# Development and analysis of a path planner for dexterous in-hand manipulation of micro-objects in 3D 

Pardeep Kumar

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Thèse de doctorat de l'Université Bourgogne Franche-Comté préparée ì L'Université de Franche-Comté École doctorale ${ }^{0} 37$
Sciences Pour l'Ingénieur et Microtechniques
Doctorat d'Automatique
Par
Pardeep Kumar

## Développement et Analyse d'un <br> Planificateur de Trajectoires pour

## la Manipulation Dextre de

## Micro-Objets en 3D

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# Doctoral Thesis from Université <br> Bourgogne Franche-Comté prepared at <br> Université de Franche-Comté <br> Doctoral School no 37 <br> Engineering Sciences and Microtechnologies <br> Doctorate in Automation <br> By <br> Pardeep Kumar <br> <br> Development and Analysis of a <br> <br> Development and Analysis of a Path Planner for Dexterous In-Hand Manipulation of Micro-Objects in 3D 

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# List of Publications 

## Article in Scientific Journal

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DOI:10.3390/mi12080986.

## Article in International Conference

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DOI:10.1109/CASE49439.2021.9551662.

Joel Bafumba Liseli, Redwan Dahmouche, Pardeep Kumar, Jean Antoine Seon, Michaël Gauthier, "Enhancing in-hand dexterous micro-manipulation for real-time applications", in Proc. of IEEE 14th International Conference on Automation Science and Engineering, CASE 2018, 20-24 Aug. 2018 Munich, Germany.

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## Chapter 1

## Introduction

For more than 5 decades, robots have been used in industries. They can perform a wide range of tasks with high speed and accuracy, and thus used for various purposes. Moreover, the recent years have seen a very quick advancement in robotic technologies, not only in their structures, but also in the applications they can be used for.

Even after the great achievements in robotics in past 10 years, the field of robotics is still at the beginning of evolution. The application areas of robotics have gradually broaden beyond the classical industrial settings in large-scale enterprises. Due to the increased capabilities and lower costs, the small-scale industries have also increased the adoption of robots [27]. Apart from the adoption of robots in industries, the robots are being used in day-to-day life, like in the health care system and domestic services. Nowadays, it has become the central development in robotics to be a part of daily life. This integration induces fundamental challenges, as the requirements are different from the industrial applications.

Besides, the robotics field at large scale which has been developing steadily for past 50 years, the robotics field at small scale has yet to see such development. There are various applications, where instead of large-scale robots we need to use small-scale robots, like in medical surgery, drug delivery inside a human body, biological cell sorting and characterization, and industries which assemble the miniaturized components. The robots at small scale are also called the mi-
cro/nano robots. Their working environment and physical laws differ from the robots at large-scale (macro-scale). One of the basic and common task of robots at both macro and micro/nano scale is to manipulate objects (pick and place, or assemble the objects). To perform these tasks, most robotic manipulators in industry use simple grippers.

Robotic manipulation can further be categorized into Traditional Manipulating and Dexterous Manipulation.

Traditional Manipulation: The manipulation performed by most of the manipulator i.e. pick and place operation, hold, or assembling remotely is considered as simple manipulation, where the manipulators used are simple grippers.

Dexterous Manipulation: Dexterous manipulation is also known as in-hand manipulation, where a robot tries to manipulate an object with dexterity. For in-hand manipulation, multiple end-effectors cooperate with each other like the fingers of a human hand, to perform a task. In contrast to traditional manipulation, dexterous manipulation is object centred, and thus the problem is formulated as per the architecture of the manipulating hand and the characteristics of the object to be manipulated (shape, material properties, etc.).

Most of the robots available in industry are macro-scale robots and work on the principle of traditional manipulation. These robots are installed to lessen the human effort by performing repetitive task. In macro-scale robotics, the physical laws that affect the manipulation process are inertia and gravity. There are various types of robots for different purposes, ranging from simple robotic arm manipulators to humanoid robots. Due to the advancement in technology, not only the commercial robots have improved, but other robots for research purpose have come into being.

However, the small-scale robots are mostly used for research/academic purpose, and have been completely industrialized only recently (Percipio-Robotics). In contrast to macro-scale robots where the governing physical forces are inertia and
gravity, in micro-scale adhesive forces are dominant over other forces. There are two categories of robots at micro-scale, Contact-less micro-robots and Contactbased micro-robots.

Contact-Less Micro-Robots: These robots manipulate the object without coming into contact with it. There are different actuation principles like acoustic, electromagnetic, magnetic, electric, and thermal.

Contact-Based Micro-Robots: These robots manipulate the object when in contact with it. Contact based micro-robots are further divided into two types: Continuum Micro-Robots and Simple Micro-Robots.

## Nota Béné:

Throughout this thesis, Fingers' Path Planning or Trajectory Generation refers to the same thing.

## Objective of the Thesis

This thesis focuses on the dexterous manipulation at micro-scale. To dexterously manipulate the micro-objects in 3D, which is the main objective of this thesis, we study the physics at micro-scale, and formalize the problem that is to be addressed to generate the fingers' trajectories. We address the problem by proposing a method that decomposes the 3D rotation into three 2-D rotation using Euler's Angles. As this is the first step to dexterously manipulate the micro-objects (of various shapes) in 3D, there is no doubt that our methodology introduces some constraints.

## Contributions of the Research

Our major contributions in this thesis are: Method to Decompose the three rotations into three 2-D rotations, Sampling Strategy to generate the contact point on object's surface for manipulation keeping the methodology constraint in the mind, Algorithm including an original heuristic enabling the calculation of optimal fingers' trajectory in a reasonable time. We also analyse the impact of two parameters, friction coefficient and adhesion on the generation of fingers' trajectories.

## Distribution of Content, and their Contributions in the Thesis

This section provided the details of the work distributed into four chapters: Chapter 2 State of the Art, Chapter 3 Dexterous Micro-Manipulation in 3D, Chapter 4 Implementation and Analysis of Methodology, and Chapter 5 Conclusion and Perspectives, and highlight the important contributions presented by each chapter.

## Chapter 2: State of the Arts

This chapter provides a detailed study, background, and analysis on the robotic systems, and techniques that are available in the literature of micro-scale robotics. Along with the micro-scale robotics, we also study some techniques of macro-scale robotics from the scientific literature, to compare the diverseness between microscale robotics and macro-scale robotics.

This chapter is further divided into 5 sections: "Robotic Manipulation", "Robot Handling at Micro-Scale", "Dexterous Handling at Macro-Scale and Micro-Scale", "Automation and Planning in Micro Manipulation", and "Planning and Automation in Dexterous Manipulation at Macro-Scale".

The chapter formally starts with the introduction of Robotic Manipulation, and its fundamental component for contact-based manipulation, i.e. Gripper (Simple and Dexterous). Then, we discuss the behaviour of physical properties of microscale to build a base for micro-robots. Once the base is developed, we provide the study of the available literature at manipulation at micro-scale (both contact-less and contact-base) thoroughly. This study provides the understanding of: (i) different principles of actuation, their working capabilities, limitations, advantages and drawbacks for contact-less manipulation, and (ii) mechanical designs of different actuators and robotic platforms, their working principles, capabilities, limitations, advantages and drawbacks for contact-based manipulation.

After that, we provide the study of various common ways through which objects can be handled dexterously by macro-scale robots, and micro-scale robots (contact-based), along with the different planning and control methods to carry out dexterous in-hand manipulation.

## Chapter 3: Dexterous Micromanipulation in 3D

In this chapter we discuss the general objective of the thesis i.e. "Contribution to the development of robotic in-hand manipulation in micro-scale". We briefly enlist the scientific challenges faced in the dexterous in-hand manipulation at micro-scale. In this thesis, we focus on one of the challenges i.e. "generation of optimal fingers' trajectories to manipulate a micro-object from one position to another position, taking into account the specificities of the microworld such as adhesion".

To formalize the problem of dexterous manipulation in micro-scale, first we provide some important assumptions. Then, we analyse the problem of Computational Complexity faced to generate the optimal fingers' trajectories in detail, and propose to reduce the computational complexity by decomposing a 3D rotation in three individual 2-D rotations. For this purpose, we propose to retain only two orthogonal planes, on which three individual 2-D rotation can be carried out. To
manipulate the object, we discretize the object surface using an ad-hoc sampling strategy. After, the sampling of contact points, we find the available equilibrium grasps using 2 or 3 fingers for three cases: (i) initial grasping of the object, (ii) general grasping of the object, and (iii) the grasping during detachment operation. We call the set of equilibrium grasps as a Map for each operation. Considering the grasps as nodes and the transition (e.g. rotation, finger gaiting) as edges, we finally build a Graph. Defining finger trajectories exists in defining an optimal path in this Graph.

## Chapter 4: Finger Trajectory Planning Methodology

The objective of this chapter is to build a planning methodology to obtain the optimal fingers' trajectory. This chapter is divided into four sections, starting from the implementation of finger trajectory planning. In this section, we discuss the graph search algorithm for fingers' path planning, and design its parameters as per our methodology.

After that, in the next section, we provide a detailed analysis of our proposed method to manipulate the micro-objects in 3D. We analyse the finger trajectories for each individual rotation, and how to interpret the output of the algorithm. Once, fingers' trajectories for all three rotations are planned, then we combine them using Euler's Angels.

The performance analysis section, provides a detailed analysis of parameter tuning. We analyse the impact of two of the most important parameters friction coefficient and adhesion, on the generation of fingers' trajectory generation and consequently on manipulation process. Besides this, we provide a detailed result on the computation time to plan the fingers' trajectories for different shapes of micro-objects.

We finalize the chapter by discussing the environment and hardware required to generate the fingers' trajectories.

## Conclusion and Perspectives

Finally, this chapter concludes the research study on the "Development and Analysis of a Path Planner for Dexterous In-Hand Manipulation of Micro-Objects in 3D", and provide a look into the different perspectives that can be carried out for future work.

## Chapter 2

## State of the Art

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## Objective

The goal of this chapter is to present the current state of the art in the area of robotic manipulation at micro-scale. It also compares the state of art at micro-scale with macro-scale.

### 2.1 Robotic Manipulation

Whenever we talk about robotic manipulation, we always consider some physical activity being performed by a machine/robot on an object. This activity is composed of grasping, picking, moving, positioning, and placing. The object being manipulated may be from various physical scales. The common terms for these physical scales are macro-scale, micro-scale, and nano-scale; where the object size ranges above 1 mm for macro-scale, from $1 \mu \mathrm{~m}$ to 1 mm for micro-scale, and 1 nm to $1 \mu \mathrm{~m}$ for nano-scale (Figure 2.1). There are two ways to manipulate these objects: first by making the contact with object (always in the case of macro-scale manipulation), second contact-less manipulation (in the case of micro-scale and nano-scale).


Figure 2.1 - Representation of various physical scales for objects ${ }^{1}$.

[^0]The contact-less/non-contact manipulation is realized using different principles: magnetic, electric, acoustic, and optical. While the contact based manipulation is performed by gripping the object with a gripper. Independent from the object scale, there are two ways to perform contact based manipulation: either by using simple gripper mounted on the carrier robot with multiple degrees of freedom (DoF), or by utilizing the dexterous gripper using a basic robot.

Gripper(s) is the fundamental component to manipulate an objects at different scales. Thus, it is necessary to develop some basic understanding of gripper(s). As mentioned earlier, for contact-based manipulate we can either use simple gripper or dexterous gripper, and are defined in detail below.

### 2.1.1 Simple Gripper

The architecture of a simple gripper may vary from application to application, but mostly it is either composed of tweezers like fingers (Figure 2.2a), or a vacuum suction cup gripper (Figure 2.2b). These grippers are mounted on a robot; consisting of either a robotic arm, or a parallel robot. The usage of such grippers is limited to only one function i.e. gripping. Indeed, such grippers with single functionality will minimize the complexity while maximizing its effectiveness for the desired task [28]. However, this architecture reduces the versatility of the manipulator to a great extent, as it is necessary to change the grip when the shape of the manipulated object is changed. Likewise, the handling capacities are also limited very quickly at the articular limits of carrier robot [29]. Thus, this architecture of gripper is suitable for the repeated tasks for identical objects in larger numbers.

It is possible to carry out different tasks with simple grippers by utilizing extrinsic techniques to the hand like gravity, and external contact etc. [30], but once again it will increase the complexity of procedure to carry out such tasks.

Recently a team from MIT [30] has proposed to manipulate objects dexterously with simple grippers at macro-scale using techniques extrinsic to the hand (gravity, external contacts or dynamic arm motions). They are able to roll the object in the gripper using gravity, or adjust the object's pose by pressing it against a surface, and can even toss the object in the air and catch it in a different pose.


Figure 2.2 - Simple Grippers: a) a tweezers like gripper mounted on the robotic arm, b) a vacuum suction cup gripper mounted on the robotic arm (OUniversal Robots).

### 2.1.2 Dexterous Gripper

Just like an anthropomorphic hand, a dexterous hand is composed of several fingers (Figure 2.3) capable of performing movements in the gripper's work-space [31]. Due to the anthropomorphic structure and the dexterity, the manipulator has a better manoeuvrability in terms of obstacles and singularities of supporting structure [32]. Such dexterous anthropomorphic hands are versatile grippers, as they are not designed to manipulate any specific object [33]. However, the difficulty lies in monitoring, and planning to move this kind of gripper. As, the gripper has two or more fingers with several degrees of freedom, thus it could be complex to control and/or use it [34]. Similarly, to carry out the rotations using such gripper, it is necessary to determine the position and movement of the fingers which
complicates the motion planning due to its nonholonomic nature [35]. Thus, this type of manipulator is more suitable for complex manipulations in which dexterity is required, and does not need the requirement of a specific robot.


Figure 2.3 - A dexterous gripper gripping a card (©Shadow Robot Company).

Well, the robotics at macro-scale and micro-scale differs in terms of physical laws, and have different constraints. At macro-scale, the dexterous manipulation has been studied for more than three decades, and is very close to mimic the operations of anthropomorphic hand $[36,37]$. Whereas, due to the differences in scales and governing physical laws, it is not possible to completely mimic the anthropomorphic operation at micro-scale. In contrast to macro-scale, the study and design of manipulators with multiple degrees of freedom at micro-scale is very recent $[15,16]$, and remains difficult and limited.

### 2.2 Robot Handling at Micro-Scale

Before coming to robotics at micro-scale, we are going to present micro-scale itself first. The world at micro-scale includes all the objects with size ranging in-between one micrometer and one millimetre. This scale differs from the one at which the humans normally operate. Although, the similar physical laws as of macro-scale are present at micro-scale but the observed behaviour are significantly different [38]. At macro-scale, if an object is released from hand, it will fall to the ground due to gravity. Whereas, at micro-scale, it can still remain in contact with the gripper [39] (Figure 2.4). This change in behaviour at different scale, is due to the change in object size which affects the surface area and volume. Thus, the size of the object influences the forces that are going to be dominant at different scales. At the macro-scale, the effect of volume predominates, and this is the reason that an object falls due to the gravity when it is released. Whereas, the effects of surface become non-negligible and are dominant over volume effects at micro-scale.


Figure 2.4 - Illustration of adhesion effect, where one finger is able to grasp the object [1].

Due to the dominance of these surface effects, it is possible to observe two phenomena. First, the weight and inertia of the object become negligible, which makes it possible to design manipulators with very high dynamics. Second, there is the presence of adhesion forces between different objects [40] which allows objects
to stick together. These adhesion forces are generated due to different physical and chemical properties of the object's material and falls in the following three categories [41]:

- Van der Waals: These forces result from low intensity electrical interactions between the molecules of different objects.
- Capillarity: These forces result from the presence of a liquid film on the surface of the objects.
- Electrostatics: These forces are generated by charged particles with a highenergy content at the surface of the objects.

Due to these phenomena, the paradigm of manipulation at micro-scale is altered, resulting in the need to change or develop manipulators and manipulation techniques. It is necessary to understand these adhesion effects first, in order to develop manipulators and manipulation techniques suitable for the micro-world. It should be noted that, the complete modelling of such tools is very complex; as some parameters are difficult to quantify, such as the distribution of charged particles on the surface [42].

Adhesion phenomena highlight several problems directly related to manipulation [43, 44]. Indeed, when these phenomena are visible, the object and the gripper are subjected to the effects of adhesion. This can be seen as an advantage since it is then possible to hold an object with a single finger (Figure 2.4). But, this can also be seen as a disadvantage because releasing the object by simply loosening the grip is no longer possible. To be able to perform micro-manipulation operations, it is therefore necessary to answer the following questions:

- Pick-up: As there is the presence of the adhesion forces between the object and the base/support (on which object is placed), then how to pick it up?
- Manipulate: How to manipulate the object in the presence of adhesion forces between the object and the fingers, keeping in mind that inertia is negligible?
- Assemble: How to place/assemble an object, in the presence of adhesion forces between the object and the finger(s)?

Solutions to these problems have been developed at micro-scale. As introduced earlier (Sec. 2.1) that it is possible to manipulate micro-objects with or without making any contact with them.

### 2.2.1 Non-Contact manipulation

Adhesion effects are often seen as a disruptive force, especially during the releasing phases. However, this phase is considered by a majority of the microrobotic community as the most important stage of micro-manipulation because the final objective of manipulation is to precisely position micro-objects or to assemble. In that case, adhesion is perceived as a phenomenon that needs to be overcome, and many works have tried to manipulate the object without making any contact with it, in order to eliminate the problem of releasing it. It is possible to manipulate the object without making any contact with it, because the mass of the object is negligible at micro-scale, thus it provides an advantage over macroscale manipulation. The non-contact manipulation is carried out through different methods/setups such as magnetic, electrical, optical or acoustic.

### 2.2.1.a Magnetic Manipulation

This manipulation strategy is based on the use of a magnetic field generated by magnets, electromagnets or coils. The magnetic force thus applied by the field will allow moving paramagnetic or ferromagnetic objects in the working space [45, 46]. This approach can be used in an ambient environment [47], liquid [48] or at the interface between both [49]. This type of manipulation permit exerting the forces between micro-newton $(\mu N)$ and nano-newton $(n N)$ on the object. Among the other methods used in non-contact micro-manipulation, the magnetic manipulation provides feasible solutions [50, 51], and is the preferred strategy in medical applications $[52,53]$. It should be noted that the fastest micro-robots are moved
using this mode of actuation [54]. Through magnetic manipulation, the movements of an object can be controlled with precision and speed. Some challenging works imagine using this type of manipulation to control micro-robot(s) directly in the body of a human or any animal [55, 56, 57] (See in Figure 2.5) [2].


Figure 2.5 - Magnetic manipulation of micro-robots inside the body and the magnetic actuator design [2].

### 2.2.1.b Electric field Manipulation

Similar to magnetic field manipulation, it is possible to manipulate objects using electric fields. Depending on the type of electrical signals, the methods used are called electrophoresis or dielectrophoresis [58]. Most of the time, the electric manipulation is used to manipulate biological objects using dielectrophoresis (AC electric field) [59, 60], but is not limited to it; other works have also employed this method, [61] manipulated the silicon based nano-object in a plane with perpendicular electric field (DC electric field), for nano-fabrications.

However, this method is disadvantageous than the magnetic manipulation in terms of the exerted forces on the object, which are much lower (typically in nanonewtons).

Furthermore, the electric field can be combined with light to manipulate micro/nano objects, where the objects are manipulated by optoelectronic tweezers (OETs). This method is called Light-Gated manipulation in electric field. Huang et al. [62] provides a detailed review on light-gated manipulation.

### 2.2.1.c Optical Manipulation

Optical manipulation is another technique of non-contact manipulation where optical beams are used (Figure 2.6). This kind of manipulation is carried out by exerting light pressures through focused light beam(s) which allows to trap and manipulate the object [63]. The first works carried out in this direction are those of Ashkin [64], in which he manipulated particles between 25 nm and $10 \mu \mathrm{~m}$ using a single beam (Ashkin was awarded the Nobel Prize in Physics - 2018, for his invention of optical tweezers and its application in biological systems). Subsequently, a lot of work has been done using this manipulation technique by utilizing multiple beams [65] or to manipulate several objects simultaneously [66]. The use of multiple beams makes it possible to reproduce a contact manipulation system [67] without the disadvantages of adhesion. That is the reason why it is common to see the term "optical tweezers" used to specify this method. On the other hand, this approach does not allow very large forces to be exerted, at best the exerted forces do not exceed a few nano-newtons. Optical manipulation is therefore well adapted to the manipulation of cells $[68,69,70,71]$ or very small particles [72, 73, 3] but is still inapplicable for micro-assembly tasks.


Figure 2.6 - Illustration of optical trapping manipulation [3]: a) trapping by multiple beams, b) trapping by single beam, c) examples of different object being trapped by optical beams including transparent beads, red blood cell, and cylindrical object.

### 2.2.1.d Acoustic Manipulation

The last major category of non-contact manipulation is the use of acoustic waves (Figure 2.7). Indeed, using acoustic waves, it is possible to apply forces on the object to avoid it and thus manipulate it [74]. Two configurations are possible in the case of acoustic manipulation: standing wave manipulation and near-field manipulation. In the first case, the manipulation is done using a standing wave generated between a source and a reflector. This wave allows, at certain distances, to exert forces sufficient to compensate for the weight of the object [75]. In the second case, the wave is generated between the object and the source, which allows generating important repulsion forces as long as the distance between the source and the object is small. This approach is often used on a larger scale to move wafers used in clean-room micro-fabrication [75, 76]. Different systems have been developed [4] using surface acoustic waves, and recently [77] has proposed the non-invasive acoustic manipulation inside a living body. The main disadvantage of this approach is the current lack of repeatability (typ. larger than the object size). Moreover, assembly tasks do not seem to be feasible with this method.

### 2.2.2 Contact Manipulation

Contrary to non-contact manipulation, objects can also be manipulated by making contact with them at micro-scale. Historically, the contact-based manipulation is the first one to be developed because it resembles to the manipulation techniques employed at macroscopic scale. The idea is to miniaturize existing robotic grippers on a macroscopic scale (especially finger grippers). Initially, one of the main concerns of the micro-robotic community was to have repeatable and reliable operating methods. As a result, a lot of work has focused on the development of actuators suitable for micro-manipulation. Thus, the wide spectrum of actuating methods envisaged for micro-manipulation includes, among others, electrothermal actuators [78, 79, 80, 81, 5] (Figure 2.8a), piezoelectric actuators


Figure 2.7 - Illustration of acoustic manipulation [4]: a) Device structure and working mechanism of the acoustic tweezers, b) Independent two-dimensional single particle and cell manipulation.
[15, 82, 83, 84, 6] (Figure 2.8b), pneumatic [85, 7] (Figure 2.8c), or electrostatic [86, 87, 8] (Figure 2.8d). The requirement of high precision positioning requires to use advanced control laws [88] or multisystem microsystem [81, 5].

As adhesive forces are considered disruptive in the contact-based micro-manipulation, and became the hurdle to realize the repeatability of and removal tasks. Thus, methods have been developed to improve the repeatability of removal operations. These methods can be divided into two categories: first, those methods that aim to counter the adhesive forces in order to fall back at the macro-scale manipulation, and second, those methods that seek to exploit these adhesive forces; as described below.

There are two ways to counteract the adhesion effects: either by exerting a higher force or by reducing the adhesive forces. The first category includes methods based on exerting pressure or phase change at the object-finger interface. The second category includes methods that control environmental and/or surface factors and the use of dynamic effects.


Figure 2.8 - Different Grippers: (a) Electrothermal [5], (b) Piezoelectric [6], (c) Pneumatic [7], (d) Electrostatic ©FemtoTools [8]

### 2.2.2.a Methods to overcome the Adhesive Forces

- Pressure

Manipulation by pressure, consists in using a suction force in order to grasp the object. This force must overcome the effects of adhesion between the substrate and the object. One of the first micro-manipulation systems by changing pressure was realized by Zesch [9]. In his work, Zesch presented a gripper consisting of a glass micro-pipette and a computer-controlled vacuum system. With this system, micro-diamonds larger than $100 \mu m$ could be captured. However, the major disadvantage of this type of manipulation is in the phase of component removal. Indeed, applying a pressure force in the opposite direction does not allow placing the object in a precise way. To perform precise positioning, an additional tool must be used. In the case of Zesch used an additional finger to push the object in order to release it
(Figure 2.9). This method of manipulation by suction using a micro-pipette has also been studied by Vikramaditya [89], Petrovic [90] and Guoliang [91] and is generally used to manipulate biological objects such as oocytes.


Figure 2.9 - Using auxiliary finger to release the object for precise positioning [9].

Other approaches to pressure change manipulation has been presented by Arai [43], Chen [92], and Rong [93]. In [43], Prof. Arai used classical gripper finger in which micro-holes have been made. Where the pressure can be controlled by the using a system to control the temperature of the finger. In this way, before gripping the object, the finger is heated to expel the air from the holes. Then, once in contact with the object, the finger is cooled and the pressure generated by this change allows to grasp the object. Although elegant, this method has the major disadvantage of being very dependent on air leakage that can occur if the holes are not completely covered. Also, temperature variations affect the quality of the results.

Chen [92] has developed a hybrid electrostatic micro-gripper with integrated vacuum tool controlled by gas pipes. The gas pipes first exert the negative pressure to attract the object towards the tip of gas pipes, after which the electrostatic actuated gripper grips the object, and then to release and
place the grasped object, the gas pipes exert the positive pressure. The experiments shows that the developed hybrid micro-gripper is able to pick and release the polystyrene balls of size ranging from $100 \mu \mathrm{~m}$ to $200 \mu \mathrm{~m}$, the designed micro-gripper is able to deflect/bend at the tip for about $25 \mu \mathrm{~m}$.

Whereas, Rong [93] has integrated the vibration capability to the vacuum micro-gripper. The direction of vibration is normal to the releasing of the object. The design consists of a vacuum pump in between the bell-mouth shaped gripper. The pickup phase is similar to that of Chen [92], where the gas pipe exert force to attract the object towards the gripper, and the vibration is applied to the gripper to release the object. The objects manipulated were polystyrene spheres in the range of $35 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$, with the releasing location accuracy of $4.5 \pm 0.5 \mu \mathrm{~m}$. The disadvantage of such gripper is that, the gripper has to be object-specific as in the case of spheres (a bell-mouthed gripper) to smoothly grasp the object.

## - Phase Changing

Exerting forces greater than the adhesion forces is also possible by controlling the interface between the manipulating finger and the object. This operation is usually carried out by using a fine layer of liquid or solidification of liquid (in the form of ice) around the gripper (Figure 2.10). In this way, the object and the manipulator are connected to each other by a liquid or solid bridge that suffices to drop or melt to release the object, respectively. The first work on this type of pliers was carried out by a group of European researchers [10]. In this work, the Peltier effect is used to freeze a layer of water between the finger and the object. The pressures generated by this method can be up to $1 \mathrm{~N} / \mathrm{m}^{2}$ and are sufficient to overcome the adhesion effects. However, the type of material and the surface condition modify exerted forces [94]. In 2008, Lopez-Walle has extended this handling principle to liquid [95]. Zhang [11] has improved the released method by controlling the liquid bridge configuration. Well, it does not impose any constraint on the shape of the
object to manipulate due to the use of liquefied or solid bridge between object and gripper [96]. However, the formation of this bridge between the gripper and the object limits this type of gripper to pick and place operations.


Figure 2.10 - Illustration of interface between finger and gripper a) Ice [10], b) Liquid [11].

## - Environmental and Surface Parameters

As, adhesion forces are formed due to the intrinsic properties of material used. Thus, it is possible to control the adhesion effects by controlling certain environmental or surface parameters. For example, humidity plays an important role in the occurrence of capillary effects. Humidity can be controlled by means controlling the temperature or by means of liquid. If the object or gripper is heated to around $200^{\circ} \mathrm{C}$, the adhesion can be reduced by a factor of 10 [97, 98]. The heating procedure can be carried out either by external source like laser [99], or by local heating [100]. This approach remains limited, since the object must be subjected to high heat which, for some materials, can damage it. Moreover, in the case of some materials, high temperatures can cause the opposite effect, i.e. an increase in adhesion. Indeed, by enough heating a surface, it is possible to soften it, which increases the contact area between the object and the gripper and thus increases the adhesion effects [101]. Yang [102] has utilised the liquid bridge to control
the relative humidity, where a monotonic decrease in adhesion forces was observed. In any case, operating in a controlled environment (in terms of humidity and temperature) allows better control of the adhesion forces [103].

In addition, various studies have shown that controlling the surface can also reduce the adhesion forces. Thus, the use of hydrophobic coatings allows to reduce the contribution of capillary forces in the effects of adhesion [98, 97]. Similarly, the use of conductive materials reduces electrostatic forces [104, 103]. Van der Waals forces can be reduced by controlling the surface condition of the materials. Arai has notably proposed manipulator fingers on which micro-pyramids of about $10 \mu m$ in height are placed [44]. In this way, the van der Waals forces become negligible compared to the weight of the object and macroscopic scale manipulation strategies can be used.

## - Dynamic Effects

Another approach to reduce the adhesion effects is to use the dynamic effects present at small scales. Indeed, at the micrometer scale, it is possible to reach extremely high accelerations so that the inertial forces become dominant over the adhesion forces. This approach has been used by Haliyo [105], Chen [106, 107], Kim [108] to detach micro-objects from the gripper. In the first two cases the manipulator is excited in vibration to reach an acceleration of $10^{6} \mathrm{~m} / \mathrm{s}^{2}$ which is enough to release the object. Moreover, sometimes an additional finger is used to provide the object with the necessary inertia to release itself. Whereas in the last case, the gripper was vibrated with the frequency of 100 Hz to release biological cells. In all cases, this method allows to release the object.

### 2.2.2.b Methods to utilize the Adhesion

The above methods allow overcoming the effects of adhesion either by reducing them or by using forces of greater amplitudes. A second way to perform micromanipulation operations is to exploit these adhesion forces. Indeed, it is possible to develop methods that exploit surface tension, electrostatic charges or Van der Waals forces.

## - Surface Tension

Previously, we studied the effect of liquid to reduce the adhesive effect, either by phase changing or humidity control. In contrast to the reducing adhesive effects, liquid can also be utilised to exploit the adhesive effect, as liquid will cause the presence of surface tension between two objects. Indeed, this force allows the object and the gripper to stay in contact. This method thus makes it possible to easily grasp and position the object on the manipulating finger [109]. This self-alignment property also allows the self-assembly of microcomponents [12] (Figure 2.11). Manipulation using capillary effects has been studied by Lambert and his team [110]. More specifically, they have been interested in optimizing this method by studying the impact of the gripper shape on manipulation. One of the advantages of this approach to micro manipulation is that it is necessary to break the liquid bridge between the gripper and the object at the time of deposition. This phase of release is generally performed using dynamic effects methods. Obata also proposed to perform the release operation using surface tension forces [111]. Uran [112] has successfully employed this method to release the micro-objects of size ranging from $5 \mu \mathrm{~m}$ to $60 \mu \mathrm{~m}$.

- Electrostatic Forces

Another approach to exploit adhesion effects for micro-manipulation is obtained by utilizing electrostatic forces. As, electrostatic forces can be generated by charging the surface of an object or any material. Thus, it is


Figure 2.11 - Illustration of self-alignment as an effect of surface tension [12].
possible to exert an electrostatic force by using the electrodes positioned on the gripper. The generated forces can be both attractive and repulsive. For example, Hesselbach [13] has developed a micro gripper consisting of a single finger with electrodes on it, through this configuration a pick-and-place operations is performed in a precise manner. In this case, the shape of the electrodes used also allows to centre the object on the finger. Experimentally, this method allows picking up and place spherical objects between $100 \mu m$ and $800 \mu \mathrm{~m}$ (Figure 2.12). On the same principle, Enikov [113] used a finger equipped with electrodes to perform insertion spots with objects of more than $500 \mu \mathrm{~m}$. The detachment of micro-objects can also be carried out using electrostatic forces. However, this approach is dependent on environmental parameters since, in the case of the Hesselbach work, objects over $400 \mu m$ can no longer be captured when the relative humidity is above $65 \%$. This method also requires the use of high voltages to generate sufficient forces which, in some cases, can dissipate heat and consequently damage the object or manipulator.

- Van der Waals Forces

The van der Waals forces correspond to the attractive interactions between the different particles and can be used as a manipulation principle. This force will depend on the geometry of the contact between the different objects. The idea is therefore to control the contact surface between the object and


Figure 2.12 - Experimental pick and place operation on glass sphere of diameter $450 \mu m$ [13].
the gripper in order to grip or release the object. The first works in this direction are those of Feddema [114] in which a single rectangular finger is used to grip and release spherical objects. For the grasping phases, the finger is positioned in such a way as to have maximum contact with the object in order to maximize the van der Waals forces. Conversely, for the dropping phase, the contact area is reduced by changing the position of the finger on the object as shown in Fig 2.13.


Figure 2.13 - Manipulation of a micro-sphere [14]

Other works have subsequently taken up the idea developed by Feddema to manipulate objects with a single finger $[115,116]$ or with several fingers [14]. However, this approach is very dependent on the surface condition of the gripper and the object since the adhesion effects are greatly reduced as the roughness of the objects increases.

In 2017, Chen [15] has developed a PZT actuated triple finger gripper to manipulate spheres of different diameter ( $80 \mu m-800 \mu m$ ) and material, it is easier to pick and place the objects with higher diameter $800 \mu m$ with two fingers, while the third finger is being used when the object of lower diameter $80 \mu \mathrm{~m}$ are needed to be released (Figure 2.14).


Figure 2.14 - Manipulation of sphere with diameter $80 \mu \mathrm{~m}$ [15]

### 2.2.2.c Strategy for Micro-Assembly

In a micro-assembly operation, the goal is to grab the object in an initial configuration (position, orientation) and then move it to the required configuration to finally perform the assembly. This task therefore requires handling the object in translation and rotation, but also to apply forces to insert it into another area, for examples in the case of puzzles.

Different approaches are possible when it comes to manipulating micro-objects. However, both for strategies favouring contact manipulation and for those favouring non-contact manipulation, it is not possible to extract a technique that allows easy manipulation of any object. In both cases, the main advantage is also the main drawback. Indeed, contactless manipulation makes it possible to make adhesion problems trivial, but at the cost of a drastic reduction in the forces applicable to the object. On the other hand, when handling with contact, the force applicable to the object is sufficiently large to achieve any assembly task, but adhesion problems must be managed. Thus, in view of the context in which this work is placed, contactless manipulation strategies therefore do not seem feasible.

Even if contact manipulation remains the most suitable for micro-assembly, it should be noted that the strategies developed so far have little interest in the realization of manipulation allowing the assembly of components. Micro-assembly tasks often require more complex operations than simple take-and-drop tasks. Likewise, the manipulated objects are not necessarily spherical or rectangular. Finally, the problem of release does not often arise since the parts are generally glued or inserted. In fact, the most restrictive problem for micro-assembly concerns obtaining rotations. Indeed, to achieve even more functional micro-systems, precise rotations must be obtained [117] [118].

As explained previously, the rotations can be obtained in two ways: either using a carrier robot with several degrees of freedom or using a right-hand gripper. The constraints of micro-manipulation severely limit the use of a carrier robot capable of orienting the gripper and therefore the object. Indeed, the use of complex robot carriers poses space problems since the entire structure must be moved to perform only one local rotation of the object. The gaps and offsets present in micro-robots also limit the use of complex robots with many degrees of freedom [119]. In particular, rotary actuators used in micro-manipulation do not reach the same level of relative precision as those used in macro-manipulation. To obtain a reliable and repeatable system, it is therefore necessary to use the most precise
actuators, that is to say the translational actuators. An original way of making rotations from translations can be done through manipulations by the gripper. This is why it seems more relevant to us to develop dexterous micro-grippers and micro-manipulation techniques in the hand.

Even if the development of dexterous grippers is relevant and necessary, the dexterity of micro-manipulation platforms currently capable of performing rotations is low. However, dexterous manipulation has long been a subject studied at the macro-scale, which is why it appears relevant to analyse the manipulation methods used at this scale in order to improve those developed for the micro-scale.

### 2.3 Dexterous Handling at Macro-Scale and Micro-Scale

Macroscopic robotic systems have the dexterity levels required to perform complex assembly tasks. This is why we present here an overview of the structures and methods of macroscopic manipulation, on the one hand, the methods that can be reused at the micro-metric scale and, on the other hand, to illustrate the specificities of each scale.

The design of robotic dexterous grippers is a very active theme on a macroscopic scale for the last three decades. Indeed, in 1986, Jacobsen [120] proposed one of the first four-finger robotic hands: the UTAH MIT hand. The latter, composed of sixteen joints and thirty-two actuators, was developed to study dexterity and manipulation by machines. Subsequently, many robotic hands have been developed whose spectrum ranges from under-actuated hands (where the number of actuators is smaller than the number of degrees of freedom) to fully-actuated anthropomorphic hands. Hands under action have the advantage of being mechanically simpler and therefore often easier to control [121, 122, 123]. These robotic hands are generally compilable thanks to elastic or flexible materials [124, 125, 126]. This approach allows the development of low-cost gripping systems capable of adapting
to the shape of the object to be gripped. This is called dexter input. It should be noted that manipulation operations in the hand are not necessarily feasible with this type of hand, since it is necessary to precisely control the movements of each finger.

It is also possible to notice that very few of these hands are used to perform manipulation tasks in the hand (although they remain the most suitable for this operation).

Despite the advantages that only a robotic hand can offer (dexterity, versatility, etc.) [127], the industry is, today, far from developing and using grippers with similar properties to the human hand. In the majority of cases, industrial grippers are developed to respond to limited tasks and their architectures are limited to two-finger grippers. The robotization of handling tasks is therefore limited to simple operations.

On a macroscopic scale, robotic manipulation is carried out under the same constraints as human manipulation, i.e. one must resist the weight of the object to be able to grasp and manipulate it. Since the objective is to perform rotational operations with a dexterous gripper, we will only focus on hand motion strategies.

### 2.3.1 Rolling

This approach consists in rolling the fingers on the surface of the object to set it in motion while avoiding slipping. The first works in this direction are those of Bicchi [128] in which he moves a sphere using two parallel plates. By taking into account the nonholonomic aspect of the rolling of the sphere, he was able to develop a trajectory planar for precise rotations. This approach does not work for all shapes of objects, especially because of the shape of the manipulator. Later, this approach of manipulation by rotation was used to manipulate spherical [129, 130, 131] or polyhedral [132, 133] objects. In 2017, Seon [16] has also used this technique to manipulate the planar micro-objects of different shapes(see Figure 2.15).


Figure 2.15 - Rolling without slipping of a micro-object [16].

### 2.3.2 Sliding

Contrary to the previous method where sliding must be prevented, this second method uses it to move the object in the hand. Although formalizable [134], this approach to manipulation remains complex to implement experimentally. Fearing [135] used sliding to adapt the position of the fingers and the object to a stable state when grasping polygons with two fingers. Similarly, Brock [136] was interested in using sliding on a three-finger robotic hand to improve dexterity. Spiers [17] has used this method with variable friction to achieve low planar sliding and rolling with low dexterity systems without complex controllers (see Figure 2.16). However, this approach requires a precise knowledge of the friction and sliding phenomena at the finger contacts. That is why this technique is difficult to realize at the micrometric scale because of the absence of tactile sensors capable of detecting the slip with precision. It should be noted that, when a human manipulates objects with their hand, the operations performed are generally combinations of rolling and sliding.


Figure 2.16 - Illustration of manipulation using sliding [17].

### 2.3.3 Pivoting

Another way to perform a dexterous manipulation is to create an axis of rotation with several fingers and then use another finger to push the object and rotate it around this axis. This approach has been formalized by Rus [137] to rotate any polyhedra. At the micro-metric scale this approach has already been used by Zhou [138] and Wason [139] to carry out rotations. As explained above, in both cases, a fixed finger is used to perform the rotation. Reorienting the utensils by human hand is one of the examples of this kind of manipulation.

### 2.3.4 Reconfiguration

A final approach to dexterous manipulation consists in changing the fingers in contact with the object when they reach physical limits (collisions, limit of the friction cone, etc.) [140]. This approach is generally used in conjunction with a rolling manipulation. Thanks to this method, the robotic hand can, in theory, perform any object movement [141, 130]. For humans, this operation is very easy to be carried out, but remains complex for robotic hands. Re-positioning is feasible at both macro-scale and micro-scale; however, in contrast to macro-scale, it becomes more difficult at micro-scale since the adhesion strongly disrupts the removal of the fingers. Seon [16] also used re-positioning along with rolling without sliding to carry out dexterous planar micro-manipulation.

## Strategy for dexterous micro-manipulation

Among the four main hand manipulation strategies used on the macro-metric scale, only three are possible for micro-manipulation. Indeed, controlled sliding is not relevant because of the absence of precise sensors and the complex nature of the phenomena present at the level of the contacts. In-hand micro-manipulation is therefore possible using rolling, pivoting or repositioning (or a combination of these three methods). It is even possible to restrict the manipulation in the hand to rolling and repositioning. Bearing effectively allows to perform any rotation as long as the finger has a suitable shape, and repositioning allows to exceed the limits of the manipulator (collisions, actuation limits, friction limits, etc.). A versatile way of performing dexterous micro-manipulation operations is therefore to consider only manipulation by rolling and repositioning.

As mentioned earlier, Seon $[1,16]$ has performed dexterous micro-manipulation by utilising Rolling without Sliding and Re-positioning, while also taking advantage of the adhesion forces to stabilize the objects.

The use of a dexterous gripper to perform rotations of micro-objects has been discussed by several researchers. Shimada [142] was one of the first to develop a dexterous micro-gripper. His approach was to use two translational fingers positioned at $90^{\circ}$ to each other. This way, he was able to perform rotations of up to $90^{\circ}$ using just two fingers. Subsequently Wason [139] developed a dexterous gripper that was also composed of two translational fingers. Again, the rotation was limited to a maximum of $90^{\circ}$. However, unlike the work of Shimada, Wason suggested using a fixed third finger to perform rotations outside the finger plane. Unlike previous grippers, Zhou [138] and Inoue [143] have developed two-finger grippers with more degrees of freedom. Indeed, in addition to translations the fingers can perform rotations around an axis. In this way, it is possible to rotate the object around two different axes. Zhou also suggests using a third fixed finger to perform the missing rotation. In both cases, the achievable rotations remain below $90^{\circ}$. Cappelleri [144] also proposed using a four-finger system to perform
micro-manipulation operations. In his system, rotations are performed using only two fingers while translations and object grabbing are performed using all fingers. The manipulation being carried out on a plane, it is then possible to obtain rotations above $90^{\circ}$. Indeed, by releasing the object after a first rotation of $90^{\circ}$, it is always possible to come and replace the fingers to repeat the operation. In all the above mentioned works, the rotations performed in the gripper remain limited to $90^{\circ}$ and the objects handled remain relatively simple. These limitation of manipulation angle i.e. $90^{\circ}$, and object shape i.e. simple, was overcomed by the proposed work of Seon et al. $[1,145,16,146]$. Seon et al. proposed to dexterously manipulate the micro-objects in a plane using three fingers (beams) by leveraging the impact of adhesive forces in his manipulation system. Through this method, large rotations of above $220^{\circ}$ were achieved for both simple and complex shaped object.

Examination of the different manipulation methods shows that improving the dexterity of micro-hands is a promising approach to improving the complexity of micro-assemblies, and that it is possible to draw inspiration from work carried out at the macro-metric level. The approach proposed in this thesis is to extend the capability of a multi-finger gripper (a micro-hand) to perform rolling and repositioning operations in order to manipulate any shape of object in plane to a 3D manipulation. Following areas are possible for the research:

- Design: Design and characterization of a multi-finger micro-gripper allowing to carry out manipulations in the hand.
- Planning: Planning and generation of movements for the fingers of a microhand in order to automate the manipulation.
- Control: Development of control laws in order to guarantee the precision and repeatability of the micro-hand and of the manipulation trajectories.

This thesis is focused on the planning area for dexterous manipulation.

The different methods used to automate and plan manipulations are presented in the next two sections. On the one hand the methods used at the micro-metric scale and on the other those used at the macro-metric scale.

### 2.4 Planning and Control in Micro-ManipuLATION

The most common micro-manipulation operations are still performed either manually using tweezers or in a teleoperated manner. However, significant progress has been made in recent years in the implementation of automation techniques. These can be categorized into two distinct areas: task planning methods on the one hand, and control-command methods on the other. A method can be called planning if it generates paths, trajectories, or sequences of tasks globally for one or more objects. The control methods provide the local transitions or the individual tasks associated with an object. Thus, planning focuses on objectives such as obstacle avoidance, minimizing completion time while control ensures that the desired actions are carried out while optimizing certain parameters of the system. The optimal automatic system therefore couples planning operations with control operations.

### 2.4.1 Planning Methods

The value of planning in micro-manipulation was first mentioned by Feddema [114]. In his work, he shows the utility of motion planning in the tasks of grabbing, holding and dropping micro-metric objects with a rectangular finger. The conclusion of his work is as follows: "even if planning techniques can be taken directly from the macroscopic domain, it is necessary to develop methods which take into account the specifics of scale" [114]. Feddema therefore laid the foundations for the development of sophisticated planning methods adapted to the micro-world paradigm.

### 2.4.1.a Minimum Path

The so-called minimal path planning method is certainly one of the simplest. Considering a starting position and an end position, this method consists in generating a rectilinear path between the two states. One of the shortcomings of this approach is that collisions are very poorly generated. In the context of micromanipulation operations by two AFM (Atomic Force Microscopy) tips, Xie used this method to plan the movements of the gripper during pickup operations for micro-spheres of $4 \mu \mathrm{~m}$ in diameter [147]. Xie reuses this approach to plan successive pick and place operations in order to achieve pyramidal assemblies of micro-spheres [18] (see Figure 2.17). Zhou [138] has also used this method to plan translations and rotations of micro-objects with a two-fingered gripper. In the case of translations, the planned movement is identical for the two fingers, while in the case of rotations a path is generated for each finger. In this work, the rotations are planned by considering that the point of contact between the object and the finger is constant, that is to say without rolling. This approximation greatly simplifies the planning operation, which partly explains the use of this method.


Figure 2.17 - Representation of planner used by Xie [18]; (a)-(d) from task planning to task execution for pick and place of nano-wire.

### 2.4.1.b The Graph Search

The most common way to plan a task is to use a graph. A graph is a set of points called nodes (or vertices) connected by segments called edges, which makes it possible to model a problem. For example, in the case of a problem of micro-manipulation by a two-finger gripper, the nodes represent the state of the manipulator (position of the fingers) and of the object (position and orientation of the object) and the edges the links between the different states. The objective is then to find the sequence which allows going from an initial state to a desired final state. The solution is found by exploring this graph. Many algorithms have been developed to ensure this exploration stage. The most commonly used are the depth search, the breadth search, the algorithm of Dijkstra [148], Kruskal [149], Prim [150] or even the $A^{*}$ algorithms [151], $D^{*}$ [152], $B^{*}$ [153] (as well as their variants). Each approach has advantages and disadvantages that depend directly on the problem modelled and the type of solution desired. For example, $A^{*}$ and $D^{*}$ allow us to provide complete and optimal paths based on heuristics and costs when exploring the graph.

These methods have shown their effectiveness at the macroscopic scale, in particular in the case of movement planning for mobile robots [154, 155]. At the micro-scale, one of the first uses of graph traversal is found in the work of Moll [19] (see Figure 2.18). The objective in this research is to orient plane polygons using two fingers. To do this, objects can be manipulated using two primitives: rolling or pressure. Knowing these two operations, a graph modelling the problem is proposed, and an algorithm allowing to find the shortest path (in number of operations) is developed. Similarly, Mitra [156] used a graph search to solve the problem of cleaning micro-biochips. In this work, the objective is to find the shortest path for one or more droplets in order to cover the entire surface to be cleaned of the chip.


Figure 2.18 - Representation of graph search algorithm utilized by Moll [19]; (a) representation of a transition graph, (b) transition of an object's state.

In the context of micro-assembly, planning methods have also been used. The first works in this direction are those of Makaliwe [157] in which a simple formalization of the problem of particle nano-assembly is presented. The objective is to move objects in the plane by pushing them with a single finger. In these works, planning can be summarized in finding the succession of positions to reach the desired position while avoiding obstacles in the scene. These positions are then simply connected by straight lines. Inspired by these first works, Malima [158] developed a simulator to plan the movements of micro-objects in the plane. The goal here, too, is to push particles around while avoiding static obstacles in the workspace. The trajectories, obtained using an algorithm $A^{*}$, are successions of lines in the plane. Likewise, Cappelleri [144] used the $A^{*}$ algorithm to determine the optimal translation-rotation sequence to achieve the plane assembly of four polygonal objects of $600 \mu \mathrm{~m}$. In this approach, objects are always pushed and the steps of rotation are not planned, since pre-recorded sequences are used for this purpose. Das and Popa [159] also developed a planner to perform the assembly
of a micro-spectrometer. Unlike previous work where the distance traveled by the manipulator is minimized during the course of the graph, Das and Popa use the precision of the path as a measure to determine the best path. According to them, the most reliable path, and therefore the most likely to achieve maximum performance for the assembly task, is not the shortest. It is possible to cite many other works using graph traversal methods, in particular those of Pawashe and Sitti [160], Cappelleri [161] or even Ju [162].

Seon $[16,1]$, FEMTO-ST Institute, has used $A^{*}$ search algorithm in his work to find the optimised finger trajectory taking the adhesion effects into account, and validated that it is possible to utilise these search algorithm for planning manipulation at the microscopic scale.

### 2.4.1.c Primitive Manipulation

The planning step can be simplified by using manipulation primitives. These primitives are pre-registered actions, such as moving the fingers in a predefined direction over a predefined distance (which corresponds to a translation primitive on a given axis). The objective is then to plan the sequence of these primitives to achieve the manipulation. It is with this approach that Thompson and Fearing [20] (see Figure 2.19) performed automatic micro-manipulation operations on $200 \mu \mathrm{~m}$ cubes. In these works, as in those of Cappelleri [144], finger trajectories allowing an object to rotate at $90^{\circ}$ are pre-recorded. The advantage of this approach is that; if the task to be performed is always the same, then more complex planning is not necessary. This approach lacks flexibility and when certain parameters change (size or shape of the object for example) the primitives are no longer guaranteed to work.

### 2.4.1.d Probabilistic planning

In the event that large uncertainties exist, the classical graph traversal method can be improved by using probabilistic planning. This type of problem is often modelled as a Markovian decision process [163]. For example, suppose an object


Figure 2.19 - Representation of Planning Primitives used by Thompson and Fearing [20].
is manipulated by fingers. At each instant the system is in a given state (position, orientation of the object) and there is a probability that the system will change state depending on the action performed (movement of the fingers). The goal is to move the object from an initial state to a final state and for each movement of the fingers on the object a reward is awarded. This reward, positive or negative, depends on the new state in which the object is found. The Markovian decision process is then summarized by: knowing my object in the state $A$ and performing a movement of the fingers $m$, then there is a probability $x$ that the object ends up in the state $B$ with a $r$ reward. The choice of actions will be directly influenced by a policy which obviously depends on the rewards obtained. At the micrometric scale, this approach to planning has mainly been used by Banerjee in the context of object manipulation by optical forceps [164, 165]. In this work, the Markov decision process is used to manage the probability of keeping the object in the optical clamp as a function of the object's distance from the laser beam. This approach allowed him to manipulate silicon balls of $2 \mu \mathrm{~m}$ in diameter while avoiding obstacles formed by other balls. However, the author himself points out a major limitation to this approach: the more complex the problem becomes (by increasing the number of objects, for example), the less suitable this method is for real-time planning.

### 2.4.2 Control Methods

It is necessary to involve the integration of a controller into the automation of manipulation system. This is because planning allows you to decide what actions to take, but to execute them accurately, the use of control methods is required. There exists a number of control methods, two of them force control and visual servoing are widely/commonly used at the micro-scale.

### 2.4.2.a Force Control

The first works in this direction are those of Zesch and Fearing [166] in which he succeeded in aligning micro-objects with precision of the order of a micron. Thanks to a piezoresistive sensor [167] and an AFM tip, the manipulation operation, which consisted of pushing the micro-objects, could be carried out effectively. This force measurement approach was subsequently reproduced with similar sensors [168] or of a different nature (visual [169], laser [18], thermal [170], electrostatic [21] or even piezoelectric [171]. Likewise, many variants of control laws have been implemented: proportional-integral [172], proportional-integral-derive [21] (Figure $2.20)$, H1 [173] or by impedance [168, 174, 175]. Despite the good precision obtained using these methods, the operations carried out remain simple (pick-up and drop off of components) and the measurement of interaction forces during handling remains a major issue. It should be noted, however, that significant progress has been made in recent years with the appearance of force sensors with multiple degrees of freedom $[176,167]$ as well as the development of high-resolution force measurement by vision [177].

### 2.4.2.b Visual Servoing

Another way to control micro-robots is to use visual servoing. This technique consists of using the information contained in an image taken by a camera to control the movements of the micro-robot. In the context of micro-assembly, Tamadazte [22] (Figure 2.21) used visual servoing to manipulate polygonal shaped


Figure 2.20 - MEMS-based microgripper with integrated two-axis capacitive force sensors [21].
objects. Thanks to this control technique, a precision in position lower than one micron has been achieved. Tamadazte [178] also used this same approach to perform the 3D assembly of these same objects without controlling the rotation phase. Other micro-structure assemblies have been made by this method [179]. This approach has also been used for the manipulation of biological objects [180] with in particular the control of intracellular injection spot $[139,181]$ whose success rate exceeds $95 \%$. Likewise, visual servoing is very often used to control movements in the case of non-contact manipulation [182]. However, this method quickly comes up against the inherent problems of small-scale optics. Indeed, it is not possible to obtain strong magnifications while having a great depth of field. This is particularly problematic during assembly tasks, where a three-dimensional vision is often required.


Figure 2.21 - A mechanical structure depicting the use of Visual Servoing [22].

### 2.5 Planning in Dexterous Manipulation at Macro-Scale

Similar to micro-manipulation, automation is needed at the macroscopic level to improve the integration of robots into society. This is especially true of socalled personal assistance robots, which must be able to grip and manipulate a wide variety of objects. Likewise, industrially, dexterous and autonomous robots can be used to perform complex and above all varied tasks. Currently, robots lack flexibility and are therefore mainly used on assembly lines for large production runs. Adding dexterity and therefore flexibility in conjunction with automation can enable the integration of robots into small and medium-sized businesses. On a macroscopic scale, it is important to plan two elements in dexterous manipulation: the grasp of the object and then its displacement.

### 2.5.1 Grasp Planning

Grasping the object is certainly one of the most important steps in manipulation on a macroscopic scale. That's why there is a lot of work around finding the best possible grip. More precisely, it is relatively easy to test whether a hold allows the object to be grasped [128] but it is significantly more complicated to determine which is the optimal hold. To do this, two approaches are possible [183]: i) analytical approaches which aim to study the holds through the prism of their geometric, kinematic or dynamic characteristics or ii) using empirical methods which aim to reproduce human gestures and learn through human mimicry to grasp objects.

### 2.5.1.a Analytical Planning

The underlying principle of this method is to calculate a set of holds/grasp points acceptable in view of the geometric properties of the object and the characteristics of the robotic hand. Historically this method was used first to determine the possible holds for objects of type polygons or polyhedra. Thus, by using the
geometric properties of objects, algorithms have been developed to determine all the acceptable configurations for grips with three fingers [184], four fingers [185] or even any number of fingers [186]. These approaches have been extended to more complex objects, both 2-D and 3D [23, 187, 24] (see Figure 2.22). However, due to the complexity of 3D objects, these approaches do not allow us to determine all the possible takes in a reasonable computing time. This is why, instead of testing the set of possibilities (exhaustively), a set of takes is generated randomly [188] or according to predefined rules. Finally, the optimization algorithm then searches for a solution on a subset of takes. This selection is made by measuring the quality of the catch through several criteria depending on the object, the manipulator and the stain [189]. For example, it is possible to quantify whether the contact points are more or less uniformly distributed over the surface of the object [190]. Likewise, it is possible to determine the influence of each finger on the seizure [191] knowing that all fingers contribute in the same way. This approach to catch planning has the advantage of being able to calculate the total catch. However, the size of this set is the main drawback of this method, and choosing the best grip requires taking into account the task to be performed. However, it is very complicated to find criteria capable of quantifying the effectiveness of a catch for a given task [183].


Figure 2.22 - Representation of grasp; (a) a cube (3D) with three fingers [23], (b) a circle (2-D) with two fingers [24].

### 2.5.1.b Empirical Planning

This planning method considers that it is not necessary to calculate the usable configurations but, on the contrary, that it is possible to find sockets based on knowledge bases (such as for example by observing humans grasping objects [185]). Based on learning methods, this approach more easily accommodates uncertainties about the shape of the object and about the execution [192]. It is then possible to distinguish three cases of planning: for known, similar or unknown objects. In the case of known objects, the idea is to generate a set of holds constructed either by simulation (using methods similar to analytical planning) as done by Rolinat et al. [25] (see Figure 2.23), or by demonstration [193, 194], or either by trial and error [195, 196]. Once this set is obtained, seizure planning is carried out by identifying the object and estimating its placement in the environment. This then allows you to choose the most suitable grip for the current position of the object. In the case of similar objects, the idea is to extract common characteristics between different objects in order to determine which outlet to use. Using discriminant functions, it is possible to determine the areas that can be used to capture objects $[26,197]$ (see Figure 2.24). It is also possible to compare the object to be manipulated with those present in the knowledge base to find the one that comes closest to it [198, 199]. Thus, the best shots of the object from the database can be used. Finally, when the object is unlike any other, planning uses a partial representation of the object in order to generate potential takes. The idea here is to approximate the object by primitives (sphere, rectangle, for example) on which acceptable holds can be generated using heuristics [200]. Obviously all these approaches are iterative since the new catches enrich the knowledge base.

### 2.5.2 Dexterous Manipulation Planning

Planning of dexterous movement/manipulation with the hand is a problem that has been clearly formalized for many years [201, 202, 203]. This problem is however little studied by the robotics community which prefers to focus on the


Figure 2.23 - Generating the set of holds on different objects (pipe, cinder block and pulley) [25].

Object Representation


Figure 2.24 - Computation of grasping points through learning methods [26].
grasping tasks. Nevertheless, various and varied solutions exist. It is possible to group the majority of these methods into two sets: on the one hand deterministic approaches and on the other hand probabilistic approaches.

### 2.5.2.a Deterministic Approach

The deterministic approaches, from which the micro-metric scale planning methods presented above are derived, are mainly based on the exploitation of graphs as described earlier. The problem to be solved is then described completely using the graph. Thus, all the positions of the fingers on the object are considered and the planning of movement is carried out while navigating in this space. This method makes it possible to return optimal displacements globally [204, 205, 206], that is to say on all the catches describing the problem, or locally [207]. This difference can only be explained by the method used to navigate the graph modelling the problem. The advantage of deterministic approaches is that they ensure that the planned manipulation is always the same and that if there is a solution it will necessarily be found. However, the more complex the problem becomes, the more expensive this approach becomes in terms of computation time.

### 2.5.2.b Probabilistic Approach

Conversely, probabilistic approaches are based on a random and partial description of the problem. In this approach, the nodes of the graph are iteratively generated randomly, then a local planner seeks to connect them [208]. Thus, the nodes represent a hold and a pose of the object in space, while the edges represent the means of passing from one configuration to another. In general, this type of planner does not take into account the rolling of the fingers on the surface of the object and assumes that the contact is punctual and does not change during the movement of the object [209]. Probabilistic approaches have the advantage of generating solutions quickly. However, it is not possible to determine whether these trajectories are optimal for the entire problem. The solution obtained de-
pends on the generated graph, and therefore for the same problem it is possible to obtain different solutions. It should be noted that few of these works (both for probabilistic and deterministic approaches) have been validated experimentally.

### 2.5.2.c Other Approaches

Among the approaches not based on the exploration of a graph, it is possible to cite the work of Daoud [133] in which the trajectory of the object is pre-calculated and then decomposed in succession of small displacements (in position and in orientation). The planner then acts locally to calculate the movement of the fingers on the surface of the object to perform the translations and rotations of each movement. If the movement of the fingers is not acceptable (collision or limit of actuators for example) then the grip is modified using the fingers which are not in contact with the object. The dexterous manipulation is then optimized locally (for each elementary displacement) and not globally. In addition, reinforcement learning techniques have more recently been implemented to teach the robot to perform desired movements using four fingers [210]. Generally speaking, the problem of planning for dexterous manipulation is only a sub-problem of a larger topic that is motion planning (for both mobile and manipulator robots). As a result, a very wide range of techniques exists [211] and can be adapted to function with the constraints of dexterous manipulation.

## Summary

Different methods exist for planning both the grip and the manipulation in the hand. At the macro-metric scale, the majority of work is focused on grasp planning, while manipulation planning in the hand is often limited to simulations.

Manipulation at the micro-metric scale has been strongly influenced by macroscopic manipulation techniques. Indeed, the first micro-manipulators were microgrippers with two gripping fingers similar to industrial grippers. However, the problems inherent in the micro-world have pushed the micro-robotics community to develop new modes of manipulation. As a result, a large part of the work carried out in micro-manipulation is currently oriented towards contactless manipulation (magnetic, optical, acoustic, etc.) which makes it possible to significantly reduce the influence of adhesive phenomena. In the context of making micro-assemblies, contactless handling is not suitable due to the low blocking forces that can be applied. Likewise, micro-manipulators capable of performing micro-assembly operations lack dexterity in that the types of objects handled, and the movements performed are not sufficient to expect to construct complex micro-systems. The explosion of the micro-system market in recent years has shown that the miniaturization of products and functionality is an extremely strong need, and that is why it is relevant to design micro-manipulators with a high level of dexterity.

As explained previously, the rotations can be obtained in two ways: either using a carrier robot with several degrees of freedom or using a right-hand gripper. The constraints of micro-manipulation severely limit the use of a carrier robot capable of orienting the gripper and therefore the object. Indeed, the use of complex robot carriers poses space problems since the entire structure must be moved to perform only one local rotation of the object. The backlash and eccentricities present in micro-robots also limit the use of complex robots with many degrees of freedom [119]. In particular, rotary actuators used in micro-manipulation do not reach the same level of relative precision as those used in macro-manipulation.

To obtain a reliable and repeatable system, it is therefore necessary to use the most precise actuators, that is to say the translational actuators. An original way of making rotations from translations can be done through manipulations by the gripper. This is why we propose to develop dexterous micro-grippers and micromanipulation techniques in the hand.

On a macroscopic scale, this high level of dexterity is achieved with complex robotic systems capable of reproducing movements similar to those of the human hand. Therefore, it is natural to want to draw inspiration from macroscopic grippers to imagine dexterous micro-grippers. However, these grippers are mainly used for gripping tasks and the rotations are obtained using the robot carrier. Therefore, the dexterous micro-grippers cannot be designed on the same model.

In order to increase the usage of micro-manipulation systems in the industrial field, it is important to improve their autonomy. Indeed, the development of planning and control tasks allows better performance of handling operations whether they are teleoperated or fully automated. The methods currently developed, in particular the planning methods, do not take into account the phenomena of the micro-world and are limited to simple tasks, which reduces the spectrum of achievable micro-manipulations.

This thesis will contribute to planning in dexterous micromanipulation. Indeed, we are going to propose the first method to perform finger path planning for 3D rotation, taking into account the micro-scale specificities.

## Chapter 3

## Dexterous Micro-Manipulation in 3-D

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THe current advent in miniaturization has opened a wide spectrum of opportunities, from watch industry to minimal invasive operations on a human body, to deploy the dexterous micro-manipulation systems. However, the current contact based micro-manipulation systems are typically limited to (i) simple 3D manipulation of spherical micro-objects through teleoperation [212] and (ii) dexterous manipulation of complex shaped micro-object in a plane [146], as presented in Chapter 2. Due to these limitations of contact-based micro-manipulation systems, many areas of applications need human intervention, for instance: a doctor needs to teleoperate/semi-operate during a surgery, a watch making industry needs a person to place the small mechanical parts in watch, and placement of pre-assembled electronics components on PCBs during surface mounting process. These limitations could be overcome by a sophisticated automatic manipulation system i.e. dexterous in-hand manipulation system to manipulate micro-objects/meso-object in 3D.

## Contributions

In this chapter, we will formalize the problem of finger trajectory planning for dexterous manipulation in 3D.

### 3.1 Manipulation of Micro-Objects in the 3-D SPACE

Our general objective is to contribute to the development of robotic in-hand manipulation in micro-scale (see Fig 3.1). Considering an initial position of an object placed on a substrate, the objective is to provide tools and methods to be able to place this object in a final position using in-hand positioning. This general objective addresses several scientific challenges. The first challenge deals with the definition of the optimal finger trajectories taking into account the specificities
of the microworld such as adhesion. The second challenge is the design of the dexterous micro-hand, requiring topological optimization of both the structure of the (compliant) micro-mechanisms and the actuator locations. The measure of the spatial position of the object and the grasping forces will be based respectively on vision and micro-fabricated force sensors. The last challenge is the optimization and the potential active control of the finger properties (geometry, contact force) along a trajectory.


Figure 3.1 - Scientific Challenges of the in-hand micromanipulation.

In this thesis, we focus on the first challenge dealing with finger trajectory planning, making some assumptions regarding the other challenges.

### 3.1.1 Thesis objective and planning strategy

In order to address the finger trajectory planning, we make the following assumptions regarding the future micro-hand and the physical properties:

- The fingers are spheres which are rolling on the object surface. We consider friction, and we are going to consider two cases in our simulation taking into account adhesion or not;
- Each finger is actuated independently using 3 translation stages. As a first assumption, we are not going to take into account the collision of the finger support.
- The CAD model of the object is known and can be used to define the trajectory and to simulate in-hand manipulation.

The problem addressed in this thesis is explained in Figure 3.2. The objective is to find relevant finger trajectories to move the object from an initial position to a final position. As the translation can be easily obtained using a similar translation of every finger, we will only consider angular position. We consequently define a grasping configuration as the location of each finger on the object and the angular position of the object. Defining the way to go from the initial position to the final one contains (i) the choice of a relevant initial grasping configuration, (ii) the finger rolling on the object and if required some finger gaiting (addition and removal). All the stable grasp configurations of the final position is considered as a final possible configuration.

The figure 3.3 describes the general proposed method to generate the fingers' trajectories to manipulate the micro-objects. The first step is the definition of the parameters such as number of fingers $(F)$, fingers' position $\left(p_{F}\right)$, fingers' radius $\left(r_{f}\right)$, friction coefficient $(\mu)$, pull-off force ( $f_{p o}$ ) defining the adhesion, and some other physical parameters. The second step is linked with object geometry. Knowing the object CAD model, we will sample the object to generate a finite number of contact points (c).

For every combination of contact points (c), we check the equilibrium grasps with 2 -fingers and 3 -fingers. The equilibrium configurations are stored in matrices known as Maps $M$. Then, these maps are converted to Graph $G$, where each


Figure 3.2 - General objective of the trajectory planner
equilibrium grasp is a Node $n$, and it is connected to its neighbouring node(s) through Edge e. After that, a graph search algorithm is utilized to traverse among these graphs for generating the fingers' trajectories to manipulate the micro-object.

### 3.1.2 Computational complexity analysis and reduction

### 3.1.2.a Computational complexity analysis

One of the challenges in planning fingers' trajectories is the computational (time) complexity. The computational complexity depends on the algorithm being used to generate the fingers' trajectories. There are various algorithms as studied in the Chapter 2 and each algorithm has its own computational complexity. We are going to use the $A^{*}$ algorithm which combines the advantages of the shortest path (Breadth Search, Dijkstra's) and the shortest time (Greedy Best First) algorithms. The computational complexity of $A^{*}$ algorithm is $O\left(b^{d}\right)$ where $d$ is the depth (number of nodes to reach the goal) and $b$ is the branching factor (average number of branches per node). We are going to analyse the complexity of our problem and provide an original approach to reduce it.


Figure 3.3 - General Block Diagram of Finger trajectory planning method.

To dexterously manipulate the micro-objects in 3D, we are using rolling without sliding and finger gaiting. The rolling operation can be performed by either 2 or 3 fingers, while for the finger gaiting we have two cases: (i) when two fingers are in use the third finger will be added, (ii) when three fingers are in use, one of the fingers can be detached. Based on these two operations rolling and finger gaiting, we have two cases for the branching factor (b): (i) when two fingers are in use, and (ii) when three fingers are in use. For the first case, when two fingers are already in contact with the object, the branching factor is the sum of operations: clock wise rotation, anti-clock wise rotation, and addition of a third finger over $c-2$ contact points. Whereas for the second case when three fingers are in use, the branching factor is a sum of operations: clock wise rotation, anti-clock wise rotation, and detaching one of the three finger.

For depth $(d)$, the total number of nodes are all the possible equilibrium grasps, which is the result of the number of contact points $(c)$ of an object, the total number of fingers $(F)$ being used to manipulate the object, and the number of possible angular positions/orientations $\left(n_{\theta}\right)$ of the object.

In planar (2-D) manipulation, where we consider manipulating an object in a single plane, the number of possible angular orientations/positions $\left(n_{\theta}\right)$ depends on the predefined rotational step size $(\Delta \theta)$ as:

$$
\begin{equation*}
n_{\theta}=\left|360^{\circ} / \Delta \theta\right|, \tag{3.1}
\end{equation*}
$$

and the depth $d$ is computed as:

$$
\begin{equation*}
d_{2 D} \approx c^{F} \cdot n_{\theta} . \tag{3.2}
\end{equation*}
$$

Let's consider a planar ellipsoid object (Figure 3.4) with 70 sampled contact points, to be manipulated with 3 -fingers and with a rotation step of $10^{\circ}$, the depth $d$ (total number of nodes) for such case will approximately be 12.34 millions.


Figure 3.4 - Sampled Ellipsoid Object in $x_{0} y_{0}$ - plane.

Whereas to manipulate an object in spatial case ( $\mathcal{S}$ ), we imagine $\mathcal{P}$ number of planes over which the contact points are generated (Figure 3.5). In this case, the depth $d$ is computed as:

$$
\begin{equation*}
d_{\mathcal{S D}} \approx(\mathcal{P} \cdot c)^{F} \cdot n_{\theta}=\mathcal{P}^{F} \cdot d_{2 D} \tag{3.3}
\end{equation*}
$$

As an example, considering an 3D ellipsoid object (Figure 3.5) with approximately 700 contact points generated over 10 -planes, to be manipulated by 3 -fingers with the rotation step of $10^{\circ}$, the depth $(d)$ in such case will approximately be 12.34 billions.

The 10 times increase in contact points induces an exponential increase (1000 times) in the nodes, which further exponentially increases the computational complexity.


Figure 3.5 - Sampled 3D Ellipsoid Object.

### 3.1.2.b Computational complexity reduction

Since, the three individual 2-D rotations will be carried out in two different planes, we consider the two intersecting points $I$ and $J$ of lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ as a common link for these three individual rotations. The three individual rotations will be carried out as: $R\left(z_{\mathcal{O}}, \theta_{1}\right)$ over $\mathcal{P}_{1}, R\left(y_{\mathcal{O}}, \theta_{2}\right)$ over $\mathcal{P}_{2}$, and $R\left(z_{\mathcal{O}}, \theta_{3}\right)$ over $\mathcal{P}_{1}$, respectively, as represented in Figure 3.7. It will limit the branching factor and reduce the number of grasps to the sum of grasping possibilities of each rotation carried out over these two planes, as:


Figure 3.6 - Illustration of proposed method to reduce the computational complexity through Euler's Angles: (a) Projection of two planes over $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$, and intersecting at points $I$, and $J$, (b) contact points on projections $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$.

$$
\begin{equation*}
d_{3 D}=2 \cdot d_{2 D_{\mathcal{L}_{1}}}+d_{2 D_{\mathcal{L}_{2}}} \tag{3.4}
\end{equation*}
$$



Figure 3.7 - Representation of continuation of decomposed 3D rotation in to three 2-D rotations over $\mathcal{L}_{1}$, and $\mathcal{L}_{2}$.

The reduction of complexity introduced by two planes also reduces the genericity of our approach. Indeed, the considered objects should have a geometry in which both planes $\mathcal{P}_{1}$ and $\mathcal{P}_{2}$ can be defined. However, this is usually the case for micro-objects manufactured using the classical microfabrication methods, having mostly 2 -D $\frac{1}{2}$ geometries.

### 3.1.3 Manipulation Constraints

Since, the object modelling is restricted only to two planes $\mathcal{P}_{1}$ and $\mathcal{P}_{2}$, it should be noted that the intersecting points $I$ and $J$ of projections $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ are the only link that connects the three decomposed rotations. Moreover, due to this only connecting link of the decomposed rotations there are some constraints induced on the manipulation process.

First the intersecting points must be included in the contact sampling. Second every transfer between $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ requires to reach the intersecting point. In other words, the following constraints have to respected:

- The first rotation should end at the intersecting points $I$ and $J$ of two lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$, as in Figure 3.8.a-b.
- The second rotation should start from these intersecting points $I$ and $J$, and end at the same intersecting points, as represented in Figure 3.8.c-d.
- The third rotation should start from these intersecting points $I$ and $J$, as depicted in Figure 3.8e-f.


### 3.1.4 Sampling Strategy

The sampling strategy defines how the configuration space is sampled. As mentioned previously, a configuration is defined by the finger positions on the object and the angular position of the object. We choose to retain a uniform sampling regarding the angular position defined by a constant predefined rotation step $\Delta \theta$. The contact point sampling along both line $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ is defined in the following way: we consider the two intersecting point $I$ and $J$ as the two first contact points in our sample. The two next points are generated from these two initial points by rotating the object with a rotation step $\Delta \theta$. By repeating this operation, we obtain the sampling of the lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$.

First Rotation Constraints


Figure 3.8 - Rotation constraints along the 3 rotations: (a-b) $1^{\text {st }}$ rotation constraint (2-D top view of $x_{O} y_{O}$ plane): (a) fingers (in red) can start from any feasible grasp configuration, (b) fingers should end at the intersection points for the desired orientation. (c-d) $2^{\text {nd }}$ rotation constraint (2-D side view of $x_{O} z_{O}$ plane): (c) rotation start from the intersecting contact points, (d) rotation should end at the intersecting contact points for the desired orientation. (e-f) $3^{\text {rd }}$ constraint (2-D top view of $x_{O} y_{O}$ plane): (e) rotation should start from the intersecting contact points, (f) rotation can end at any feasible grasping configuration for the desired orientation.

In other words, we consider that the rolling distance between two successive sample (contact) points has to induce an elementary $\Delta \theta$ rotation of the object. We formalize that the curvilinear distance $s_{d}(t)$ between two contact points is the function of finger radius $r_{F}$, the fixed rotational step $\Delta \theta$, and the local curvature radius of the object $r_{O}(t)$. To formulate the equation, we will refer to Figure 3.9,
where $c_{1}$ is the contact point from where the object starts rotating around the finger, and $c_{2}$ is the contact point where the rotation finishes. As the object's total rotation $(\Delta \theta)$ is the sum of the two angles $\alpha_{1}$ and $\alpha_{2}$,

$$
\begin{equation*}
\Delta \theta=\alpha_{1}+\alpha_{2}, \tag{3.5}
\end{equation*}
$$

and since both rolling distances on the finger and on the object are equal:

$$
\begin{equation*}
s_{d}(t)=\alpha_{2} \cdot r_{F}=\alpha_{1} \cdot r_{o}(t), \tag{3.6}
\end{equation*}
$$

we can determine the instantaneous curvilinear sampling distance $s_{d}(t)$ :

$$
\begin{equation*}
s_{d}(t)=\frac{|\Delta \theta| \cdot r_{F}}{r_{o}(t)+r_{F}} \cdot r_{o}(t), \tag{3.7}
\end{equation*}
$$

where, the curvature radius of the object $r_{o}(t)$ on $x_{\mathcal{O}} y_{\mathcal{O}}$-axis can be determined using the curvature formula defined for parametric equation:

$$
\begin{equation*}
l_{1}(t)=1 / \kappa=\frac{\left(x^{\prime}(t)^{2}+y^{\prime}(t)^{2}\right)^{3 / 2}}{\left|x^{\prime}(t) y^{\prime \prime}(t)-y^{\prime}(t) x^{\prime \prime}(t)\right|}, \tag{3.8}
\end{equation*}
$$

where $x^{\prime}, y^{\prime}, x^{\prime \prime}$, and $y^{\prime \prime}$ are the first and second derivatives of the parametric equation.


Figure 3.9 - Representation of finger rotating an object to formulate the sampling formula.

### 3.2 Maps Generation

Following the sampling strategy, we now are able to define a finite number of configuration considering both 2 -fingers grasping and 3 -fingers grasping. The next step in our process is to test if these configurations are stable or not. The collection of the stable configurations for a given angular position of the object will be called the "Equilibrium Maps" (see Figure 3.3, Page 62). A second type of map called "Reconfiguration Maps" will be also defined in order to characterize the ability to remove one finger or to remove the object from the substrate. Indeed, considering a stable 3 -fingers configuration, when removing a finger (e.g. finger 3), this finger will pull on the object (because of the adhesion between the object and the removing finger) and this pull-off force applied by the removing finger could disturb the grasping done by the two remaining fingers (e.g. Fingers 1 and 2). For every stable 3 -fingers grasping, if the finger 3 can be removed, this configuration will be stored in the "Finger 3 Reconfiguration Map". The same process will be considered for taking into account the adhesion between the object and the substrate for the initial grasping.

The following subsection provides the insight on physical modelling to generate Maps.

### 3.2.1 Physical Modelling

The static equilibrium of a configuration requires to analyse the forces and torques applied to the manipulated objects. As mentioned previously, the behaviour of physical laws differs at micro-scale from macro-scale. While, gravitational and inertial forces prevails at macro-scale, adhesive forces dominates the other forces like gravitation and inertia at micro-scale. In Chapter 2, we presented the impact of these adhesive forces, which most of the time make it difficult to manipulate objects at micro-scale. However, it also provides the advantage to im-
prove the stability of the object equilibrium while manipulating. We present in this section a simplified model of the interaction force between the finger and the object which can be used in our finger trajectory planning method.

### 3.2.1.a Grasping Forces and Contact Modelling

In contact-based manipulation, some forces are applied to grasp and manipulate the object. These forces are transmitted at the intersecting point of finger and object (contact point). The contact model maps these transmitted forces to the resultant wrenches $(w)$ relative to the object.

There are many contact models [213], whereas in robotics, three of them are widely used in robotic grasping [214]. These contact models are: point contact model with and without friction, and soft-finger contact model. The former are used for rigid bodies, where the last one is used for deformable bodies. We assume in micro-scale that the applied forces can be modelled using a frictional model. In this model, when there is some friction, the forces are transmitted in the normal and tangential direction to the surface at the contact point. One of the classical model, Coulomb friction, is based on the idea that friction opposes motion and that its magnitude is independent of the velocity and contact area. This empirical model asserts that the allowed tangential force is proportional to the applied normal force by:

$$
\begin{equation*}
f_{t} \leq \mu f_{n} \tag{3.9}
\end{equation*}
$$

where $\mu$ is friction coefficient, and $f_{t}$ and $f_{n}$ are tangential and normal components of force. The friction forces can be geometrically represented as a friction cone (Figure 3.10), where all applied forces can be considered in-side a cone with angle $\beta=\arctan (\mu)$. According to the Coulomb Friction, if the exerted forces lie inside the friction cone, there will be no slippage.


Figure 3.10 - Friction Cone at the contact point between object and finger for both non-sticky contact (a), and sticky contact (b), and the impact of pull-off force on the friction cone.

In the presence of adhesion, which acts as attractive force between manipulated object and fingers at micro-scale, the Coulomb Friction model is slightly changed. This attractive force is known as pull-off force $\left(f_{p o}\right)$, and represents the force required to detach the finger from the object. So, the Coulomb's Law can be rewritten as [146]:

$$
\begin{equation*}
\sqrt{f_{t 1}^{2}+f_{t 2}^{2}} \leq \mu\left(f_{n}+f_{p o}\right) \tag{3.10}
\end{equation*}
$$

Due to the presence of this pull-off force, the friction cone is shifted. Furthermore, this produces the possibility to apply negative force (pulling the object) in micro-scale until the applied force lies in the modified friction cone, whereas in macro-scale only the positive grasping force (pushing the object) is utilized.

### 3.2.1.b Solid Object Equilibrium

On a miccro-metric scale, since we are considering quasi-static manipulation, the planning space is made up of the grasps ensuring the balance of the force applied to the object. To define the stable grasp configuration, we are going to use the contact model selected in the previous section. In addition, two cases of equilibrium are to be considered:

Static equilibrium: which allows you to determine if a grasp using N fingers keeps the object in balance.

Stable detachment: which allows you to know if the removal of a finger (or a removal from the substrate) can be carried out without disturbing the grasping with the two remaining fingers.

The first problem exists whatever the scale of manipulation considered, while the second is a consequence of adhesion effects.

### 3.2.1.c Grasping Equilibrium

The object must be in equilibrium during the whole manipulation process. As the fingers exerts grasping forces on an object and the contact model maps those forces to the resultant wrenches $(w)$. The condition of a rigid object to be in equilibrium is that, the sum of all these wrenches should be equal to zero. The wrench vector is composed of forces and torques at the contact point as provided by:

$$
w^{\prime}=\left[\begin{array}{ll}
f & \tau \tag{3.11}
\end{array}\right]
$$

where $f$ and $\tau$ represents the force and torque respectively. As mentioned, the finger grasp will be in equilibrium if:

$$
\begin{equation*}
\sum_{i=1}^{F} w_{c_{i}}+w_{e x t}=0 \tag{3.12}
\end{equation*}
$$

where $w_{c_{i}}$ is the grasping wrench at $i^{\text {th }}$ contact and $w_{\text {ext }}$ is the external wrench applied to the object. The grasping wrench $w_{c_{i}}$ applied at the $i^{\text {th }}$ contact point is a linear combination of wrenches that approximate the cone and written as:

$$
\left\{\begin{array}{c}
w_{c_{i}}=\sum_{j} \alpha_{1_{i, j}} \cdot w_{l_{j, i}}+\alpha_{2_{i}} \cdot w_{p o_{i}}  \tag{3.13}\\
\alpha_{1_{i, j}} \geq 0 \\
1 \geq \alpha_{2_{i}} \geq 0
\end{array}\right.
$$

where $w_{l_{j, i}}$ is one wrench that approximates the $i^{\text {th }}$ friction cone, $w_{p o_{i}}$ is the wrench induced by pull-off forces (sticking effect), and $\alpha_{1_{i, j}}$ and $\alpha_{2_{i}}$ are coefficients that must be positive to stay inside the friction cone.

Then, the equilibrium problem (3.12) of an $F$ fingers grasp can be rewritten as a function of the $F$ friction cones wrenches:

$$
\left\{\begin{array}{c}
\sum_{i=1}^{F} w_{c_{i}}+w_{e x t}=\sum_{i=1}^{F}\left(\sum_{j} \alpha_{1_{i, j}} \cdot w_{l_{j, i}}+\alpha_{2_{i}} \cdot w_{p o_{i}}\right)+w_{e x t}  \tag{3.14}\\
\alpha_{1_{i, j}} \geq 0 \\
1 \geq \alpha_{2_{i}} \geq 0
\end{array}\right.
$$

Thus, the equilibrium problem is equivalent to finding a set of positive coefficients $\left(\alpha_{1_{i, j}}, \alpha_{2_{i}}\right)$, not all of them null, verifying the equation (3.14).

### 3.2.1.d Stable Detachment

For micromanipulation, considering only grasps that ensure the object's balance is not sufficient. During a dexterous handling operation, the fingers are generally repositioned to achieve certain limits (e.g. limit of the friction cone). On a micrometric scale, the removal of a finger can upset the balance of the grasp. Indeed, due to the adhesion, the detachment of a finger generates a pull-off force on the object which can cause a loss of the force balance. Thus, the trajectory planning requires
the identification of a subset of configuration which we will call the reconfiguration maps, including the balanced configuration for which one of the fingers can be removed.

Detachment of a finger
Let us consider the case of a grasp with $F$ fingers for which the $F^{t h}$ finger is removed. We consider that this $F^{t h}$ finger is placed at the $j^{\text {th }}$ contact point. To guarantee the balance of the object, it is necessary that the $F-1$ remaining fingers resist the force generated by the adhesion forces at the $j^{\text {th }}$ contact point, as well as other external forces acting on the object. This can take the following form:

$$
\begin{equation*}
\sum_{i=1, i \neq j}^{F-1} w_{c_{i}}+w_{e x t}+w_{p o}=0 \tag{3.15}
\end{equation*}
$$

where $w_{p o}$ is the wrench caused by the release of finger from $j^{\text {th }}$ contact point.
Similarly to the previous grasp balance problem, it is possible to rewrite Equation 3.15 according to the friction cones of the remaining $F-1$ fingers. The problem of detachment of the $F^{\text {th }}$ finger is then to find positive coefficients $\left(\alpha_{1_{i, j}} ; \alpha_{2_{i}}\right)$ verifying the equation:

$$
\left\{\begin{array}{c}
\sum_{i=1}^{F-1} w_{c_{i}}+w_{e x t}+w_{p o}=\sum_{i=1}^{F-1}\left(\sum_{j} \alpha_{1_{i, j}} \cdot w_{l_{j, i}}+\alpha_{2_{i}} \cdot w_{p o_{i}}\right)+w_{e x t}+w_{p o}  \tag{3.16}\\
\alpha_{1_{i, j}} \geq 0 \\
1 \geq \alpha_{2_{i}} \geq 0
\end{array}\right.
$$

The reconfiguration maps is thus made up of the grasps, which admits a solution to the problem of static equilibrium (3.14) and to the problem of detachment (3.16).

## Detachment from substrate

On the micrometric scale, another problem induced by adhesion is the detachment of the object from the substrate. This specific case corresponds to the fact that the initial grasp must make it possible to counter the force of adhesion between the object and the substrate. Considering that the substrate represents a finger of infinite radius, the problem of detaching from the substrate is identical to that of detaching one of the fingers during a grasp. Thus, the same methods can be used to test whether a grasp qualifies as an initial grasp.

The systems of equations (3.14) and (3.16) generally present more unknowns than equations, making the calculation of solutions algebraically impossible. It is therefore necessary to use optimization techniques in order to find numerical solutions. However, the construction of the planning space does not require an explicit calculation of the forces. It suffices to prove the existence of a solution to determine if a grasp is in equilibrium or not.

### 3.2.2 Equilibrium Maps

### 3.2.2.a General principle

The existence of a solution of the systems of equations (3.14) and (3.16) can be characterized using the convex hull formed by the friction cones wrenches $\left(w_{l_{j, i}}\right)$. Indeed, it has been proven in [184] that, without external perturbation, if this convex hull contains the origin of the wrench space, then a solution to the equilibrium problem exists (Figure 3.11). In fact, the grasp can exert all the wrenches that lie inside the convex hull.

Figure 3.12 illustrates this property in the case of a planar problem. In this example, the wrenches are represented by forces on the $x$ and $y$ axes and moments/torques on the $z$ axis. The objective is to determine if the two-finger grasp (Figure 3.12a) is a stable grasp or not. The convex hull shown in Figure 3.12 is formed by the wrenches $w_{l_{1,1}}, w_{l_{2,1}}, w_{l_{1,2}}$ and $w_{l_{2,2}}$ which delimit the friction cones.


Figure 3.11 - Representation of a convex hull formed by three non- sticky fingers for a planar problem (six wrenches with three coordinates). The origin is included in this envelope, thus the grasp is stable.

In the absence of external forces, it suffices that the origin is included in the envelope to guarantee the existence of a solution. As in this example, the center of the framework is not in the convex hull, we notice that this grasp is not stable.

In case we consider adhesion, the convex hull formed by the wrenches $w_{l_{i, j}}$ and $w_{p o_{i}}$ does not exactly represent the set of applicable forces. To fully describe the convex hull linked to the contact model presented previously, it is necessary to consider wrenches $w_{l_{i, j}}$ slightly modified. Indeed, the normal component corresponding to the offset of the friction cone must be added to them. These new wrenches are $w_{l_{i, j}}^{*}$. Figure 3.13 illustrates convex hulls with and without taking into account the additional normal component in the case of a planar grasp. Note that both the resultant convex hulls (Figure 3.13b, and Figure 3.13c) are slightly different, and that it is therefore the same for the applied forces. It should be noted that the grasp is in equilibrium in the absence of external forces, since the origin is included inside the convex hull.


Figure 3.12 - Illustration of the convex hull representing the set of forces applied on the object in the case of a planar two-finger grasp without adhesion: (a) representation of the grasp and the friction cones, (b) representation of the resulting convex hull.

As mentioned previously, there are three types of operations performed during the manipulation process: (i) Rolling on the object, (ii) Initial Grasping of the object (Detachment from the substrate), and (iii) Finger gaiting (Detachment of a finger). Thus, it is necessary to generate the maps for all these operations. In order to construct the different maps, we assume that the object is known and represented numerically by a set of points (contact points).

### 3.2.2.b Equilibrium Maps

Obtaining the equilibrium maps is done by testing, for all the combinations of grasps, if the convex hull formed by the wrenches of the friction cones ( $w_{l_{j, i}}$ and $\left.w_{a d ; i}\right)$ contains the wrench of external forces $\left(w_{e x t}\right)$. Thus, the equilibrium map corresponding to the grasps of the object at equilibrium using fingers 1 to k , can be formalized in the following way:

$$
\begin{align*}
M_{F}^{\text {roll }}= & \left\{c=\left(c_{1}, . ., c_{F}\right) \in \Re^{(3 \times F)} \mid\right.  \tag{3.17}\\
& \left.-w_{e x t} \in \operatorname{Convhull}\left(w_{l_{1,1}}, \ldots, w_{l_{j, N}}, w_{p o_{1}}, \ldots, w_{p o_{N}}\right)\right\},
\end{align*}
$$



Figure 3.13 - Illustration of the convex hull representing the set of forces applied on the object in the case of a two-finger planar grasp with adhesion: (a) representation of the grasp and friction cones, (b) representation of the resulting convex hull without taking into account the additional tangential force, (c) representation of the convex hull resultant taking into account the additional tangential force.
where $c$ is a vector containing the contact coordinates on the object surface and Convhull $\left(w_{l_{1,1}}, \ldots, w_{l_{j, N}}, w_{p o_{1}}, \ldots, w_{p o_{N}}\right)$ represents the convex hull.

For every angular position, it is possible to draw a planar 2-D map of 2-fingers grasp (see Figure 3.14), in which the two axes are the contact point number of each two fingers. Considering every angular positions, we may represent the 2 -fingers equilibrium grasps as a collection of 2-D equilibrium maps. The coloured areas on Figure 3.15.c represent the equilibrium configurations for a two fingers grasp,
without any pull-off forces. Since permuting the two contact points leads to the same grasp, the equilibrium map shows a symmetry axis. When the fingers roll on the object enabling to rotate it, we navigate along equilibrium grasps from one planar map to another. The example of the rotation going from Figure 3.15.a to Figure 3.15.b is represented by the red arrow across the equilibrium maps on Figure 3.15.c.


Figure 3.14 - Representation of a grasp with finger-1, and finger-2 in a map: (a) $F_{1}$ and $F_{2}$ represent the finger used, and $c_{1}$ and $c_{33}$ represent the indexes of contact points to grasp the object. (b) Map representing the stable grasp configurations, and highlighting the grasp configuration that is being used.

### 3.2.2.c Reconfiguration Maps

In finger gaiting, to guarantee that a given finger $i$ can be pulled-off from the object without disturbing the grasp, we ensure that the resulting wrench $w_{p o_{i}}$, induced by the pull-off force $f_{p o_{i}}$, is included in the convex hull formed by the friction cones' wrenches of the $F-1$ remaining contacts. The re-grasping map, corresponding to the detachment of the $i^{\text {th }}$ finger in a $F$-finger grasp, can be formalized as follows:


Figure 3.15 - Representation of a rolling operation in maps when same fingers are used in initial configuration and final configuration: (a)-(b) rotation of $80^{\circ}$ when the rotational step $(\Delta \theta)$ is $20^{\circ}$, (c) Stable grasp in $5^{t h}$ layer of rolling map is accessed from $1^{\text {st }}$ layer of rolling map.

$$
\begin{align*}
M_{F_{i}}^{\text {detach }}= & \left\{c=\left(c_{1}, . ., c_{i}, . ., c_{F}\right) \in \Re^{(3 \times N)} \mid\left(c_{1}, . ., c_{i-1}, c_{i+1},\right.\right.  \tag{3.18}\\
& \left.. ., c_{F}\right) \in M_{F-1}^{\text {roll }},-w_{e x t}-w_{p o, i} \in \operatorname{Convhull}\left(w_{l_{1,1}}, . ., w_{l_{j, i-1}},\right. \\
& \left.\left.w_{l_{j, i+1}}, . ., w_{l_{j, F}}, w_{p o_{1}}, . ., w_{p o_{i-1}}, w_{p o_{i+1}}, . ., w_{p o_{F}}\right)\right\} .
\end{align*}
$$

### 3.2.2.d Initial Reconfiguration Maps

Additionally, when the pull-off forces between the object and the substrate is not negligible, it is possible to consider a third set of grasps that represents the initial grasps enabling to detach both the object from the substrate (resist the external wrench $w_{p o, s u b}$ induced by the substrate) and stably pick-up the object. This can be formalized as follows:

$$
\begin{align*}
M_{F}^{\text {init }}= & \left\{c=\left(c_{1}, . ., c_{F}\right) \in \Re^{(3 \times N)} \mid\left(c_{1}, . ., c_{F}\right) \in M_{F},\right.  \tag{3.19}\\
& \left.-w_{e x t}-w_{p o, s u b} \in \text { Convhull }\left(w_{l_{1,1}}, \ldots, w_{l_{N, j}}, w_{p o_{1}}, \ldots, w_{p o_{F}}\right)\right\} .
\end{align*}
$$

These $M_{F}^{\text {init }}$ maps are very similar to the previous maps but are just used to select the admissible initial grasp in case the substrate is sticky.

### 3.2.3 Collision Constraints

Some other constraints are also taken into account to build the Maps such as the collisions. Collision is an event when two or more objects intercept or collide with each other. In manipulation, it is one of the main aspect that should be avoided, otherwise it will halt the manipulation process. Consequently, there is necessity to take the collisions into account, and these collisions can be categorized as:

- Internal Collisions: The collisions between fingers, including finger to finger collisions, and finger collision with the support of other fingers.
- External Collisions: The collisions between fingers and other components, like object, substrate, and other components of the environment.


### 3.2.3.a Internal Collisions

Finger to finger collision occurs, when two or more fingers intercept each other's path, or when they try to access the same contact point (See figure 3.16). The other possibility of finger-finger collision is when a finger tries to access a contact point that is in the proximity of a contact point which is already occupied by another finger. Thus, it is necessary to develop an algorithm that avoids these interceptions of finger-finger collisions.

The first case can be avoided while generating an off-line trajectory. The latter is avoided during the path generation, while the last is avoided while generating the maps.

Currently, we ignore the collision between a finger and its support, as we are not using any finger support in our simulations. This point should be addressed in future works.


Figure 3.16 - Illustration of Fingers' Collision: (a) when $1^{\text {st }}$ finger is already in contact, and the $2^{n d}$ finger tries to access the neighbouring contact point, (b) when both fingers are approaching their desired contact points on the object.

### 3.2.3.b External Collisions

The object-finger collision occurs when a finger tries to pass through the object. Thus, to avoid object-finger collision, the area of an object can be considered as a block or inaccessible space when a finger is moving from one contact point to another contact point (see figure 3.17).


Figure 3.17 - Illustration of the possible Finger-object collisions. Left: When a finger tries to access only one contact point; but due to the shape of the object, it accesses multiple contact at a same time.
Right: Example of finger object collision; the light grey area represent the solid object, and the finger tries to pass through this area to reach the other end or any other contact point.

### 3.3 Graphs Construction

In the above section, we studied about Maps and how are they generated. However, Maps are insufficient to generate the fingers' trajectories, as they are independent entities, and there are no links among the Maps and Maps' elements. Thus, to generate the fingers' trajectories, we need something where we can traverse among the equilibrium grasp space. Since, the equilibrium grasp space is discrete, we can generate the graph space from the equilibrium grasp space (Maps). In general this graph space is known as $\operatorname{Graph}(s)(G)$ where the equilibrium grasp points are connected with each other. Each element of Graph is called a node ( $n$ ), and each node is connected to one or more nodes through edge (e).

Considering a 2 -fingers grasp node (see top graph on Figure 3.18), it is connected to two other 2-fingers grasp nodes modelling a clockwise and counterclockwise rotation. It is also connected to a maximum of $(c-2) 3$-fingers grasp nodes, representing the every possible addition of the $3^{\text {rd }}$ finger. In case of a 3 -fingers grasp node (see bottom graph on Figure 3.18), in the same way, it is also connected to two other 3 -fingers grasp nodes related to the two possible rotation directions.


Figure 3.18 - Representation of a graph generated from different Maps; a node $(n)$ is connected to other nodes via Rolling (Clockwise, Counter-Clockwise), Finger Addition and Finger Removal Maps.

It is also connected to a maximum of 3 2-fingers grasp node, representing the possible finger removing taking into account the criteria modelled in the finger reconfiguration (detachment) maps.

Considering these rules to build the edges between nodes, we get a full $\operatorname{Graph}(s)$ $(G)$. A trajectory planner, presented in chapter 4, will explore the $\operatorname{Graph}(s)$ $(G)$, to determine optimal trajectories. Since, the micro-object is manipulated through three individual 2-D rotations, three graphs (one for each rotation) will be considered and the optimal path in each rotation / each graph will be defined independently.

### 3.4 Conclusion

An original analysis of the impact of micro-scale specifications on the dexterous manipulation problem has been presented in this chapter. Taking into account the effects of adhesion changes the paradigm of manipulation and makes it quasistatic. Therefore, dexterous micromanipulation can be seen as a succession of stable grasps. The space on which the trajectories will be planned is therefore made up of the grasps, ensuring that the object is kept in equilibrium. In order to build this space, it is necessary to model the contact between the fingers and the object to take into account the phenomena of adhesion. This is why a modified Coulomb friction model has been presented. Thanks to this model, it is possible to identify the stable grasps space for the purpose of fingers' trajectory planning. This space was subsequently formalized in three types of maps:

- The equilibrium maps: to represent the static equilibrium grasp.
- The Finger Reconfiguration maps: to determine that which one of the fingers can be removed without disturbing the balance.
- The Initial Reconfiguration maps: to represent the grasps for grasping the object when it is on the substrate.

Finally, these maps represent the set of equilibrium grasps that can be used to perform a dexterous micro-manipulation operation and integrate the grasp constraints, namely, adhesion, friction and collisions.

In the next chapter, we will present the implementation of the proposed methodology to explore the graph space in order to define fingers' trajectories. Moreover, we will also discuss the impact of different parameters (adhesion, and friction coefficient) on the trajectory generation.

## Chapter 4

## Fingers' Trajectory Planning Methodology

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IN Chapter 3, we modelized the grasping possibilities as a graph $(G)$ considering accessible and stable grasps as nodes. The edges, the links between nodes, represent the manipulation abilities. In this chapter, we are going to present the methodology to define finger trajectories enabling to perform object manipulation. It consists in a navigation in the graph $(G)$ introduced in the previous chapter. We will also analyse the performances of the proposed finger trajectory planning methodology.

### 4.1 Implementation of Fingers' Trajectory Planning

A sophisticated planar dexterous micro-manipulation was proposed previously in FEMTO-ST by Seon et al. [16, 146]. This previous works were focused on planar manipulation and use a $A^{*}$ Algorithm using an original cost and heuristic dedicated to 2-D dexterous micro-manipulation. This method is not able to plan trajectories taking into account the particular constraints of our works linked to the existence of intersecting points $I$ and $J$. An original methodology has consequently been developed and is presented in this chapter. This methodology uses also $A^{*}$ Algorithm with a new definition of both cost and heuristic functions enabling to take into account the constraints coming from intersecting points $I$ and $J$

### 4.1.1 The $A^{*}$ algorithm

Considering two nodes, one as a starting points (initial node) and the other as an ending points (goal node), the $A^{*}$ algorithm searches for the shortest/optimal path in the graph in order to connect the two selected nodes. It combines the advantages of the shortest path (Breadth Search, Dijkstra's) and the shortest time (Greedy Best First) algorithms. It tries to explore the path in the direction of goal node, through an estimation function (i.e. Heuristic Function $(h(n))$ ). Each node $n$ is assigned a heuristic value $h(n)$, that estimate the distance from that
node to the goal node. Similarly, each edge is assigned a cost $g(n)$ to go from current node $n_{c}$ to next node $n_{c+1}$. Thus, when a node is explored it is possible to assign it a value i.e. total cost $f(n)$, which is the sum of its path cost (edge(s) traversed) $g(n)$, and the heuristic cost $h(n)$. This value represents the total cost of the node and is used to explore the graph. Indeed, the objective being to find the optimal path (with minimum cost), the total cost then makes it possible to select the most promising node, that is to say the one with the lowest cost. In case of having two nodes with the same value of function $f(n)$, we chose a classical "Tie breaking" strategy consisting in exploring first the node having the minimal heuristic $h(n)$. In other words, it means that if two nodes have the same function $f(n)$, we choose to explore first the nodes which is closer to the final goal, meaning having the smallest $h(n)$. Moreover, for the path to be optimal, it is necessary that the heuristic chosen never overestimates the remaining total cost to reach the goal node.

### 4.1.2 Cost Function $g(n)$

As per the formalized problem described in Chapter 3 there are three types of action (represented by edges): (i) initial grasp of the object, (ii) rolling of the object, and (iii) reconfiguration of the fingers (finger gaiting). Thus, there is need to define the cost function $g(n)$ for all these operations.

### 4.1.2.a Value of $(g(n))$ for initial grasping of the object:

For the "initial grasping", the fingers make contact with the object from their predefined positions, as illustrated in Figure 4.1. Since, this is the first node which is going to be selected, therefore the cost for initial grasping operation $\left(g\left(n_{o}\right)\right)$ will be initialized as 0 .


Figure 4.1 - Representation of the initial grasp operation: (a) fingers approaching the object for grasp, (b) grasping the object.
4.1.2.b Value of $(g(n))$ for rolling operation:

The "rolling operation", changes the orientation of object when 2 or 3 fingers are used, reaching to node $n$ from previous node $n_{\text {previous }}$ without any reconfiguration. Thus, we formalize the value of cost when a rolling operation is performed as

$$
\begin{equation*}
g(n)_{\text {rolling }}=g\left(n_{\text {previous }}\right)+F_{\text {used }} \cdot|\Delta \theta|, \tag{4.1}
\end{equation*}
$$

where $F_{\text {used }}$ is the number of fingers used to roll the object, and $g\left(n_{\text {previous }}\right)$ is the cost of the previous node. It means that a rotation using 3 fingers will induce a higher cost than when using 2 fingers. This choice has been made to encourage the 2 -fingers grasping, which requires less resources. However, the proposed methodology could be easily modified to promote 3 -fingers grasping.

For instance, in Figure 4.2 an object is being rotated for a predefined angle $(\Delta \theta)$ from the initial grasp (Figure 4.2a). The current node (Figure 4.2b) is reached by rolling operation carried out by 2 fingers $\left(F_{u s e d}=2\right)$. In this scenario, the cost of rolling operation $\left(g(n)_{\text {rolling }}\right)$ will be (Equation 4.1):

$$
g(n)_{\text {rolling }}=2 \cdot|\Delta \theta|+0 .
$$

The value of $g\left(n_{\text {previous }}\right)=0$, because previous node was an initial node and its cost was initialized as 0 .

## Rolling Operation



Figure 4.2 - Representation of the rolling operation: (a)-(b) rotation of object from initial grasping.

### 4.1.2.c Value of $(g(n))$ for reconfiguration operation:

When the "reconfiguration operation" is performed, either a finger is added or removed while the object remains in the same orientation as illustrated in Figure 4.3; thus, the cost $g(n)_{\text {gaiting }}$ is formalized as

$$
\begin{equation*}
g(n)_{\text {gaiting }}=g_{r}+g\left(n_{\text {previous }}\right), \tag{4.2}
\end{equation*}
$$

where $g_{r}$ is the reconfiguration cost. This value has to be compared with the rolling cost introduced in Equation (4.1). Indeed, the relative weight between both provides the relative weight between a reconfiguration operation and a rotation. In other words, a low $g_{r}$ (compared to rolling cost already defined) will encourage to perform lot of reconfiguration and reduces as possible the rotations. A high $g_{r}$ will reduce the number of reconfiguration and encourages the rotations. Concretely, we define the value of reconfiguration cost $g_{r}$ at $\left|180^{\circ}\right|$. It means that we assume that a reconfiguration has a similar cost to a quarter-turn of rotation using two fingers $\left(2 \times\left|90^{\circ}\right|\right)$.

## Reconfiguration

Operation


Figure 4.3 - Representation of the reconfiguration operation: (a)-(b) When two fingers are already in contact, a third finger can be added, (b)-(c) When three fingers are already in contact, one of the fingers can be removed.

### 4.1.3 Heuristics $h(n)$

### 4.1.3.a Nodes ( $n$ ) General form

In order to present our original heuristic function, we first should introduce the general form of the Nodes $(n)$. As mentioned previously, a Node $(n)$ represents a configuration defined by the finger locations on the object and the angular position of the object. As we are going to consider 2-D-rotations, a node is a 4 values vector: (i) the three first coordinates are the index of the contact of each finger and the fourth is the index of the angular position. By convention, (i) if a finger is not used his index is null and (ii) the angular position index " 1 " is the initial configuration.

Consequently, a node $(n)$ is described by:

$$
n=\left[\begin{array}{lll}
i_{F 1} & j_{F 2} & k_{F 3} \tag{4.3}
\end{array} l_{\theta}\right],
$$

where $i_{F 1}, j_{F 2}, k_{F 3}$ are the index of location of the finger $1,2,3$ respectively; $l_{\theta}$ is the index of the angular position.

Let us consider the node [15 2506 ], it represents a 2 -fingers grasp using finger 1 and 2 respectively placed at the location 15 and 25 on the object, and an angular position $\theta$ verifying:

$$
\begin{equation*}
\theta=\left(l_{\theta}-1\right) \cdot \Delta \theta=5 \cdot \Delta \theta . \tag{4.4}
\end{equation*}
$$

### 4.1.3.b Heuristic General form

In search algorithms, the heuristic function $h(n)$ estimates the cost from the current node $n=\left[i_{F 1} j_{F 2} k_{F 3} l_{\theta}\right]$ to the goal node $n_{g}=\left[i_{F 1 g} j_{F 2 g} k_{F 3 g} l_{\theta g}\right]$. The best heuristic function is the one that approaches the minimal cost without overestimating it. Indeed, in order to guarantee the convergence of the $A^{*}$ algorithm, the heuristic must underestimate the remaining cost. At the current node $n$, two operations are possible, either the rolling operation or the reconfiguration operation. Since the heuristic estimates the cost from $n$ to $n_{g}$, it is necessary to consider these two operations while developing the heuristic function. To develop the heuristic function, we take into account all the parameters of a node (number of fingers being used, contact points on object, and angular position of object) as:

$$
\begin{equation*}
h(n)=2 \cdot a b s\left(l_{\theta}-l_{\theta g}\right) \cdot|\Delta \theta|+t_{r}\left(\left\{\kappa_{i}, h_{j}, \kappa_{k}\right\}\right) \cdot g_{r} . \tag{4.5}
\end{equation*}
$$

This heuristic function combines the two possible operations (rolling and reconfiguration) when estimating the cost required from current node $n$ to goal node $n_{g}$. The first part i.e. $2 \cdot a b s\left(l_{\theta}-l_{\theta g}\right) \cdot|\Delta \theta|$ represents the rolling operation, and the second part i.e. $t_{r}\left(\left\{\xi_{i}, \zeta_{j}, h_{k}\right\}\right) \cdot g_{r}$ represents the reconfiguration operation.

In Equation (4.5), 2 represents the minimum number of fingers with which a rolling operation can be performed, $a b s\left(l_{\theta}-l_{\theta g}\right)$ is the difference between current orientation and goal orientation of object, $\Delta \theta$ is the pre-defined rotational step, and $t_{r}$ is the function of the non-ordered set $\left\{\hbar_{i}, \hbar_{j}, \hbar_{k}\right\}$ which will provide the total number of estimated reconfigurations (addition/removal operation).

### 4.1.3.c Principle of the Estimated reconfiguration

Each element i.e., $\kappa_{i}, \kappa_{j}$ and $\kappa_{k}$ provides one of the four conditions in set $\mathcal{H}=$ $\{n u, a r, d p, i p\}$ based on which fingers are used corresponding to $i_{F 1}, j_{F 2}, k_{F 3}$ indexes of $n$ and $n_{g}$ respectively.

The conditional output of $\kappa_{i}, \kappa_{j}$, or $\kappa_{k}$ is:

- " $n u$ " (not used), when the same finger is not used in current node and goal node. Figure 4.4 illustrates an example, where a rolling operation is performed from $n=\left[\begin{array}{lll}10 & 20 & 1\end{array}\right]$ to $n_{g}=\left[\begin{array}{lll}15 & 25 & 6\end{array}\right]$. We can see in Figure 4.4, that the rolling operation is performed using finger 1 and finger 2 , and finger 3 is not utilized; in this case, the status of finger 3 i.e. output of $\xi_{k}$ is " $n u$ ".


Figure 4.4 - Representation of " $n u$ " case: (a)-(b) rotation of object only with finger 1 and finger 2 . In such a case finger 3 not used in both configurations obtained a status $\kappa_{k}=" n u$ "

- "ar" (addition/removal), when the current and goal nodes do not use the same finger. Figure 4.5 corresponds to such a case, where a rotation operation is performed from $n=\left[\begin{array}{lll}10 & 20 & 1\end{array}\right]$ to $n_{g}=\left[\begin{array}{lll}150256\end{array}\right]$. Note that, the rotation
is starting with finger 1 and finger 2 , however it is ending with finger 1 and finger 3. Thus, it can be concluded that finger 2 will be removed during the manipulation process, and finger 3 will be added. Therefore, the status of finger 2 and finger 3 i.e. the output of $\boldsymbol{K}_{j}$ and $\boldsymbol{K}_{k}$ is "ar" respectively.

(a)

(b)

Figure 4.5 - Representation of "ar" case: (a) rotation starting with finger 1 and finger 2, (b) rotation ending with finger 1 and finger 3. In such a case finger 2 and 3 used in only one of the two configurations obtained a status $\kappa_{j}=\kappa_{k}=" a r "$.

- "dp" (direct path), when the same finger is being used in both $n$ and $n_{g}$, and can directly reach from $n$ to $n_{g}$, by rolling only. Figure 4.6a-b illustrate such a case.
- "ip" (indirect path), when the same finger is being used in $n$ and $n_{g}$, but can not directly reach from $n$ to $n_{g}$ by rolling only, as illustrated in Figure 4.6c-d.

The determination of the two last states " $d p$ " and " $i p$ " requires checking if the finger can directly go from $n$ to $n_{g}$ by rolling only. In that way, we compute:

$$
\begin{align*}
& p_{i}=a b s\left[\begin{array}{lll}
\left(i_{F 1}-i_{F 1 g}\right) & -\left(l_{\theta g}-l_{\theta}\right) & ]
\end{array}\right] \\
& p_{j}=a b s\left[\begin{array}{lll}
\left(j_{F 2}-j_{F 2 g}\right) & -\left(l_{\theta g}-l_{\theta}\right)
\end{array}\right],  \tag{4.6}\\
& p_{k}=a b s[\underbrace{\left(k_{F 3}-k_{F 3 g}\right)}_{\text {finger index distance }}-\underbrace{\left(l_{\theta g}-l_{\theta}\right)}_{\text {angle index distance }}] .
\end{align*}
$$


(a)

(c)

Final position reached by rolling only


Final position NOT reached by rolling only


Figure 4.6 - Representation of " $d p$ " and " $i p$ " case (for finger 1): (a-b) starting from configuration (a), the final configuration (b) is reached by rolling only ("dp" case). (c-d) starting from configuration (c), the position of finger 1 after rolling is different from the final required location, the final configuration (d) is thus not reached by rolling only ("ip" case).

When $p_{i}=0, p_{j}=0$, or $p_{k}=0$, it indicates respectively that the Finger-1, 2 or 3 can move from current node to goal node directly by rolling. In such a case, the output of $\xi_{i}, \zeta_{j}$ or $\xi_{k}$ is respectively " $d p$ " (direct path). Otherwise, if the value is $p_{i} \neq 0, p_{j} \neq 0$, or $p_{k} \neq 0$ it will need a reconfiguration; thus, the output of $\kappa_{i}, h_{j}$ or $\kappa_{k}$ will be "ip" (indirect path).

In other words, as the finger is rolling on the object during its rotation, at every rotation step $\Delta \theta$, the index of rotation increase by 1 and the index of finger contact point decrease by 1 . The comparison between the finger index distance (between current and final nodes) and the angular index distance (see (4.6)) enables to define if both the finger final position and the angular final position will be reached synchronously.

### 4.1.3.d Calculation of Estimated Reconfigurations $t_{r}$

To estimate the total number of reconfigurations, we compute the minimum reconfiguration operations $t_{r}$ that are required to move from current node $(n)$ to goal node $\left(n_{g}\right)$. Figure 4.7 describes the minimal required reconfiguration following an example. The example illustrates the worst case where the initial configuration uses the Finger 1 and 2 already used in the final configuration. The first step considered is a rotation which enables to reach the configuration (a). Starting from these points, the minimum following reconfigurations are required to reach the final configuration (see Figure 4.7) :

- (b) adding the Finger 3 somewhere;
- (c) remove one of the Fingers (e.g. Finger 1);
- (d) place Finger 1 on its final position;
- (e) remove Finger 2;
- (f) place Finger 2 on its final position;
- (g) remove Finger 3 to reach the final configuration.

Following the general principle described in the example on figure 4.7, the Table 4.1 defines this value $t_{r}$ for every possible case considering a 2 fingers final grasp.

The examples described in Table 4.1 enable to illustrate the general principle. Let us take the first data (a), i.e., $n=\left[\begin{array}{lll}1163 & 0 & 1\end{array}\right]$, and $n_{g}=\left[\begin{array}{lll}1 & 38 & 0\end{array}\right]$; for both used fingers ( 1 and 2), the output is " $i p$ ", and the third finger is not used in both current and final nodes (" $n u$ " case). We are going to show that this case requires at least 6 reconfiguration operations $\left(t_{r}=6\right)$ as:

- First, we have to add an unused finger, i.e., finger-3 to any admissible node, which corresponds to case (b);

Table 4.1 - Estimated number of reconfiguration $t_{r}$ in function of the non-ordered set $\left\{\hbar_{i}, \hbar_{j}, \kappa_{k}\right\}$ for a path $n \longrightarrow n_{g}$, considering a 2-fingered grasp $n_{g}$ and some examples considering the final node $n_{g}=\left[\begin{array}{lll}1 & 38 & 0\end{array}\right]$.

| $t_{r}$ Calculation Table |  |  | Examples: $n \longrightarrow n_{g}=\left[\begin{array}{lllll}138 & 5\end{array}\right]$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\left\{h_{i}, h_{j}, h_{k}\right\}$ | $t_{r}$ | $F_{\text {used }}$ | $n$ |  | $h_{i}$ | $h_{j}$ | $h_{k}$ | Ref. |
| \{ip,ip,nu\} | 6 | 2 | 11630 | 1 | ip | ip | nu | (a) |
| \{ip,ip,ar\} | 5 | 3 | 116325 | 1 | ip | $i p$ | $a r$ | (b) |
| \{ip,ar,ar\} | 4 | 2 | 06325 | 1 | $i p$ | $a r$ | $a r$ | ( $\mathrm{c}_{1}$ ) |
|  |  |  | 11025 | 1 | $a r$ | ip | ar | ( $\mathrm{c}_{2}$ ) |
| \{dp,ip,nu\} | 4 | 2 | 5630 | 1 | $d p$ | ip | nu | (c3) |
| \{dp,ip,ar\} | 3 | 3 | 56325 | 1 | $d p$ | $i p$ | $a r$ | (d) |
| \{dp,ar,ar\} | 2 | 2 | 5025 | 1 | $d p$ | $a r$ | $a r$ | (e) |
| \{dp,dp,ar\} | 1 | 3 | 54225 | 1 | $d p$ | $d p$ | $a r$ | (f) |
| $\{d p, d p, n u\}$ | 0 | 2 | 5420 | 1 | $d p$ | $d p$ | nu | (g) |




Figure 4.7 - Representation of estimated steps for reconfiguration operations: (top view) desired orientation of the object and finger positions, (a) some initial rotation of the object, (b) addition of $3^{\text {rd }}$ finger, (c) removal of finger-1, (d) placement of finger- 1 at its desired position, (e) removal of finger-2, (f) placement of finger-2 at its desired position, (g) removal of $3^{\text {rd }}$ finger which was added to carry out the steps from (d)/(b)-(g).

- Then, remove finger- 1 or finger- 2 , respectively, corresponding to the case $\left(c_{1}\right)$ or $\left(c_{2}\right)$. We consider case $\left(c_{1}\right)$ in the following;
- Then, place finger- 1 in such a way that a direct path is possible with this finger, corresponding to case (d) with $\kappa_{i}=" d p "$;
- Then, remove finger-2, which corresponds to case (e);
- Place finger-2 in such a way a direct path is possible with this finger, corresponding to case (f) having $\kappa_{j}=" d p "$;
- At the end, remove finger-3 leading to the case (g) where the final node $n_{g}$ can be reached by rolling without reconfiguration.

This example illustrates the number of reconfigurations required for most of the cases described in Table 4.1. The last case is $\left(\mathrm{c}_{3}\right)$, where the first step is to add an unused finger, i.e., Finger-3 to any admissible node, leading to case (d) already mentioned above.

For all the possible nodes $(n)$, the Table 4.1 enables to estimate the minimum number of reconfigurations $t_{r}$ required from $n$ to $n_{g}$. The cost function and heuristic function are thus completely defined.

We have defined both the cost function and the heuristic function to be used by the $A^{*}$ algorithm to find an optimal path in the graph (G) described in the previous chapter. The obtained trajectories will be defined in the next sections.

### 4.2 Analysis of Proposed Methodology

The proposed methodology presented in the previous sections has been simulated and implemented to generate the finger trajectories for three objects with different curvatures in 3D space, i.e., Ellipsoid, Convex shaped object and Concave shaped object provided in Figure 4.8, using 3 fingers with $9 \mu \mathrm{~m}$ diameter spherical tips. For the simulations, we have considered the physical properties of Silicon
for all the fingers and the objects, a pull-off force of $1.5 \mu \mathrm{~N}$ [215], and a maximal grasping force of $30 \mu \mathrm{~N}$. As described in Section 3.1, we propose to decompose the movement in 3 successive rotations as: $R\left(z, \theta_{1}\right)$ over XYplane $\mathcal{P}_{1}, R\left(y, \theta_{2}\right)$ over X Zplane $\mathcal{P}_{2}$, and $R\left(z, \theta_{3}\right)$ over XYplane $\mathcal{P}_{1}$, respectively. The sampling of the objects along $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ has been done using Equation (3.7) (page 68) considering $\Delta \theta=20^{\circ}$.

The principles will be illustrated using the ellipsoid geometry and the analysis of the performances will be done on the three geometry.


Figure 4.8 - CAD model of the ellipsoid used to illustrate the finger path planning.

### 4.2.1 Planar Fingers' Trajectory Generation

On-contact finger trajectories to manipulate the object is represented by a sequence of nodes (searched in the graph $G$ ). It contains all the operation, initial grasping, rolling, and reconfiguration.

The table, in the centre of figure 4.9, provides an example of fingers' trajectory (i.e. sequence of nodes) for the manipulation of an object. In this example, the search algorithm $\left(A^{*}\right)$ is only considering a goal node $n_{g}=[14404]$, which shows that the fingers used in the goal orientation should be Finger-1 and Finger-2, and a desired orientation should be $(4-1) \cdot \Delta \theta$. Since, the algorithm is only provided with the goal node, thus the algorithm chooses the initial node itself from the graph for an optimal path.


Figure 4.9 - General representation of on-contact trajectory.

Figure 4.9, contains a sequence of 4 nodes from the initial orientation to desired orientation. We can see that, in the whole sequence, Finger-3 is not used, and the orientation index $\left(l_{\theta}\right)$ is continuous. Thus, the operation performed to manipulate the object from its initial orientation to the desired orientation is pure rolling.

### 4.2.1.a Fingers' Trajectories for $1^{\text {st }}$ Rotation

As described in Chapter 3, the first rotation must end at the intersecting points $I$ and $J$ of two lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$. Thus, we have the goal node $n_{g}$ for the first rotation, but we do not define the initial node $n_{i}$ for it. The initial node $n_{i}$ is chosen from the available nodes of initial reconfiguration maps $M^{\text {init }}$, with the minimum value of heuristic $h(n)$ as the cost $g\left(n_{i}\right)$ is 0 .

Moreover, we are using a maximum of 3 fingers for the manipulation of microobjects. Therefore, there are six possible ways to end the first rotation, representing the ${ }^{3} P_{2}=6$ possibilities of placing 3 fingers on the two intersecting points $I$ and $J$. As, the initial cost $g\left(n_{i}\right)=0$, thus all the 6 possible ways will yield the same total cost $(f(n))$ for the desired goal. Thus, to simplify the manipulation process, we chose always end the first rotation with Finger-1 and Finger-2.

Let suppose, we want to rotate an ellipsoid object for $80^{\circ}$. Keeping the first constraint of manipulation "the first rotation should end at the intersecting points I and $J$ of lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ " in mind, and the desired orientation of the object, we define the goal node $n_{g}$. As discussed earlier that we chose to end the rotation with Finger-1 and Finger-2. Thus, we enforce the position of Finger-1 and Finger-2, when defining the goal node. For the ellipsoid object, the indexes of intersecting points $I$ and $J$ are 1 and, 38 respectively, and Finger- 3 is not used at the final orientation, thus we define it as 0 . Now, we have the three parameters (i.e $i_{F_{1}}, j_{F_{2}}$, and $k_{F_{3}}$ ) for the goal node.

As for the fourth parameter, we know the total rotation for which the object will be manipulated, from this rotation we directly define the orientation index $l_{\theta}$ as:

$$
\begin{equation*}
l_{\theta}=\left|\frac{\text { Desired Orientation }}{\text { Rotational Step }}\right|+1 . \tag{4.7}
\end{equation*}
$$

For this example, the desired orientation is $80^{\circ}$, and the rotational step is $20^{\circ}$, thus the orientation index $\left(l_{\theta}\right)$ is 5 .

Now, the goal node $n_{g}$ is $[13805]$. Since, there is no initial node $n_{i}$ defined, the algorithm will choose a node itself from the nodes of initial orientation, which provides an optimal trajectory for the goal node. Table 4.2 provides a detailed trajectory, which contains the node sequence, value of path cost $(g(n))$, value of heuristic function $(h(n))$, and the total cost $(f(n))$.

Table 4.2 - Fingers' Trajectories for the first rotation of the ellipsoid object in the presence of adhesion.

| Sequence of Nodes |  |  |  | Parameters of $A^{*}$ algorithm |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $i_{F 1}$ | $j_{F 2}$ | $k_{F 3}$ | $l_{\theta}$ | $g(n)$ | $h(n)$ | $t_{r}$ | $f(n)$ |
| 5 | 42 | 0 | 1 | 0 | 160 | 0 | 160 |
| 4 | 41 | 0 | 2 | 40 | 120 | 0 | 160 |
| 3 | 40 | 0 | 3 | 80 | 80 | 0 | 160 |
| 2 | 39 | 0 | 4 | 120 | 40 | 0 | 160 |
| 1 | 38 | 0 | 5 | 160 | 0 | 0 | 160 |

The left side of Table 4.2 provides the sequence of nodes for the rotation, and the right side provides the corresponding details of $A^{*}$ algorithm. The algorithm has chosen the initial node $n_{i}$ as [54201]. Since, the rotation is staring from the initial orientation, thus the value of $l_{\theta}$ is 1 . We see that, the desired rotation is performed by rolling only, and there is no reconfiguration operation, as in the whole sequence of nodes the value of contact index for Finger-3 $\left(k_{F 3}\right)$ is 0 , and there is no repetition of orientation index $\left(l_{\theta}\right)$ in the trajectory.

At the initial node, we see that the value of $g(n)$ is 0 , as it is the grasping point from where the rotation will start, and the algorithm estimates the value of $h(n)$ as 160 , making the total cost $f(n)$ equal to 160 . Indeed, this case is the case (g) in

Table 4.1 where both grasping finger can reached the final goal by direct rolling. It means that the number of estimated reconfiguration $t_{r}$ is null, and the heuristic function is only a function of the required rotation. In the second step, the node changes from [54201] to [44102], which indicated that a rolling operation has be performed, and here we see that the value of $g(n)$ has changed from 0 to 40 , this increase in the cost $g(n)$ is the result of rolling operation, and the value of heuristic $(h(n))$ has decreased from 160 to 120 . In such a case the heuristic $(h(n))$ perfectly estimates the future cost. The next three operations are performed in the same way, and we see that the total cost $(f(n))$ remains the same. The reason behind such behaviour is that only the rolling operation is being performed, which means there exists a direct path through which we can achieve the desired manipulation. Figure 4.10 represents this manipulation operation, i.e. the first rotation of an ellipsoid object along $z_{0}$.


Figure 4.10 - Representation of first rotation's sequence: (a) grasping of the object, (b)-(e) rotation of $80^{\circ}$, where rotational step $(\Delta \theta)$ is $20^{\circ}$.

### 4.2.1.b Fingers' Trajectories for $2^{\text {nd }}$ Rotation

The second rotation is the intermediate rotation, and it is the most affected by the manipulation constraints. The second rotation constraint "the rotation should start from and end at the intersecting points I and J of Lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ ", makes it very challenging to carry out the manipulation as it requires one or more reconfigurations. It differs from the first rotation, because we also need to specify the starting node along with the goal node for the second rotation. The contact point indexes $i_{F 1}, j_{F 2}, k_{F 3}$ of the starting node for the second rotation will always be the same as the node on which the first rotation ended, and the orientation index will start from 1. For instance, in the case of ellipsoid object the goal node for first rotation is $n_{g}=[13805]$, now the contact point indexes for the initial node $n_{i}$ of second rotation will remain the same, and the orientation index $l_{\theta}$ will be 1 thus providing the initial node $n_{i}=[13801]$ for second rotation.

Once the initial node is defined, we need to specify the goal node $n_{g}$. Since, it is the intermediate rotation, and at the end of rotation the fingers must make the contact with intersecting points $I$ and $J$, and after that the third rotation will start. Thus, we finish the second rotation only with two fingers, and the goal node should only contain two contact point indexes. Since, there are a total of three fingers, and the rotation should finish with only two fingers, therefore there are six possible options due to fingers' permutation $\left({ }^{3} P_{2}=6\right)$, from which a goal node $n_{g}$ can be selected. In the case of an ellipsoid object, where $I$ and $J$ are 1 and 38 respectively, the goal node $n_{g}$ can be one of the following 6 permutations:

$$
n_{g} \in\left\{\left[\begin{array}{llll}
1 & 0 & 38 & l_{\theta}
\end{array}\right] ;\left[\begin{array}{llll}
0 & 1 & 38 & l_{\theta}
\end{array}\right] ;\left[\begin{array}{llll}
3 & 0 & 1 & l_{\theta}
\end{array}\right] ;\left[\begin{array}{lllll}
3 & 1 & 0 & l_{\theta}
\end{array}\right] ;\left[\begin{array}{lllll}
0 & 3 & 1 & l_{\theta}
\end{array}\right] ;\left[\begin{array}{llll}
1 & 38 & 0 & l_{\theta} \tag{4.8}
\end{array}\right]\right\}
$$

Since, the initial node is already specified and there are six possibilities to choose the goal node, our task is to generate the fingers' trajectories for all six permutations, and evaluate which node from these six options will yield an optimal trajectory.

To find out which node will provide an optimal trajectory, the first task is to find the number of estimated reconfigurations (defined in Table 4.1) for each possible $n_{g}$. Let us consider the example of the rotation to rotate an ellipsoid object for $220^{\circ}$, which means the orientation index $l_{\theta}=12$. We know the initial node, i.e. $n_{i}=[13801]$, and select the first option, i.e. $n_{g}=[103812]$ for goal node. We compute the set $\left\{\xi_{i} G_{j} f_{k}\right\}$ to estimate the minimum number of reconfigurations $\left(t_{r}\right)$ as:

- Finger-1 is being used in both $n_{i}$ and $n_{g}$, thus, we need to find whether

Finger-1 will access the contact point index of goal node from initial node directly through rolling or reconfiguration. Therefore, using Equation (4.6), we find that $p_{i} \neq 0$, making $\kappa_{i}=i p$.

- Finger-2 is being used in $n_{i}$, but not in $n_{g}$, thus providing the value of $\boldsymbol{K}_{j}=a r$.
- Similar to Finger-2, the status for Finger-3 (i.e. $\mathscr{F}_{k}$ ) is "ar".

Thus, the output of set $\left\{\left\{_{i} f_{j} f_{k}\right\}\right.$ is $\{i p, a r, a r\}$, and estimates the minimum number of reconfigurations to be carried out as $t_{r}=4$ (Table 4.1(c1)). Similarly, we compute the minimum number of reconfigurations for other possibilities too, and Table 4.3 provides its result.

Table 4.3 - Estimating the minimum number of reconfigurations $\left(t_{r}\right)$ for all the six permutations of second rotation.

| $n$ | $\boldsymbol{n}_{\boldsymbol{g}}$ | $\left\{h_{i}, h_{j}, h_{k}\right\}$ | $t_{r}$ | Ref. Table 4.1 |
| :---: | :---: | :---: | :---: | :---: |
| 13801 | 103812 | $\{i p, a r, a r\}$ | 4 | (c1)/(c2) |
|  | 013812 | $\{a r, i p, a r\}$ | 4 | (c1)/(c2) |
|  | 380112 | \{ip, ar, ar $\}$ | 4 | (c1)/(c2) |
|  | 3811012 | $\{i p, i p, n u\}$ | 6 | (a) |
|  | 038112 | $\{a r, i p, i p\}$ | 5 | (b) |
|  | 138012 | $\{i p, i p, n u\}$ | 6 | (a) |

We see that, in Table 4.3 the value of $t_{r}$ varies from 4 to 6 , and multiple possibilities has the same value of $t_{r}$.

## Intuitive Perception

Our intuitive perception here is that, the three possibilities in Table 4.3 estimating the minimum number of reconfigurations $t_{r}=4$, will provide the optimal trajectories. But is it, as our intuition tells us?

To see whether our perception is true or not, we generate the trajectories for all the six possibilities to finish the second rotation, and compare the results in Table 4.4, which includes the total cost of the generated trajectories, executed reconfigurations and time taken to generate the trajectories.

Table 4.4 - Comparison of cost and time computations for Ellipsoid's second rotation. $\ddagger$ represents the time to generate path. $t_{r}^{e x e}$ is the number of reconfiguration in the optimal path.

| $n$ | $n_{g}$ | $\left\{h_{i}, h_{j}, h_{k}\right\}$ | $t_{r}$ | $t_{r}^{\text {exec }}$ | $f(n)$ | Time (s) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 13801 | $1 \begin{array}{ll}103812\end{array}$ | \{ip, ar, ar $\}$ | 4 | 10 | 2240 | 10 |
|  | $\begin{array}{llll}0 & 1 & 3812\end{array}$ | \{ar, ip, ar $\}$ | 4 | 10 | 2240 | 50 |
|  | 380112 | \{ip, ar, ar $\}$ | 4 | 10 | 2240 | 78 |
|  | $\begin{array}{lllll}38 & 1 & 0 & 12\end{array}$ | $\{i p, i p, n u\}$ | 6 | 8 | 1880 | 3 |
|  | 038112 | \{ar, ip, ip $\}$ | 5 | 10 | 2240 | 48 |
|  | 138012 | \{ip, ip, nu\} | 6 | 12 | 2600 | 857 |

In Table 4.4, we can see that the number of executed reconfigurations during the manipulation process is higher than the estimated reconfigurations. It illustrates the fact the heuristic does not overestimate the remaining cost. The executed reconfigurations $\left(t_{r}^{\text {exec }}\right)$ and the total cost $(f(n))$, for $1^{\text {st }}, 2^{\text {nd }}, 3^{\text {rd }}$ and $5^{\text {th }}$ permutations are the same, despite the different number of estimated reconfigurations for the $5^{t h}$ permutation. While, the number of executed reconfigurations $\left(t_{r}^{e x e c}\right)$ and total cost $(f(n))$, for $4^{\text {th }}$ and $6^{\text {th }}$ permutations differs, despite the same number of estimated reconfigurations $\left(t_{r}\right)$. We see that the $4^{t h}$ permutation provides the optimal trajectory, having the lowest number of executed reconfigurations ( $t_{r}^{\text {exec }}$ ) i.e. 8 , and lower total cost $(f(n))$ i.e. 1880 . The time to generate the trajectories varies for each permutation, because of the different numbers of traversed nodes within the graph. Thus, the node that provides the optimal trajectory for sec-
ond rotation to manipulate the ellipsoid object for $220^{\circ}$ is the $4^{\text {th }}$ permutation, i.e. $n_{g}=[381012]$. Table 4.5 represents the complete optimal trajectory from $n_{i}=\left[\begin{array}{llll}1 & 3 & 0 & 1\end{array}\right]$ to $n_{g}=\left[\begin{array}{lll}3 & 1 & 0\end{array} 12\right]$.

In Table 4.5, we can see that, the estimated cost (i.e. heuristic) at the initial node is 1520 , but the total cost $(f(n))$ at the end of trajectory i.e. 1880 is higher than the initial predicted/estimated cost. The reason behind this increased amount in total cost is that, the number of executed reconfigurations is higher than the number of estimated reconfigurations. From $1^{\text {st }}$ to $10^{\text {th }}$ iteration, the rolling operation is performed, and then from $11^{\text {th }}$ to $16^{\text {th }}$ iteration, six reconfiguration operations are performed, after that one operation of rolling, and then three reconfiguration operations.

As mentioned, the second rotation is the most challenging to carry out because of the constraints about the initial and final positions of the fingers on the object. Figure 4.11 represents some steps involved in the second rotation, where the current node $n=\left[\begin{array}{lll}1 & 38 & 0\end{array}\right]$ (Figure 4.11a), and goal node $n_{g}=[381012]$ (Figure 4.11i). It means that we expect a rotation of $11 \cdot \Delta \theta$ (going from 1 to 12 in the fourth coordinates) which represents $220^{\circ}$. In the initial configuration, finger- 1 is placed on I (1 as the first coordinate of $n_{i}$ ), finger-2 is placed on J (defined by 38 as the second coordinate of $n$ ), and finger- 3 is not used (defined by 0 as the third coordinate of $n_{i}$ ). In the final configuration, finger-1 will be placed on point $J$, finger- 2 will be placed on point $I$, and finger- 3 will not be used.

Going from the initial configuration Figure 4.11a to the final configuration Figure 4.11i is performed in four major phases. The first phase is a half turn of the object, going from Figure 4.11a to Figure 4.11b, where the fingers are rolling on the object. The second phase is a sequence of finger gaiting in order to reach Figure 4.11f. In the third phase, the object reaches the final orientation Figure 4.11 g in which finger-2 rolls to its final position $I$. The last phase is a second sequence of finger gaiting to place the finger-1 on point J and remove finger-3. This sequence is highly constrained by the adhesion. Indeed, in the case of 3 fingers

Table 4.5 - Fingers' Trajectories for the second rotation of the ellipsoid object in the presence of adhesion.



Figure 4.11 - Example of a second rotation: (a) initial configuration, (b) configuration after a first object rotation of $180^{\circ}$ using finger rolling, (c) placement of finger-3, (d) moving finger-1,
(e) moving finger-2, (f) removing finger-1, (g) finger-2 on its desired place I after object rotation of $40^{\circ}$ using finger rolling (h) placement of finger-1 on its desired place J, (i) removal of finger-3.
grasping, when a finger is being removed, it pulls the object and may detach the object from the two other fingers. Concretely, only few configurations exist where a finger can be removed. This particularity of the micro-object's behaviour induces the original sequence of finger gaiting presented on Figure 4.11c-i.

Typically, on Figure 4.11d, we could expect that the finger-1 goes directly to the point $\mathrm{J}^{\prime}$, from where it could reach its final position by rolling. The algorithm makes another choice, because if finger- 1 is directly placed on $\mathrm{J}^{\prime}$, then finger- 2 will not be able to be removed in the next step, i.e., Figure 4.11e.

At the end, because of the constraint of the finger removing, the final configuration is reached after 4 finger-placements and 4 finger-removals, a total of 8 reconfiguration operations. As per the estimated reconfigurations table (Table 4.1), the heuristic function expects to have only 6 reconfigurational operations ( $\kappa_{i}$ is " $i p$ ", $\zeta_{j}$ is " $i p$ ", and $\epsilon_{k}$ is " $n u$ "). However, the optimal path contains 8 operations to carry out this second rotation.

### 4.2.1.c Fingers' Trajectories for $3^{r d}$ Rotation

The third rotation is the last one to complete the required manipulation of an object. It is constrained only for the starting positions of fingers, as "The rotation should start from the intersecting points $I$ and $J$ of lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ ". We notice that the constraint of the third rotation is a complete opposite of the first rotation's constraint. Similar to the second rotation, the contact point indexes of the three fingers for the third rotation's initial node is taken from the second rotation's goal node, and the orientation index will start from 1. Thus, for the ellipsoid object, the third rotation's initial node will be $n_{i}=[38101]$, and instead of a complete goal node i.e. in the form of $n_{g}=\left[i_{F 1 g} j_{F 2 g} k_{F 3 g} l_{\theta g}\right]$, we only define the desired orientation because it is the final rotation and the fingers can make a contact on any feasible equilibrium grasping points. Thus, the heuristic function for third rotation only uses the rolling part (minimum estimated cost to reach the desired orientation of the object), i.e.

$$
h^{\prime}(n)=2 \cdot a b s\left(l_{\theta}-l_{\theta g}\right) \cdot|\Delta \theta| .
$$

Let us consider manipulating the ellipsoid object for $100^{\circ}$. Since, the initial node is already defined, and instead of defining a complete goal node, we only define the desired orientation angle i.e. $l_{\theta g}=6$ (using Equation (4.7)). The algorithm finds an optimal trajectory from the initial node to the desired orientation. Table 4.6 provides an optimal trajectory for this case, and Figure 4.12 represents the

Table 4.6 - Fingers' Trajectories for the third rotation of the ellipsoid object in the presence of adhesion.

| Sequence of Nodes |  |  |  | Parameters of $A^{*}$ algorithm |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $i_{F_{1}}$ | $j_{F_{2}}$ | $k_{F_{3}}$ | $l_{\theta}$ | $g(n)$ | $h^{\prime}(n)$ | $f(n)$ |
| 38 | 1 | 0 | 1 | 0 | 200 | 200 |
| 37 | 74 | 0 | 2 | 40 | 160 | 200 |
| 36 | 73 | 0 | 3 | 80 | 120 | 200 |
| 35 | 72 | 0 | 4 | 120 | 80 | 200 |
| 34 | 71 | 0 | 5 | 160 | 40 | 200 |
| 33 | 70 | 0 | 6 | 200 | 0 | 200 |

steps to carry out the third rotation for an ellipsoid object. In Table 4.6, it can be seen that by only providing the desired orientation, the algorithm choose an optimal trajectory.

### 4.2.2 Complete Fingers' Trajectory in 3-D

Our goal is to achieve 3D manipulation of a micro-object. To manipulate a micro-object in 3D, we proposed to decompose the 3D rotation into three 2-D rotations and then combine them through Euler's Angles as described in Section 3.1 All three individual rotations have been carried out in their object frame $\mathcal{O}$; thus, for all the three individual rotations the coordinates have to be converted in the world frame $\mathcal{W}$ in order to build the complete fingers' trajectory. As an example, the transformation matrix from $3^{\text {rd }}$ rotation to world frame $\mathcal{W}$ i.e., ${ }^{\mathcal{W}} T_{3}$ is

$$
\begin{equation*}
{ }^{\mathcal{W}} T_{3}={ }^{\mathcal{W}} T_{\mathcal{O}} \cdot{ }^{\mathcal{O}} T_{1} \cdot{ }^{1} T_{2} \cdot{ }^{2} T_{3} . \tag{4.9}
\end{equation*}
$$

Figure 4.13 shows the complete 3D rotation of an ellipsoid object. Figure 4.13a,b represent the initial grasp of the object by finger-1 and finger-2, and its rotation on the object's $z$-axis of $80^{\circ}$ placing the finger- 1 and finger- 2 at intersecting points of $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$. Figure 4.13 c represents the end of the second rotation of $220^{\circ}$ on the object's $y$-axis initializing from desired fingers grasp (intersecting points of $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ ) encompassing all the reconfigurational steps (some steps represented


Figure 4.12 - Representation of third rotation's sequence in object's frame (2-D view): (a) grasping of the object, (b)-(f) rotation of $1000^{\circ}$, where rotational step $(\Delta \theta)$ is $20^{\circ}$.
in Figure 4.11) to reach another desired fingers grasp with finger-1 and finger-2. Figure 4.13 d represents the end of the last rotation of $100^{\circ}$ on the object's $z$-axis starting from desired finger grasp. It is to be noted that in this example (ellipsoid object), the first and third rotations are executed directly by rolling (without any reconfiguration).


Figure 4.13 - Representation of combined rotations: (a) initialization, (b) first rotation, (c) second rotation, (d) third rotation. The first and third rotations are obtained using rolling only without finger gaiting; the trajectory of the second rotation is detailed in Figure 4.11.

### 4.3 Performance Analysis

In this section, we are analysing the performance of our methodology. The analysis is based on the parameters like friction coefficient, adhesion forces, that affect the manipulation process. We will also analyse the computation time.

### 4.3.1 Impact of Friction and Adhesion

The Friction and Adhesion between Object and Finger plays an important role during the manipulation process. These two parameters are modeled by the friction cone as studied in Section 3.2, and the object's equilibrium also depends on these parameters. Then through the equilibrium, we generate the Maps/Graph to plan the fingers' trajectories. Thus, these parameters are analysed to study their impact on the equilibrium and consequently on Maps/Graph. The impact is analysed by varying the value of friction coefficient for two cases: (i) when adhesion is taken into account for the manipulation purpose, and (ii) when adhesion forces are ignored.

Table 4.7 represents the impact of friction coefficient on the grasp stability (no. of nodes) when adhesion is considered and when it is ignored. The contact points are sampled on the lines $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$ curves that represent the intersection of the object illustrated in Figure 4.8 (page 101) with the two considered rotation paths. The other parameters (finger radius, adhesion forces, and grasping forces) are constant. We see that in the presence of adhesion forces, the number of nodes generated are the same for different values of friction coefficient. However, in the absence of adhesion forces, the friction coefficient plays an important role in the stability. Indeed, the higher the friction coefficient, the higher the grasping possibilities.

As a conclusion, taking into account the adhesion in microscale induces a graph $G$ whose size is almost independent of the friction coefficient but whose size is significantly larger than without adhesion.

Table 4.7 - Impact of friction coefficient ( $\mu$ : 0.1-0.5) on the number of admissible stable grasps (no. of nodes).

| Object |  | Number of Nodes (in Millions) |  |  |  | Ratio: <br> nwoa/nwa |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | With Adhesion ( $n w a$ ) | Without Adhesion (nwoa) |  |  |  |  |  |
|  |  | $\boldsymbol{\mu} \in[0.1 ; 0.5]$ | 0.1 | 0.3 | 0.5 | 0.1 | 0.3 | 0.5 |
| Ellipsoid | $\mathcal{L}_{1} ; \mathcal{L}_{2}$ | 3.373 | 0.6325 | 1.527 | 2.020 | 19\% | 45\% | 62\% |
| Convex | $\mathcal{L}_{1}$ | 40.65 | 12.35 | 21.14 | 26.32 | 30\% | 52\% | 65\% |
| Concave | $\mathcal{L}_{1}$ | 134.4 | 16.96 | 31.25 | 43.68 | 13\% | 23\% | $33 \%$ |
| Convex <br> Concave | $\mathcal{L}_{2}$ | 42.72 | 8.409 | 18.0 | 25.97 | 20\% | 42\% | 61\% |

### 4.3.2 Computation Time

The last performance analyzed in this paper is the computation time which is one way to evaluate the relevance of the proposed heuristic function. The current results were simulated using MATLAB ${ }^{\circledR}$ with core programming, where the specifics of systems are: Intel Core i7-9750H ( 6 core CPU), 24-GB RAM.

Table 4.8 presents the computation time for three examples using the three objects' geometries described in Figure 4.8 (page 101) and considering both cases with or without adhesion, and a friction coefficient of 0.3 . The ellipsoid case shows an example where the required rotations can be reached with adhesion and cannot be reached without adhesion. In such a case, the friction coefficient 0.3 is not sufficiently large to provide a sufficient number of stable grasps to connect the initial node and final node in the $\operatorname{Graph}(G)$. It means that it is not physically possible to find a succession of stable grasps to perform the rotations. In the two other cases, the total computation times of both cases of adhesion have a similar order of magnitude ( 5 to 10.5 s ). This example describes a global trend regarding the impact of adhesion on the number of reconfigurations. As presented in the two last examples, in most of the cases, the number of reconfigurations is higher without
adhesion than with adhesion. Indeed, without adhesion, the reachable rotation with a grasping is limited by the friction cone and possible collision between fingers, when with adhesion the rotation is only limited by the second constraint.

Please note that the computation time is also impacted by the sampling strategy defined by the parameter $\Delta \theta$. A smaller $\Delta \theta$ will enable to consider more values of rotations but will increase the number of Nodes and thus the computation time.
Table 4.8 - Comparison of the computation time to generate the finger trajectories for the objects presented in Figure 4.8; where $\theta_{i}$ represents the $i^{t h}$ rotation to be carried out for $\theta^{\circ}$, and "NPA" represents that No Path Available.

| Object and Rotations$\theta_{1}, \theta_{2}, \theta_{3}(\mathrm{deg} .)$ |  | With Adhesion |  |  |  | Without Adhesion |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $t_{r}^{e x e}$ | Time (s) | Nodes |  | $t_{r}^{e x e}$ | Time (s) | Nodes |  |
|  |  | To Be Visi. |  | Visited | To Be Visi. |  |  | Visited |
| Ellipsoid | 80 |  | 0 | 0.38 | 12474 | 5 | NPA | 34207 | 654859 | 654859 |
|  | 220 | 8 | 1.1 | 4291 | 1202 | NPA | 0.09 | 164 | 164 |
|  | 100 | 0 | 0.01 | 206 | 6 | NPA | 0.08 | 164 | 164 |
| Convex | 60 | 0 | 4.96 | 41829 | 4 | 0 | 0.13 | 2661 | 4 |
|  | 80 | 6 | 0.22 | 1469 | 25 | 8 | 8.80 | 30253 | 1211 |
|  | 40 | 0 | 0.17 | 2246 | 106 | 2 | 0.17 | 2123 | 121 |
| Concave | 100 | 0 | 7.13 | 60254 | 6 | 2 | 0.29 | 3836 | 25 |
|  | 60 | 4 | 2.85 | 5586 | 101 | 8 | 6.62 | 25873 | 1122 |
|  | 20 | 0 | 0.27 | 3359 | 166 | 2 | 0.12 | 1046 | 162 |

### 4.4 Discussion and Chapter Conclusion

### 4.4.1 Discussion

In the simulations of "with adhesion cases", we consider a constant value of pull-off force representing the force required to remove a finger from the object. Concretely, this force is highly dependent on the surface properties of both the object and the finger (local oxidation, local roughness, etc.) and may vary along the trajectory. We can show that until the pull-off force is significantly larger than the weight, the $\operatorname{Graph}(G)$ and thus the optimal trajectory are independent of the exact value of the pull-off force. Thus, the obtained trajectory described in this manuscript] is robust to pull-off force variation along the trajectory.

The current simulation takes into account the adhesion phenomena, the friction force, the object geometry and the collision between the fingers considered as spheres. Concretely, the fingers should be placed on supports linked to translation micro-actuators. The optimal shape of the supports in order to reduce their collisions and the impact of these potential collisions on the finger trajectories will be studied in future works.

### 4.4.2 Chapter Conclusion

In this chapter, we proposed a new method to perform finger path planning for 3D dexterous manipulation of micro-objects following the strategy introduced in Chapter 3. We proposed an algorithm to cope with the constraints to starting and/or ending the rotation with predefined finger positions on the object and to ensure the continuity of the manipulation process over three successive angles. The simulation results show that the desired 3D manipulation of micro-objects can be carried out by performing three 2-D rotations with large rotation angles. Currently, the time to compute fingers' trajectories for first and third rotations is a few seconds, while it is a few minutes for the second rotation, which is in
acceptable range for various applications. We also conclude that the presence of adhesion forces enables more feasible trajectories in contrast to the absence of adhesion forces, as the number of equilibrium grasp is higher.

## Chapter 5

## Conclusion and Perspectives

## Conclusion

The miniaturization of industrial and/or commercial devices and their components (electronic, electrical, mechanical etc.), the availability of miniature prosthetic components for medical surgery, etc., have smoothed the way for many opportunities for small-scale robotics for different applications. However, these opportunities also bring forth many challenges to be dealt with. These challenges not only include the specificities of microscale physics, but also the different technical aspects (mechanical, materialistic, electrical, etc.). One of the opportunities in microscale robotics is the automation of task (assembling, manipulating). This research focuses on the automation of manipulation task at microscale robotics. Once again, there are different areas to work on for automation of manipulation tasks (mechanical design, physical properties, perception, motion planning). This research concentrates on the motion planning.

The current state of the art is limited to normal/teleoperated manipulation of spherical micro-objects in 3D, and dexterous manipulation of micro-objects in a plane (2-D). This limits the application areas for micro-robots. Thus, the objective of this research study is to propose a method that allows dexterous manipulation of the micro-objects in 3D.

The direct extension of previous methods i.e. from 2-D to 3D postulates the exponential increase in computational complexity of motion planning. Thus, this research takes the first step to reduce the computation complexity for the manipulation of micro-objects in 3D by decomposing 3D rotations into three 2-D individual rotations. This approach induces some constraints on the manipulation process. Thus, to ensure that the manipulation of micro-objects remains in continuity, we develop the motion planner that takes into account not only the specificities of microscale but also all the manipulation constraints induced by the decomposition of 3D rotations.

The following paragraphs summarize the contributions of each chapter.

The first chapter provided a general context of robotic manipulation, as well as the details for the distribution of work throughout the remaining chapters.

In the second chapter, we have thoroughly studied the preceding bibliographical work on micro-manipulation, micro-assembly, and dexterous manipulation at macro-scale. From this literature study, we see that, almost all manipulation techniques at microscale (both contact-less and contact-based) are developed for basic manipulation task i.e. pick and place of spherical or rectangular object, and manipulation of spherical object in 3D by teleoperation. As a result, limiting the use of micro-robots for different areas of application. Subsequently, the literature work available in the dexterous manipulation of macro-scale robotics shows that some techniques can be used for dexterous manipulation at microscale too. A combination of such technique (Rolling without sliding and Reconfiguration) was used by Seon et al. for the planar dexterous manipulation, and the obtained results demonstrate the success of dexterity at microscale. Thus, the proposed methodology for dexterous in-hand manipulation of micro-objects in 3D in the following chapter, employs these two combined techniques.

The third chapter provides an original method to manipulate the micro-objects in 3D, based on the manipulation through rolling without sliding and reconfiguration techniques for dexterous manipulation. We proposed the dexterous manipulation of micro-objects in 3D by decomposing the 3D rotations into three individual 2-D rotations. The way to decompose 3D rotations into three individual 2-D rotations is by introducing 2 orthogonal planes, that will project a 3D object (surface) into two planar objects (curves). The common point, obtained by such method, is only the two intersecting points of the projection on the 3D object. Without any doubt, this proposition induces some constraints on the manipulation process (as there is only one link between the two projections of 3D object i.e. intersecting points), and reduces the genericity of the manipulation approach. To tackle these constraints, we proposed: (i) the sampling method to generate the contact points on these two projections of object, which take into account the different parameters of manipulation system, (ii) the search algorithm $A^{*}$ that ensures the continuity of the manipulation so that the three individual 2-D rotation can be combined to form a complete 3D rotation. Moreover, we provided the background for physical modelling (grasp forces, and the contact model between object and fingers), discussed the equilibrium grasps with 2 -fingers and 3 -fingers, and detachment of one finger when 3 -fingers are in contact and its impact. We analysed through examples that the Maps generated through equilibrium grasp (rolling, finger addition, finger removal) were insufficient to generate the fingers' trajectory for manipulation purpose, thus we also discussed a way to generate the Graphs from the Maps.

Chapter four dealt with the implementation and analysis of the fingers' trajectory planning and the important parameters that impact the manipulation process. To generate the optimal fingers' trajectory, we have used the $A^{*}$ algorithm. The designed algorithm takes into account the specificities of microscale robotics (adhesion, friction), physical constraints (collisions), and the manipulation constraints
induced by the methodology. Through various examples and demonstrations, it is shown that the algorithm provides the optimal fingers' trajectories in the defined manipulation space. The various results show that leveraging the adhesive forces is advantageous to the object's equilibrium during the manipulation process, and provides more results. In contrast, the absence of adhesive forces may result in not being able to achieve the desired manipulation of the object. Moreover, in the presence of adhesive forces, the different value of friction coefficient does not impact the object's equilibrium (generate same number of nodes for different values of friction coefficient). Whereas, in the absence of adhesive forces, it affects the equilibrium, higher the value of friction coefficient larger the number of nodes. Furthermore, we saw that all the trajectories are generated within acceptable time on a general purpose system.

## Perspectives

There are numerous perspectives which can be carried out through this research. Some important perspectives are briefly described below.

## Experimental Validation:

The first step, after achieving the results through simulations, is to validate the planning methodology experimentally. As the interest of our approach is to take into consideration the adhesion between the manipulated object and the gripper finger, the experiments have to be done in microscale inducing some significant difficulties. Indeed, there are many things to be taken into account for the experimental validation, such as: the design of robotic structure having 3 fingers having a total of 9-DOF, the real-time value of different parameters like adhesion and friction, the vision system to track both the object and the finger positions. The design of the robotic structure will require to define a relative position of each finger and also finger movement range. It will be also important to have a defined adhesion
and some surface treatment (such as having sticky polymer on fingers) should be required. The vision system should be able to track the 6 -DOF position of the object despite the low depth from focus. This experimental device will enable to test the relevance of the finger trajectories provided by our methodology on a real case.

## Improvements of the Planning Strategy:

The planning strategy proposed in this manuscript enables to define finger trajectories based on several assumptions. Some assumptions could be reconsidered in order to extend the current methodology to a more realistic handling problem. The first improvement is to integrate the gravity in the force equilibrium in order to simulate the impact of gravity on the grasping equilibrium. The second improvement is to take into account the collision between the finger basis. In other words, it consists in not considering a finger as a sphere, but a sphere connected to a basis. Moreover, the range of the finger actuators could also be added as a constraint in future finger trajectory planning strategies.

## Micro-Hand Design:

In a more general way, this manuscript focused on finger trajectory planning in microscale contributes to the largest objective: the advent of full dexterous in-hand micro-manipulation. This general scientific objective induces some other challenge than the finger trajectory planning itself. One of these challenge is the design of an optimized micro-hand integrated in a small volume containing all the actuators and the fingers. In macro-scale, the robotic hand design has been based on anthropomorphic design, assuming the fact that the robot would manipulate objects already designed for humans. In microscale, the design of a robotic hand is an open scientific problem. The robotic hand can be considered as a poly-actuated system based on active material such as piezoelectric actuator and a compliant mechanism. Topological optimization could be an interesting method to design both the structure of the compliant mechanism and the actuator locations. The
methodology provided in this manuscript enabling to define finger trajectories will be helpful to define the design constraint of the micro-hand such as the finger motion range.

## Perception:

As the finger trajectory planning is planned using CAD based geometries of both object and fingers and also predefined physical data (e.g. pull-off force value), an open loop control could not be sufficient to concretely guarantee the stability of the manipulation. The closed loop control will require the implementation of perception aims of both the grasping force and the 6-DOF relative position of object and finger. The grasping force can be measured using a force sensor placed on the gripper finger. Several methods can be foreseen, such as piezoresistive force sensors directly built in silicon fingers. The 6-DOF position will require advanced vision tools in order to measure the position, despite the low depth from focus. Confocal microscopes could be considered to reach a full 6-DOF reconstruction.

## Fingers' Properties:

Robotic dexterous in-hand manipulation in microscale could be also drastically improved if the adhesion between the object and the fingers could be actively controlled. Indeed, adhesion enables to improve the grasping stability during object rotation but has also the drawback to disturb the grasping during finger removal. Having a high adhesion during in-hand rotation and a low adhesion during finger gaiting (especially reducing the adhesion of the removal finger) could the most optimal physical situation to perform in-hand operations. This active adhesion is also an open problem where several methods could be investigated, such as the active modification of the chemical properties on the surface or the modification of the geometry of the finger or both approaches.

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Titre : Développement et Analyse d'un Planificateur de Trajectoires pour la Manipulation Dextre de Micro-Objets en 3D

## Mots clefs: Micro-Manipulation, Manipulation Dextre, Planification de Trajectoire

Résumé : L’ère technique actuelle a évolué, de plus en plus de fonctions sont intégrées, et le volume des dispositifs (électroniques, électriques, mécaniques, etc.) a diminué. Cette tendance à la miniaturisation a ouvert la voie à la conception de robots de petite échelle, capables de manipuler ces petits objets pour les assembler. L'état actuel de l'art permet la manipulation planaire et dextre de micro-objets de forme arbitraire, tandis que certains objets sphériques peuvent être manipulés en 3D par téléopération, en tenant compte des forces d'adhésion qui existent à l'échelle micro et nanométrique. En raison de la limitation des techniques de manipulation à l'échelle micro, les applications sont également très limitées. Cependant, il existe de nombreux domaines d'applications où nous avons besoin de manipuler des micro-objets en 3D, comme la chirurgie invasive minimale, le montage en surface de composants électroniques, et le placement et l'assemblage de composants mécaniques. Notre objectif est donc de développer un système capable de manipuler des micro-objets en 3D en tenant compte des spécificités physiques à l'échelle microscopique. Il existe de nombreux défis scientifiques à l'échelle de la robotique, qui nécessitent une attention particulière pour leur utilisation et leurs applications appropriées. Cette recherche se concentre sur l'un de ces défis, à savoir la "planification des trajectoires des doigts" pour manipuler avec dextérité les micro-objets. L'extension directe de la méthode précédente, c'est-à-dire la manipulation dextre planaire, à la 3D impliquerait une augmentation exponentielle de la complexité informatique. Nous proposons donc une approche qui permet de planifier la manipulation dextre en 3D avec une augmentation modérée de la complexité. L'idée principale est de décomposer tout mouvement 3 D en trois rotations 2 D individuelles autour d'axes spécifiques liés à l'objet. Cette approche induit certaines contraintes sur le processus de manipulation, ainsi pour s'assurer que les trois rotations 2D individuelles peuvent être combinées pour former une rotation 3D complète, nous développons également l'algorithme de recherche qui respecte les contraintes de manipulation. Enfin, nous analysons également l'impact des paramètres physiques (coefficient d'adhérence et de friction) qui affectent le processus de manipulation. La méthode développée permet de manipuler et d'orienter l'objet (sur lequel deux plans orthogonaux peuvent être projetés) en 3D, et a été validée par des simulations.

Title : Development and Analysis of a Path Planner for Dexterous In-Hand Manipulation of Micro-Objects in 3D

## Keywords : Micro-Manipulation, Dexterous Manipulation, Trajectory Generation

Abstract : The current technical era has evolved, as more and more functions are integrated, and the volume of devices (electronic, electrical, mechanical etc.) has decreased. This trend of miniaturization has opened an opportunity to design small-scale robots, that can manipulate these small objects for assembly. The current state-of-the-art provides the planar dexterous manipulation of micro-objects of arbitrary shaped objects, while some spherical objects can be manipulated in 3D through teleoperation; taking into account the adhesion forces that exist at the micro and nanoscales. Due to the limitation of manipulation techniques at micro-scale, the applications are also very limited. However, there are many areas of applications where we require manipulating the micro-objects in 3D, like minimal invasive surgery, surface mounting of electronic components, and placement and assembling of mechanical components. Thus, our goal is to develop a system that can manipulate the micro-objects in 3D considering the physical specificities at microscale. There are many scientific challenges at small-scale robotics, that require the attention for their appropriate use and applications. This research focuses on one of these challenges is the "planning the finger trajectories" to dexterously manipulate the micro-objects. Direct extension from previous method i.e., planar dexterous manipulation to 3D would involve an exponential increase in computational complexity. Thus, we propose an approach that allows to plan for 3D dexterous in-hand manipulation with a moderate increase in complexity. The main idea is to decompose any 3 D motion into three individual 2 D rotations about specific axes related to the object. This approach induces some constraints on the manipulation process, thus to ensure that the three individual 2 D rotations can be combined to form a complete 3D rotation, we also develop the search algorithm that complies with the manipulation constraints. In the last, we also analyse the impact of physical parameters (adhesion and friction coefficient) that affects the manipulation process. The developed method allows manipulating and orient the object (on which two orthogonal planes can be projected) in 3D, and have been validated through simulations.

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[^0]:    ${ }^{1}$ https://askabiologist.asu.edu/bacteria-overview

