Preface

0.1 Context

In the current context of trend to miniaturization, the main goal defined at the very beginning of this work was to study the influence of miniaturization on the manipulation tasks performed in microassembly, because for a few years, most papers dealing with microassembly have referred to overviews that mentioned the importance of forces related to the microworld. The reader can have a quick overview on the scales covered by the term microworld in Fig. 0.1.

In this figure, several domains can be distinguished:

1. The "macro" domain, related to conventional manufacturing and assembly technologies
2. The "micro" domain where the limits of conventional means can be undergone and new strategies arise. Sometimes the upper area of the micro domain is called "meso" domain
3. The "nano" domain fills the gap between the micro domain and the atoms and molecules world. It is the ultimate domain of mechanical engineers

As a comparison, the accuracy of conventional manufacturing is about 10 μm and the size of hair is between 10 and 100 μm. This book deals with components

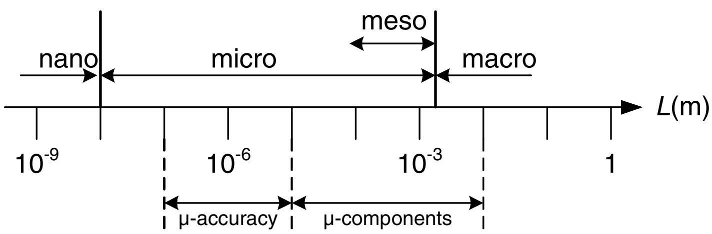

Fig. 0.1. Sizes and scales

ranging from 10 μm to a few millimeter, with part features that can reach the micron: The chosen case study consists in a watch ball bearing with 0.3 and 0.5 mm diameter balls.

More generally, the current breakthrough of the miniaturization of electronic components and the development of their related production equipment make it possible today to produce cheap components integrating a lot of functionalities. These production techniques allow the 2D manufacturing to use several materials: glass, silicon, metals. Beside these applications from the semiconductor industry, the conventional mechanical design also tries to reduce the size of the products and the emergence of micromechatronics develops new miniaturized robots with a lot of functionalities (sensing, actuation, guiding). This trend does not spare assembly and the products are not only reduced in size but also the assembly and production equipment are downscaled, giving rise to several concepts like microfactory or new assembly strategies such as parallel assembly. The pieces of equipment and especially the grippers are downscaled, but new grippers based on microworld related physics are now commercially offered by a lot of industries and laboratories. The first representation that crosses the mind when talking about micro is that it surely must be "small." The prefix micro can of course be understood as defining the size of a component (10^{-6} m), but a microproduct has not to be understood as a product with a size of a few microns. Let us give an overview of some definitions that can help us better define the concepts of micropart, microcomponent, microproduct, microsystem, microassembly. Benmayour [19] proposes a general definition of a microproduct using an analogy with the term "microscopic" object. In the same way as a microscopic object cannot be seen with bare eye, a microproduct is a product that can neither be manufactured nor assembled with bare hand: The production of a microproduct requires adapted manufacturing and assembly equipment. Unfortunately, this definition is quite general and some conventional products like cars cannot be considered as microproducts even when assembled with dedicated equipment. Moreover, this definition can give us an upper boundary but cannot provide any indications about the lower limit of a microproduct. However, it conveys the idea that the size criterion alone cannot be taken into account.

We consider in this book microproducts like a watch ball bearing made of microparts or microcomponents (like balls). Roughly speaking, we will consider that microproducts have sizes ranging from a few cm^3 to a few dm^3. For example, we use to speak about a micropump for a product that has external dimensions of a cylinder with a 8 cm diameter and 2 cm height.

These microproducts are made of several microparts or microcomponents that have a size ranging from 10 μm to a few millimeter, but they can have some features with a size reaching 1 μm. For example, the pumping mechanism of a micropump can be smaller than a cube with 10 mm edge, having at least one dimension smaller than 100 μm. Nelson [130] generally refers to 1 μm–100 μm as "microscale" and 100 μm to 1 mm as "mesoscale."

As far as assembly equipment is concerned, most microfactories are actually desktop factories, that is having external dimensions of 1 $m^2 \times 40$ cm. Bohringer et al. [22] locates the field of microassembly between conventional assembly, dealing with part dimensions higher than 1 mm and what they call "the emerging field of nanoassembly" (with part dimensions ≤ 1 µm).

A microgripper can be a gripper to handle microcomponents, even if the whole gripping mechanism is still quite big compared to the handled part, or it can refer to the terminal tip(s) of the gripper that is(are) in contact with the microcomponent (for example, a particular kind of micromanipulation tool is the Atomic Force Microscope (AFM): This equipment is not designed like a gripper but several laboratories try to use it to push microcomponents. In this case, the AFM tip can be considered as a gripper, made of a cantilever ($100 \times 10 \times 2\,\mu m^3$) with a tip of conical or pyramidal shape of 10 µm height and a tip radius of about 10 nm). Other criteria can be considered to characterize microcomponents, such as, for example, the required tolerances and clearances in order to ensure the function (the pumping mechanism of the micropump cannot show clearances bigger than a few micron in order to guarantee that drug can be transferred from the tank to the patient). A less quantifiable way to define a micropart is to verify whether the models and the techniques used in the macroworld are still valid. For example, macroassembly is clearly based on the mechanical grip force to pick up and the own weight of the component to release, while microassembly has to turn to other techniques due to relative decrease of the gravity force compared to surface forces (see Fig. 0.2). As the main goal of this work is to consider the modeling of the forces acting in the manipulation of a micropart, we consider that the use of these forces make sense in our microcomponents. We prefer to refer to model assumptions and compare the sizes of a part or the roughness of a component with several cut-off lengths arising from model assumptions. We consequently identify a domain between a "van der Waals" cut-off length of a few tens of nanometer

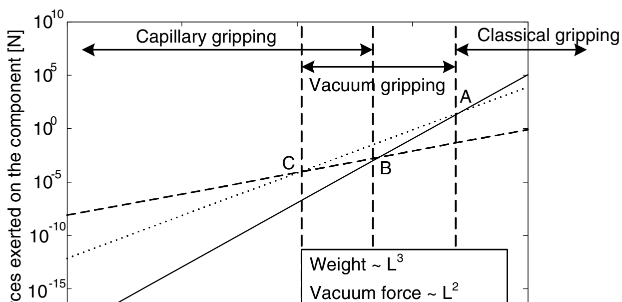

Fig. 0.2. Scaling laws and micromanipulation

Table 0.1. Comparison between micro and macroproducts

Criterion	Macroproduct	Microproduct	Ref.
Size		Below 1 mm	[166]
		Below 500 μm	[41]
Accuracy		0.1–10 μm	[166]
		5 μm	[91]
Clearances		Very small	[166]
Complexity	Made of several elementary components	Multifunctional, complex products, few components	
		Compact design products	[154]
Maintenance	Maintenance and replacement of the defective components	No maintenance, replacement of the product in case of failure	
Heterogeneousness		Several parts from different technological domains involving new joining techniques	[166]

Table 0.2. Comparison between micro and macroassembly

Criterion	Macroassembly	Microassembly	Ref.
Automation	Automatic	Manual and semiautomatic, to be automated.	[65, 166], [159, 185]
Batch size	Single parts, serial assembly	Batches of parts, parallel assembly	
Resource consumption		Expected to be lower	[6]
Response time		Expected to be shorter because of lower inertia	

(limit of the nonretardated van der Waals forces, see page 10) and a capillary cut-off length of a few millimeter (see (8.1)): This domain will be considered as our microworld.

To give the reader a broader overview, we summarize some criteria related to micro/macroproducts and to micro/macroassembly (Tables 0.1 and 0.2).

0.2 Contributions of this Book

This book falls into five parts whose main contributions are summarized in Fig. 0.3 (the fifth part containing the appendices is not shown in this figure).

The first part introduces the concept of microassembly (Chap. 1), proposes in Chap. 2 a classification of the forces acting in microworld (which has been defined in the previous section), and summaries in Chap. 3 the numerous gripping principles proposed in the scientific literature. This summary (which is essentially a review of the literature) serves as a basis for a gripping principles classification from which it turns out that the forces generated by surface tension can suit the microgripping task.

Part I: Microassembly Specificities

- Different kinds of microassembly
- What are the forces in action
- What are the possible handling principles

-- classification of the handling principles
-- proposal: the capillary gripper

Part II: Modeling and simulation of Capillary Forces

- Parameters involved in a gripping based on surface tension
- Classical methods for capillary forces computing: energy derivation method, geometrical approximations, resolution of the Laplace equation at equilibrium

-- Proof of equivalence between the energy derivation and the Laplace equation based methods
-- Implementation of a double iterative numerical scheme to compute forces in the axially symmetric case, based on the solving of the Laplace equation
-- Determination of the limits of this static simulation
-- Determination of approaching contact distance, rupture distance and residual volumes after rupture
-- Approximation of cycle times
-- Application to the watch ball bearing case study

Part III: Experimental Aspects

<u>Testbench:</u>
-- Set up of a force measurement testbench (from 10μN to 10mN)
-- Set up of a contact angles measurement testbench
    -- Tested liquid: water, isopropanol and silicone oil, from 0.1μL to 1μL
    -- Tested materials: steel, silicon, PTFE, zirconium
    -- Tested geometries: concave and convex cones, spheres, cylinders

<u>Studied parameters and phenomena:</u>
-- Inputs: gap, geometries, contact angles, surface tension, dynamic release, volume, relative orientation, evaporation
-- Outputs: forces and liquid bridges profiles

<u>Watch ball bearing case study:</u>
-- Study of the picking errors and solutions
-- Study of the releasing reliability
-- Measurement of the picking force and reliability study

<u>Answered questions:</u>
-- Advancing vs receding contact angle, tension term vs. Laplace term
-- Quantified comparison between picking principles
-- Quantified comparison between releasing strategies
-- Design rules for a surface tension based gripper

Part IV: Perspectives

<u>Modelling and Simulation</u>
- Dynamic simulation
- Capillary condensation simulation

<u>Design and manufacturing perspectives</u>
- Surface tension control (i.e. electrowetting)
- Design and manufacturing of a surface tension based gripper prototype for SMD components

Fig. 0.3. Contributions of this book

The second part concerns the modeling aspects. Therefore, Chap. 6 presents the underlying parameters (such as surface tension and contact angles) and models (Young-Dupré and Laplace equations), which rule the surface tension forces (also called capillary forces). This chapter explains the action of these forces on a solid, thanks to two terms: the so-called "Laplace" or pressure term and the so-called "interfacial tension" term (see Sect. 6.5). Based on these parameters, Chap. 7 reviews some approximations to compute capillary forces at equilibrium: energy differentiation methods, geometrical methods assuming a given shape of the meniscus (typically arc or parabola). Chapter 8 details how to implement a numerical resolution of the so-called Laplace equation to determine the meniscus shape in axially symmetric cases. This allows the computation of the capillary forces linking a component and a gripper, relying on the following assumptions: equilibrium, vanishing Bond number (i.e., gravity is neglected), axial symmetry, constant contact angles, constant volume of liquid. The originality of this model relies on the fact that the volume of liquid can be imposed, which leads to a double iterative scheme for the resolution. Another contribution of this book is to prove analytically the equivalence of this approach and the energy minimization method (in the case of a prism–plane interaction, see Chap. 9). The proposed model is applied to the case study of a watch ball bearing, showing the interest for a gripper geometry conforming with that of the component (Chap. 10). This model is then enriched, thanks to a second set of parameters (Chap. 11), showing how surface roughness and surface impurities can be included in the model through the value of the contact angle. The contact angle hysteresis is introduced in this chapter; however, it will be shown (thanks to experiment) how to chose between both. Finally, this chapter illustrates with a figure from the literature an interesting damping effect, which prevents high contact forces. The limits of the proposed model are discussed in Chap. 12, showing the suitability of this model even in the case of highly accelerated components. This chapter provides some approximations of the damping time of the oscillations of the meniscus, which indicates a first order of magnitude of the cycle time of a surface tension based picking task. Some conditions of meniscus rupture are given in Chap. 13. To conclude this second part, a detailed implementation of the proposed models is given in Chap. 14.

The third part of this book focuses on experimental aspects. First, we detail in Chap. 17 the set up of an experimental test bed allowing the measure of the models inputs (contact angles, volumes of liquid) and outputs (forces and meniscus shapes). Then, Chap. 18 provides numerous model validation and exhaustive results concerning the influence of the gap, the gripper geometry, the surface tension, the contact angles (including the choice between the advancing and the receding contact angles), the relative orientation of the gripper with respect to the component, the conditions of dynamical release, and the rupture distance of the meniscus. Theses results are discussed in Chap. 21 in terms of picking and releasing strategies; therefore, we introduce the concept of adhesion ratio ϕ:

$$\phi = \frac{F_{\min}}{F_{\max}}, \quad (0.1)$$

where $F_{\min}$ and $F_{\max}$ are, respectively, the minimal and the maximal values of the capillary force, which is assumed to be tuned between the picking stage ($F_{\max}$) and the releasing stage ($F_{\min}$). Ratios tending to zero indicate a very flexible gripping strategy (components with a large mass range can be picked), while a ratio tending to 1 indicates a nonsuitable gripping strategy. These results have been then applied in a final illustration of the surface tension gripping based on a watch ball bearing case study. The characterization of the underlying parameters is led in Chap. 19 while Chap. 20 presents the results of picking and releasing tasks of the 0.3 and 0.5 mm diameter balls of this bearing. The conclusions presented in Chap. 21 discuss the results of Chaps. 18, 19, and 20.

The fourth part contains the general conclusions and the perspectives of this work (Chap. 22).

Finally, the fifth part contains the appendices, which includes modeling and geometry complements, some elements of the proof of equivalence of both capillary force models, some tracks toward a dynamical simulation, and finally, a list of the main symbols and abbreviations used in this book.

The book is ended by a list of references and an index.

0.3 What this Book Does Not Tell

This book is an attempt to present on a comprehensive way the elements ruling a reliable surface tension based gripping of a small component with a gripper (typically a sub-millimeter sized component), in gaseous environment (typically ambient atmosphere). However, the analysis proposed to understand the role of the underlying parameters ruling capillary forces is very general, and the proposed model is only valid for axially symmetric cases. In a whatever geometrical configuration, the reader will have to turn himself (herself) toward an energy minimization tool such as, for example, the well-known Surface Evolver software. The case of lateral capillary forces is hardly treated in the experimental part, and we refer the interested reader to the work of Peter A. Kralchevsky [105]. On the same way, the so-called self-assembly or auto-assembly is not treated in this book: These aspects of self-assembly, which are not restricted to capillary forces, are presented, for example, in the work of Karl F. Böhringer. It will be shown that a static modeling is quite sufficient for our purpose; nevertheless, the reader will find additional information concerning dynamical simulation in [156]. Finally, the case of immersed environments is treated in [64].

Let us note that the example treated in this book concerns the case of watch bearing balls with a diameter ranging from 0.3 to 0.5 mm. The use of surface tension has an upper limit (the so-called capillary length equal to a few millimeter for water), it is not limited in terms of miniaturization. Nevertheless, the manufacturing of micron-sized grippers would require adapted manufacturing techniques that have not been considered in this book, but this is more a perspective than a limitation.

0.4 Reading Suggestion

For a quick reading, the chapters and sections listed in Table 0.3 are essential for a good understanding of this book. Let us emphasize the presentation of four examples (Table 0.4).

Table 0.3. Quick reading suggestions

Chapter/Section	Title	Page
	Preface	
3	Handling Principles for Microassembly	13
6	First Set of Parameters	41
7.1	Introduction to the State of the Art on the Capillary Forces Models	51
8	Static Simulation at Constant Volume of Liquid	65
17	Test bed and Characterization	143
21	Final discussion of Part III	211
22	Conclusions and Perspectives	221
Appendix D	List of symbols	247

Table 0.4. Examples

Chapter	Title	Page
10	Application to the Modeling of Microgripper for Watch Bearings	83
14	Numerical Implementation of the Proposed Models	127
19	Watch Bearing Case Study: Characterization	189
20	Watch Bearing Case Study: Results	199

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