reached is well above the operating velocity, since there is no control of velocity. The third phase is initiated when the finger collides with the obstacle. The impact halts the movement of the motor. This is associated with an increase in the current and the velocity drops until the motor stops. The drop in the velocity reflects the existence of slackness between the gears of the gearbox. This slackness is taken up and the gears are kept loaded. This implies that, after contact and the joint immobilisation, the motor can still rotate loading the gearbox until the slackness of the gears is taken up. This behaviour is still clear in the test T2 (Figure C.4) but for test T3 (Figure C.5) it is difficult to distinguish these three phases. This is due to the use of a lower commanded reference of torque that limits the torque developed by the motor. The motor was still in an acceleration phase when the impact occurred, as can be seen in the plot of velocity in Figure C.5.

The performance of the motor in the initial phase can be explained by the behaviour of the amplifier employed. When the reference signal is fed to the amplifier, it is able to supply the motor with the maximum current set by the reference signal. As the velocity of the motor increases, the back electromotive force generated by the motor increases and a point is reached where the amplifier can no longer impose an output current. From this saturation point the amplifier acts as a voltage driver, with
the motor driven by a voltage signal instead of a current signal. The current at the motor drops to a value that is dependant on the maximum voltage that the amplifier can supply and on the magnitude of the back electromotive force. This leads to a further increase in the velocity until an equilibrium situation develops, with the velocity of the motor stabilising. It is only when the velocity of the motor decreases, forcing the back electromotive force to decrease, that the amplifier is again able to impose a current. The saturation of the amplifier of the motor imposes that the torque control can only implement the control of the limit of the current rather than the control of the current.

The results also show that the higher accelerations of the motor are obtained when using the higher torque reference signals, as seen in the plot of velocity in Figure C.6.

From the results obtained on the torque control of a joint of a finger the following implications in the use of the gripper can be established:

- it is possible to limit the force exerted by a finger through the use of torque control
- low values for the reference signal of torque delay the time response of the velocity of the finger.
Figure C.3 Torque control (test T1): current and velocity response to a torque step signal followed by impact on obstacle
Figure C.4 Torque control (test T2): current and velocity response to a torque step signal followed by impact on obstacle
Figure C.5 Torque control (test T3): current and velocity response to a torque step signal followed by impact on obstacle
Figure C.6  Torque control: comparison of tests T1, T2 and T3
C.2.2 Velocity control

The performance of the velocity control mode is examined through the response of a finger joint to a velocity step signal (see Figure C.7). The velocity reference signal drives the motor that moves the finger towards a fixed and rigid obstacle (the mechanical end stop of the carrier). As in the previous experiments of torque control, the impact of the finger on the obstacle halts the movement of the finger. A set of nine tests was conducted using different control conditions, combining three values of the velocity reference signal with three values of the torque limit signal (see Table C.3).

![Diagram of velocity control system]

Figure C.7 Velocity control: configuration of the control loop used in the experiments

Table C.3 Test conditions for experiments with velocity control

<table>
<thead>
<tr>
<th>Test</th>
<th>Velocity reference signal</th>
<th>Torque limited to</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>step 100 %</td>
<td>100 %</td>
</tr>
<tr>
<td>V2</td>
<td>step 100 %</td>
<td>50 %</td>
</tr>
<tr>
<td>V3</td>
<td>step 100 %</td>
<td>25 %</td>
</tr>
<tr>
<td>V4</td>
<td>step 50 %</td>
<td>100 %</td>
</tr>
<tr>
<td>V5</td>
<td>step 50 %</td>
<td>50 %</td>
</tr>
<tr>
<td>V6</td>
<td>step 50 %</td>
<td>25 %</td>
</tr>
<tr>
<td>V7</td>
<td>step 25 %</td>
<td>100 %</td>
</tr>
<tr>
<td>V8</td>
<td>step 25 %</td>
<td>50 %</td>
</tr>
<tr>
<td>V9</td>
<td>step 25 %</td>
<td>25 %</td>
</tr>
</tbody>
</table>
The velocity and current response of each test was grouped into three sets, according to the magnitude of the velocity step signal used as the command reference. The first set of results, refers to tests V1, V2 and V3 that used a 100% reference step signal, are presented in Figure C.8, Figure C.9 and Figure C.10, with the results summarized in Figure C.11. The second set of results, referring to tests V3, V4 and V5 that used a 50% reference step signal, are presented in Figure C.12, Figure C.13 and Figure C.14, with the results summarized in Figure C.15. Finally, the third set of results, which refers to tests V6, V7 and V8 using a 25% reference step signal, are presented in Figure C.16, Figure C.17 and Figure C.18, with the results summarized in Figure C.19.

The analysis of the velocity response to a velocity step signal, presented in Figure C.11, Figure C.15 and Figure C.19, shows that the reference velocity was reached within a steady state error. These results were obtained independently of the value of the torque reference used in each experiment. This steady state error is due to the use of a proportional type controller for the velocity controller. The effect of using a different value for the limit of torque is a modification on the system time response. The lower value of the limit of torque used implied a slower response to reach the requested velocity, imposing a limit on the acceleration that can be achieved.

The performance of the movement of the joint when the finger collides with the fixed obstacle can be seen in the plots of the current response presented in Figure C.11, Figure C.15 and Figure C.19. The results show that the level of current that is reached when the joint is halted is directly proportional to the value of the torque limit used in the reference parameters of the velocity control. This value is independent of the velocity that the joint had when moving towards the obstacle. The drop in velocity when the finger collides with the obstacle (results summarized in Figure C.11, Figure C.15 and Figure C.19) has a similar behaviour to the one seen in the experiments of torque control (Figure C.6). The drop in velocity is accomplished by taking up the slackness of the gears of the gearbox. The higher the torque available, the higher load the motor applies to the gearbox. Thus the higher the values of the torque limit, the longer the time until the motor stops.
The control of velocity of a joint can be applied in the control of the fingers of the gripper during a grasp action. The movement of approach of a finger towards a product can be made under velocity control and the force that the finger can exert when contacting the product can be limited. This is achieved by setting the value of the reference velocity and the value of the limit of torque in the velocity control loop. In this way, velocity and torque are controlled in an integrated way. The limitation of this strategy is, that the minimum force that is possible to control reflects the minimum torque that is necessary to move the motor at the requested velocity.
Figure C.8 Velocity control (test V1): current and velocity response to a velocity step signal followed by impact on obstacle
Figure C.9 Velocity control (test V2): current and velocity response to a velocity step signal followed by impact on obstacle
Test V3
vel.: 100% step, torque limit: 25%

[Graph]

impact on obstacle

Figure C.10 Velocity control (test V3): current and velocity response to a velocity step signal followed by impact on obstacle
Figure C.11 Velocity control: comparison of tests V1, V2 and V3
Figure C.12 Velocity control (test V4): current and velocity response to a velocity step signal followed by impact on obstacle
Figure C.13  Velocity control (test V5): current and velocity response to a velocity step signal followed by impact on obstacle
Figure C.14 Velocity control (test V6): current and velocity response to a velocity step signal followed by impact on obstacle
Figure C.15  Velocity control: comparison of tests V4, V5 and V6
Figure C.16 Velocity control (test V7): current and velocity response to a velocity step signal followed by impact on obstacle
Figure C.17 Velocity control (test V8): current and velocity response to a velocity step signal followed by impact on obstacle
Test V9
vel.: 25% step, torque limit: 25%

Impact on obstacle

Time [s]

Figure C.18 Velocity control (test V9): current and velocity response to a velocity step signal followed by impact on obstacle
Figure C.19  Velocity control: comparison of tests V7, V8 and V9
C.2.3 Position control

The performance of the position control mode was evaluated considering the response of a finger joint to a position step reference signal (see Figure C.20). The position reference signal drives the joint of the carrier movement of a finger. The control parameters of the position control mode used in the tests are presented in Table C.4. The value of the position step signal was chosen to allow the motor to reach the velocity limit set in the parameters of the position controller.

![Diagram of position control configuration](image)

*Figure C.20 Position control: configuration of the control loop used in the experiment*

<table>
<thead>
<tr>
<th>Table C.4 Test conditions for experiments with position control</th>
</tr>
</thead>
<tbody>
<tr>
<td>position reference</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Test P1</td>
</tr>
<tr>
<td>Test P2</td>
</tr>
</tbody>
</table>

The response of the motor to the position step reference is evaluated in terms of the time response of position, velocity and current signals. The results of test P1 are presented in Figure C.21 and of test P2 in Figure C.22. A detailed view of the position values, when the motor reaches the reference position, is presented in Figure C.23. For comparison purposes, the results of test P1 and P2 are presented together, in the plots shown in Figure C.24.
The analysis of the results of the performance of the position control, presented in the plots of position in Figure C.21 and Figure C.22 and detailed in Figure C.23, shows that it was possible to implement the control of the requested position without overshoot but with a steady state error. This error is due to the use of a proportional controller in the position control loop. It should be pointed out that this error occurs in the positioning of the motor and not of the finger. The gearbox has the effect of reducing the error in the position of the finger but at the same time can introduce a position error due to the backlash of the gears.

The analysis of the plots of velocity, torque and position of both tests, presented in Figure C.24, shows that with the control architecture it was possible to integrate the control of position with the control of velocity and torque. The same reference of position was reached but the velocity and torque were limited to different values in test P1 and test P2. During the movement of approach (under position control) to the requested reference position, the motor was driven as if it was under control of velocity. The velocity was controlled and the current was limited to the values set in the parameters of the position control. This is shown by the analogous plots of the velocity and the current signals of these tests (Figure C.21 and Figure C.22) and the ones presented for the control of velocity (Figure C.8 and Figure C.13).

The effect of using different values for the parameters of velocity and torque in the control of position is reflected in the time response of the motor, as seen in Figure C.24. The lower values of those parameters are associated to a slower response of the motor.

The use of this control mode in positioning the fingers of the gripper enables the integration of the control of velocity during the movement of approach and imposes a limit on the force that the finger can exert during the movement and after reaching the requested position.
Figure C.21  Position control (test P1): position, velocity and current response to a position step signal
Figure C.22  Position control (test P2): position and velocity response to a position step signal
Figure C.23 Position control: detailed view of the position signal during tests P1 and P2
Figure C.24  Position control: comparison of tests P1 and P2
C.2.4 Implicit force control

The implicit force control of a joint uses a position signal in the feedback loop of force. This position signal, representing a force, is obtained using a finger configured as a position/force sensor, as described in Appendix A.4.

The test of the implicit force control of a joint involved the use of two fingers of the gripper. The gripper is set to grasp a product between the two fingers. The joint of the carrier movement of one finger, that is under the implicit force control, is excited with a force step signal. This leads the finger to move towards the product and to press the product against the other finger. This second finger is configured as a position/force sensor. The position data from this sensor is used to measure and control the force exerted on the product by the first finger. The architecture of the control loop of the joint takes the configuration presented in Figure C.25. The parameters of the implicit force control and of the configuration of the position/force sensor are given in Table C.5. The high value that was set to the position limit parameter is used to remove any position limitation in the movement of the finger. The product used in the test was specimen A (see Appendix B for properties of tested products). The time response of the position, velocity and current signals of the motor and the time response of the force signal are used to evaluate the achieved force control.

![Diagram](image)

*Figure C.25 Implicit force control: configuration of the control loop used in the experiment*
Table C.5 Test conditions for experiments with implicit force control

<table>
<thead>
<tr>
<th></th>
<th>Control parameters for implicit force control</th>
<th>Configuration of position/force sensor (see Appendix A4, Table A.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force reference</td>
<td>Position limit</td>
<td>Velocity limit</td>
</tr>
<tr>
<td>Test IF1</td>
<td>step signal of 2.7 degrees</td>
<td>10° degrees</td>
</tr>
</tbody>
</table>

The results of the position and velocity response of the motor to the force step reference are presented in the plots shown in Figure C.26. The force signal measured with the position/force sensor and the current of the motor are presented in the plots shown in Figure C.27. These results show that it was possible to obtain, in the response to a force step signal, a null error of force at the steady state. It must be stressed that the performance achieved in this test is not only dependent on the characteristics of the motor, sensors and controller, but also on the product. The product acts as a filter of the signal of force and can mask the real force that the finger exerts.

The implicit force control mode enabled the automatic transition of control of velocity, during the approach motion, to the control of force that was initiated when the contact occurred. As seen in the plots presented in Figure C.26 and Figure C.27, the joint is under velocity control until the signal of force is made available. At that instant the control loop of force starts to have an influence on the control and the joint is driven according to the requested reference force. The velocity and torque parameters are seen as limit values that must not be exceeded during the implicit force control.

The control architecture and the implicit force mode, as seen in this experiment, has particular interest in the coordination control of the fingers of a gripper. It enables the integration and transition between the force control and the velocity and torque control.
Figure C.26 Implicit force control (test IF1): position and velocity response of the motor to a force step signal
Figure C.27  Implicit force control (test IF1): current and force response to a force step signal
C.2.5 Explicit force control

The explicit force control of a joint uses a truly contact force signal in the feedback loop of force. This force signal is obtained using the tactile sensor that was constructed (see Appendix A.5).

To test the implementation of the explicit force control using the constructed tactile sensor, the joint of the carrier movement of a finger is excited with a force step reference signal. This signal drives the finger against a product and the contact force is controlled. The tactile sensor, that is mounted in the finger, measures this contact force. The architecture of the joint control loop takes the configuration presented in Figure C.28. The parameters of the explicit force control and of the tactile sensor are given in Table C.6. Note that the position limit of the control loop is set to a large value. This ensures that the movement of the joint is not confined by any limitation in position. The product used in the test was specimen A (see Appendix B for properties of tested products). For the analysis of the test, the position, velocity and current signals of the motor are measured and the plots are shown in Figure C.29. The plots shown in Figure C.30 present the contact area and the contact force signals obtained with the tactile sensor.

![Diagram](image)

*Figure C.28 Explicit force control: configuration of the control loop used in the experiment*
Table C.6 Test conditions for experiments with explicit force control

<table>
<thead>
<tr>
<th>Control parameters for explicit force control</th>
<th>Parameters of tactile sensor (see Appendix A5, Table A.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force reference</td>
<td>Contact area signal</td>
</tr>
<tr>
<td>Position limit</td>
<td>range:</td>
</tr>
<tr>
<td>Velocity limit</td>
<td>0 to 16</td>
</tr>
<tr>
<td>Torque limit</td>
<td></td>
</tr>
<tr>
<td>Test EFl</td>
<td></td>
</tr>
<tr>
<td>step signal</td>
<td></td>
</tr>
<tr>
<td>75% of max. force signal</td>
<td></td>
</tr>
<tr>
<td>$10^6$ deg</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>

The results of the performed test show that it was possible to implement the commanded force but with a noticeable instability at the instant of contact (as seen in the plot of velocity in Figure C.29). After the initial contact, the force controller was able to stabilize the contact force. This oscillation in the movement of the joint was due to the sudden drop in the contact area associated with the reduction of the contact force, as seen in the plots presented in Figure C.30. It should be noted that the signal of force was obtained from only one sensing site of the tactile sensor. The contact area remained at its minimum non zero value (6.25%) as can be seen in the plot of the contact area in Figure C.30. A tactile sensor with a better position resolution would enable a smoother signal of force and the control of force would be easier to implement. This shows that the performance of the explicit force control is affected by the reduced resolution of the signal of force.

The plots of the velocity, position and current signals show that the control architecture integrates the control of force with the control of velocity and torque. It can be seen that during the controlled motion velocity and current (see Figure C.29) are limited by the values defined in the parameters of the force control. In the absence of the force signal, the joint motor moves at a constant velocity since the velocity limit acts as the command signal. It is only when the force signal is present (after the contact is achieved) that the effective control of force takes place.
Figure C.29  Explicit force control (test EF1): position, velocity and current response of the motor to a force step input
Figure C.30  Explicit force control (test EF1): tactile sensor - contact force and contact area - response to force step input
C.2.6 Switch between control modes

One of the features of the adopted control architecture is the capability to combine and switch between the different control modes, as discussed in Chapter 3. This capability has been partially shown in the previous tests and will now be looked at in more detail.

In order to observe and test this capability, the joint of the carrier movement of a finger is subjected to a sequence of different control modes. This involves moving the joint for a fixed angular displacement while switching the control mode at equally timed intervals. Two tests were performed using the sequence of control modes and the control parameters of each mode presented in Table C.7.

\textit{Table C.7 Test conditions for experiments when switching between control modes}

<table>
<thead>
<tr>
<th>Sequence of control modes</th>
<th>Control parameters</th>
<th>Torque reference</th>
<th>Velocity reference</th>
<th>Position reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test SW1 (T-V-P-T-P)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>50%</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>100%</td>
<td>50%</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>100%</td>
<td>50%</td>
<td>32400 deg (*)</td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>50%</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>100%</td>
<td>50%</td>
<td>32400 deg (*)</td>
<td></td>
</tr>
<tr>
<td>Test SW2 (P-V-T-P)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>100%</td>
<td>100%</td>
<td>32400 deg (*)</td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>50%</td>
<td>50%</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>50%</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>50%</td>
<td>50%</td>
<td>32400 deg (*)</td>
<td></td>
</tr>
</tbody>
</table>

\textit{(*) this value corresponds to an angular displacement at the output of the gearbox of 131.7 deg}

The response of the motor to the sequence of control modes is evaluated by the time response of the current, velocity and position signals. The results are presented in the plots shown in Figure C.31 for the test SW1 and Figure C.32 for the test SW2.
The analysis of the results presented in Figure C.31 and Figure C.32 shows the feasibility of the implementation of switching between control modes. The transition between the control modes is accomplished with a smooth behaviour on the motion of the joint.

Referring to the results of test SW1 (Figure C.31), the first transition is from torque control to velocity control. Under torque control the current is limited to the value set by the reference of torque. The current and velocity response of the motor are similar to the results of the tests already described and discussed in the experiments of torque control. When the controller switches to velocity control the motor is rotating at a steady velocity that is higher than the new velocity reference. This prompts the controller to adjust the value of the current supplied to the motor and the velocity drops to the requested value. The peak of current that occurs during this transition has a value that is limited by the torque limit used in the velocity control mode. The velocity reaches a steady value and the current reaches a fairly constant value. This level of current is the minimum necessary to keep the motor rotating at the requested velocity.

The next transition is between velocity control and position control. The parameters of current and velocity in the position control are identical to the ones being used in the velocity control. The requested position reference has a large value when compared to the position of the motor at the instant, when the control switches. This results in a large position error that saturates the position controller. As a result, the motor is still driven under velocity control, and no alteration occurs in the velocity and current signals. The motor continues rotating at a controlled velocity.

The third transition of test SW1 is between position control and torque control. This is achieved by disengaging the position and velocity control loops. Under torque control the motor is able to accelerate, with the velocity and the current having an identical response to the one that occurred in the first period of control.

The fourth and last transition is between the torque control and the position control. As under the torque control the motor is rotating at a higher velocity than the value of the velocity limit of the
position controller, the velocity of the motor is reduced. The motor is kept under velocity control until the moment when the position error is reduced to a value that takes the position controller out of saturation. True position control is initiated and the velocity starts falling until the motor stops at the requested reference position. The current used by the motor keeps the joint at the requested position and has the minimum value necessary for this. The maximum value that the current could reach to maintain that position is set by the value of the torque limit used by the position controller.

The test SW2 covers two other transitions between the control modes, position to velocity and velocity to torque, that were not implemented in the test SW1. The motor behaves in a predictable and similar way as during the switching conditions of the previous test. For that reason, the detailed analysis of the results will be omitted.

The capability to switch between control modes as shown has potential applications in the movement control of the fingers of a gripper. The switch from velocity to torque control can be applied in situations where a finger has to move at a requested velocity and after contact, the force the finger exerts has to be controlled. Switching from position to torque can be applied in a situation where the finger is set to move to a requested position and, around that position, must be able to exert or withstand different forces.
Figure C.31 Switch between control modes (test SW1)
Figure C.32 Switch between control modes (test SW2)
C.3 CONCLUSIONS

In this appendix experimental results are presented on the implementation of the proposed control architecture for the control of a joint of the gripper. The performance of the different control modes - torque, velocity, position and force - that the proposed architecture can implement was evaluated. The capability to combine and switch between the different control modes was shown. The implications and potential application in the movement control of the fingers of the gripper were highlighted.
APPENDIX D

EXPERIMENTAL CONDITIONS OF THE TESTS

This appendix presents the experimental conditions of the tests for detection of contact and implementation of perception procedures mentioned in Chapter 5. For each test, the experimental conditions are presented in a Table; the settings of the control parameters refer to the operating conditions of the gripper (presented in appendix A.6); the tested specimens refer to the products (presented in Appendix B).

Table D.1  Experimental conditions for detection of contact using the current of the motor

<table>
<thead>
<tr>
<th>Test</th>
<th>detection of contact using the current of the motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested products</td>
<td>Specimen A</td>
</tr>
<tr>
<td>Control mode</td>
<td></td>
</tr>
<tr>
<td>Control parameters</td>
<td></td>
</tr>
<tr>
<td>velocity reference</td>
<td></td>
</tr>
<tr>
<td>torque limit</td>
<td></td>
</tr>
</tbody>
</table>

Table D.2  Experimental conditions for detection of contact using the tactile sensor

<table>
<thead>
<tr>
<th>Test</th>
<th>detection of contact using the tactile sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested products</td>
<td>Specimen A</td>
</tr>
<tr>
<td>Control mode</td>
<td></td>
</tr>
<tr>
<td>Control parameters</td>
<td></td>
</tr>
<tr>
<td>velocity reference</td>
<td></td>
</tr>
<tr>
<td>torque limit</td>
<td></td>
</tr>
<tr>
<td>Tactile sensor variable</td>
<td></td>
</tr>
<tr>
<td>contact area range</td>
<td></td>
</tr>
</tbody>
</table>
Table D.3  Experimental conditions for detection of contact using the finger configured as a position/force sensor

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen A</th>
<th>Specimen B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control mode</td>
<td></td>
<td>velocity control</td>
</tr>
<tr>
<td>Control parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>velocity reference</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>torque limit</td>
<td></td>
<td>25%</td>
</tr>
<tr>
<td>Finger as a position/force sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>spring</td>
<td></td>
<td>S1</td>
</tr>
<tr>
<td>location of connection point</td>
<td></td>
<td>$p_l = 72 \text{ mm}$</td>
</tr>
<tr>
<td>stiffness of sensor</td>
<td></td>
<td>$K_r = 84 \text{ N/m}$</td>
</tr>
<tr>
<td>force resolution (for $30 &lt; \phi &lt; 150$)</td>
<td></td>
<td>better than 0.08 N</td>
</tr>
</tbody>
</table>

Table D.4  Experimental conditions for identification of size and deformation

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen A</th>
<th>Specimen B</th>
<th>Specimen C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>product size in grasp direction</td>
<td>Specimen A</td>
<td>Specimen B</td>
<td>Specimen C</td>
</tr>
<tr>
<td></td>
<td>69 mm</td>
<td>75 mm</td>
<td>80 mm</td>
</tr>
<tr>
<td>Finger as a position/force sensor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spring</td>
<td></td>
<td>S2</td>
<td>S1</td>
</tr>
<tr>
<td>location of connection point</td>
<td></td>
<td>$p_l = 64 \text{ mm}$</td>
<td>$p_l = 72 \text{ mm}$</td>
</tr>
<tr>
<td>stiffness of sensor</td>
<td></td>
<td>$K_r = 1818 \text{ N/m}$</td>
<td>$K_r = 84 \text{ N/m}$</td>
</tr>
<tr>
<td>force resolution (with $30 &lt; \phi &lt; 150$)</td>
<td></td>
<td>better than 2.3 N</td>
<td>better than 0.08 N</td>
</tr>
<tr>
<td>Control mode</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>force reference</td>
<td></td>
<td></td>
<td>3.6 degrees</td>
</tr>
<tr>
<td>position limit</td>
<td></td>
<td></td>
<td>$10^6$ degrees</td>
</tr>
<tr>
<td>velocity reference</td>
<td></td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>torque limit</td>
<td></td>
<td></td>
<td>25%</td>
</tr>
</tbody>
</table>
### Table D.5 Experimental conditions for identification of compliance

<table>
<thead>
<tr>
<th>Test</th>
<th>identification of compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gripper configuration</td>
<td>two fingered gripper, with the fingers fitted with rigid walls in substitution of the flexible finger walls</td>
</tr>
<tr>
<td>Tested products</td>
<td>Specimen C 80 mm</td>
</tr>
<tr>
<td>size of product in grasp direction</td>
<td></td>
</tr>
<tr>
<td>Finger as a position/force sensor</td>
<td>S2</td>
</tr>
<tr>
<td>spring</td>
<td>( p_1 = 72 \text{ mm} )</td>
</tr>
<tr>
<td>location of connection point</td>
<td>( K_T = 2040 \text{ N/m} )</td>
</tr>
<tr>
<td>stiffness of sensor</td>
<td>better than 2.6 N</td>
</tr>
<tr>
<td>force resolution (with ( 30 &lt; \phi &lt; 150 ))</td>
<td></td>
</tr>
<tr>
<td>Control mode</td>
<td>velocity control</td>
</tr>
<tr>
<td>Control parameters</td>
<td></td>
</tr>
<tr>
<td>velocity reference</td>
<td>10%</td>
</tr>
<tr>
<td>torque limit</td>
<td>25%</td>
</tr>
</tbody>
</table>

### Table D.6 Experimental conditions in the tests for identification of product profile

<table>
<thead>
<tr>
<th>Test</th>
<th>identification of profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested products</td>
<td>Specimen E</td>
</tr>
<tr>
<td>Control mode</td>
<td>roller movement</td>
</tr>
<tr>
<td>Control parameters</td>
<td>velocity control</td>
</tr>
<tr>
<td>force reference</td>
<td>--</td>
</tr>
<tr>
<td>position limit</td>
<td>--</td>
</tr>
<tr>
<td>velocity reference</td>
<td>10%</td>
</tr>
<tr>
<td>torque limit</td>
<td>100%</td>
</tr>
<tr>
<td>Finger as a position/force sensor</td>
<td>S2</td>
</tr>
<tr>
<td>spring</td>
<td>( p_1 = 64 \text{ mm} )</td>
</tr>
<tr>
<td>location of connection point</td>
<td>( K_T = 1818 \text{ N/m} )</td>
</tr>
<tr>
<td>stiffness of sensor</td>
<td>better than 2.3 N</td>
</tr>
<tr>
<td>force resolution (with ( 30 &lt; \phi &lt; 150 ))</td>
<td></td>
</tr>
</tbody>
</table>