Evaluation of adhesion forces between arbitrary objects for micromanipulation

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Abstract—This paper describes a numerical method to estimate adhesion forces that are present in different handling operations in the micro- and nanoworld. Emphasis is on the calculation of the van der Waals force, although the results can be generalized in a straightforward manner to also cover the electrostatic force. The presented method enables force calculation between objects that have arbitrary shapes and material properties together with arbitrary alignments relative to each other. The estimation accuracy is enhanced and the computational complexity is reduced by using surface formulation of the force instead of conventional volume formulation. The surface formulation also enables division of the surfaces into separate regions. This guarantees better accuracy in the computations and makes it possible to use only partial surfaces in the force evaluation.

Keywords: Modelling; simulation; adhesion forces; van der Waals force; manipulation; handling.

1. INTRODUCTION

In most industrial sectors, the trend in manufacturing nowadays is towards miniaturized dimensions and integrated functionalities. New mechatronic products that are introduced on the market combine precision mechanisms, sensors, actuators and electronic circuitry for signal processing and control purposes, as well as have ever-decreasing sizes. Evidently, there is a vast amount of complex hybrid structures that need to be manipulated in different phases of the life cycle of miniaturized products. For example, assembly, testing, modification, maintenance and repairing all need accurate and preferably fast object handling.

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Problems in manipulation arise when the object dimensions reach the sub-millimeter range and adhesion forces begin to dominate the interaction instead of gravitational and inertial forces. Adhesion forces include van der Waals force, electrostatic force, and in humid environment also surface tension force. All these forces can be neglected in the macroworld. However, at micro- and nanoscale, adhesion forces can be several orders of magnitude greater than gravity. In literature, the term scaling effect is used to describe the change of dominance between the different forces in relation to object dimensions.

The most obvious difference induced by the scaling effect between different size scales is the irreversibility of the handling actions. Unlike in the macroworld, in the micro- or nanoworld the handling procedures are not necessarily reversible. This phenomenon manifests itself, e.g., in a pick-and-place operation. At macroscale, where the dominating force is gravity, placing an object requires simply the same motions that have been used in the pick-up phase but in reverse order. However, at micro- or nanoscale, the picking phase is usually easy but accurate placing can be really demanding. Difficulties emerge because adhesion forces cause the objects to adhere to the tools. Additional problems arise in contact situations, where adhesion forces alone (or combined with an external load) can induce plastic and/or elastic deformations in the contacting surfaces. These deformations change the contact area between the interacting objects and increase the contact force when compared to the initial attraction force thus creating hysteresis in the values of the interaction forces [1–3]. Because of the adhesion forces and the contact force, the placing operation at microscale usually requires several release attempts and totally different motions than the pick-up phase.

Basically all micro- and nanomechatronic systems have to take adhesion forces into consideration in order to function properly. Thus, it is obvious that a thorough understanding of adhesion forces is a fundamental requirement for research and application development. Issues related to adhesion forces have been constantly dealt with in micro- and nanomanipulation, including design of special sensors, end-effectors, manipulation strategies, etc. Also the area of modeling and simulation has been thoroughly examined, since simulation provides an effective tool for system design and for studying and understanding the effects of adhesion forces. Analysis and discussion of the adhesion phenomena in microworld can be found, e.g., in Refs [4–8], whereas Refs [9, 10] concentrate on the analytical modeling of microhandling. The numerical modeling of the van der Waals force and the electrostatic force is discussed in Ref. [11]. In addition, Refs [12, 13] deal with the analytical and numerical dynamic simulation of micromanipulation, respectively.

Regardless of the considerable efforts and achievements in the area, modeling and simulation of micro- and nanomanipulation is limited to simple object shapes. This kind of limitation reduces the accuracy of the results and, thus, noticeably restricts the applicability of the methods. The objective of this work is to develop a method to numerically estimate the van der Waals force between arbitrary objects at the micro- and nanoscale. The term arbitrary refers to arbitrary shape, alignment, and