

Chapter 1

Introduction

1.1 Background and motivation of the present Work

In the late 50's, as the famous lecture entitled "There is Plenty of Room at the Bottom", addressed by Prof. Feynman, researchers started to look at the possibilities of using miniaturization devices to build a hybrid microsystem (Feynman, 1992). The trend towards miniaturization of products has marked the electronics, precision engineering, biomedical and optics industries for the past decades. Consequently, there is also a trend towards miniaturization of the tools used for the fabrication of the small components. Today, as more Micro-Electro-Mechanical-Systems (MEMS), optoelectronic (photonic) and microfluidic devices become commercially available, the cost and complexity of equipment and the level of human skills required to assemble such devices have also increased.

Microgripper is one of the key elements in microrobotics and microassembly technologies for handling and manipulating micro objects such as micro mechanical parts, electrical components, biological cells, micro materials etc. As the trend towards miniaturization continues, microgrippers will become indispensable tools for handling, manipulating as well as assembly of micro components in various application fields (optics, electronics, mechanics, fluidics, chemistry and life science). Particularly, for assembly of micro parts made by different materials present there is a need to develop microgripping devices. In these applications, large opening displacement (for handling a range of different object sizes), large output force and easy handling of micro parts are desired along with ease in manufacturing. The microgrippers can be used for pick and place of other MEMS components, nanotubes and nanowires. Microgrippers could also find application in manipulation of micrometer-sized samples for microscopy in general. Other applications include microoptics manipulation, fiber optics assembly, precision assembly and biological sample manipulation.

Conventional mechanisms built with revolute joints and transmission based mechanisms are not suitable to cater to the requirements of precision handling as they

cannot precisely control their motion and the gripping force due to the presence of backlash and coulomb friction in their joints. Components such as bearings and/or linear sliders, etc., often exhibit backlash and coulomb friction in their motion, leading to stick-slip effect. This drawback affects the control of the mechanism in terms of positioning and precision force. Recently there is considerable interest and development in flexural joint based mechanisms which can provide a solution to overcome the drawbacks, due to the absence of coulomb friction and backlash in their motion. With a “no-assembly” gripper design, many critical specifications such as linear displacement, micro accuracy, zero backlash, no friction, and no wear can be addressed through exploitation of compliant mechanism design. In addition, such mechanisms in form of monolithic grippers can be easily miniaturized and manufactured.

Bio-inspired design uses biological phenomena to inspire solutions for engineering problems. The natural world contains some of the most elegant, innovative and robust solution principles and strategies. Bio-inspired design aims to fully leverage the insight of the natural world into the engineered world. Because of numerous challenges, bio-inspired design is still undeveloped as a method for formal concept generation (Tinsley *et al.*, 2007).

Recent research on insect physiology has revealed the importance of passive compliance and damping in achieving robustness and simplifying control (Dollar and Howe, 2005). The traditional design requirements imposed on robotic mechanical structures (that means very high stiffness, high precision, etc.) can be substituted or at least integrated by different requirements, like local or distributed compliance, reduction of mass, structural and assembly simplification, reduction of cost. Bio-inspired mechanism is considered to explore the feasibility of using actuation and control of motion using compliant mechanisms. The motivation of this work is to examine the compliant mechanism design methodologies combined with bio-inspired structural and motion capabilities and exploit the same in the design of microgrippers usable in different micro manipulation applications.

1.2 Literature review

1.2.1 Microgrippers based on actuation methods

Reviews of different available microgrippers reveal that different actuation methods are used for different applications. These can be classified into the following categories:

1.2.1.1 Microgrippers based on piezoelectric actuation

The piezoelectric materials have the advantage of having the ability to be formed in different arbitrary geometries and are compatible to some practical applications in microsystem areas. Piezo materials also gain specific interest in MEMS communities and researchers. Particularly, piezo materials were found to be increasingly utilized in microsensors and microactuator devices. Piezoceramics are very well suited to replace manual positioning elements as well as motorized systems. Piezoelectric actuators, with their smooth motion, extremely high resolution and high stiffness, offer an attractive choice for use as a driving element. The resolution can be increased, and the overall size of the system becomes smaller. The working principle of piezoelectrically-driven microactuator is by transforming electrical signal into motion as shown in Fig. 1.1.

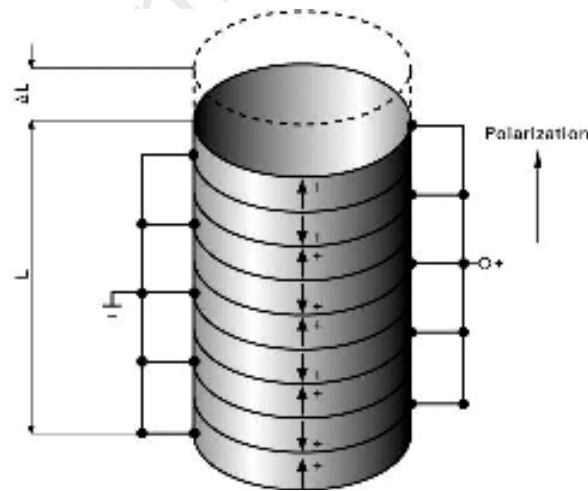


Fig. 1.1 Piezoelectric stack actuator.

In recent years, the continuing rapid growth of miniaturization technology has brought many attractive solutions for the development of micromanipulators. One of the earliest microgripper was developed by etching Beryllium Copper plates actuated by piezoelectric stack actuators (Ando *et al.*, 1992). Some authors also proposed the microgripper design with the piezoactuator-driven source and have analyzed the working efficiency by Finite Element Analysis (FEA) and fabricated using Lithography,

Electroplating, and Molding (LIGA) process (Ballandras *et al.*, 1997). Another work was presented where the piezoelectric microgripper was made of glass material and pattern-transferred using the UV lithographic process to define the device geometry (Salim *et al.*, 1997). Also several successful attempts were made for manipulating mechanical micro objects by several prototypes of microgrippers using various fabrication processes like laser-machining, photo-etching and LIGA (Carrozza *et al.*, 2000). Another attempt to fabricate a microgripper on glass using UV lithography was made and an analytical design with FEA verification was proposed (Keoschkerjan *et al.*, 2002). A more systematic design procedure for microgrippers was described by some authors (Chang *et al.*, 2003). They selected a design among available conventional gripper mechanisms and applied precision manufacturing process (NC machine) to develop a polymer mesoscopic gripper prototype.

A flexure-based gripper for optical fiber handling actuated by piezoelectric actuator was developed by researchers (Chen *et al.*, 2003). They presented a gripper mechanism that was fabricated from monolithic aluminum plate through a wire electrical discharge machining (WEDM) process. The overall dimensions of the gripper are 42 mm length, 22 mm width and 4 mm thickness. It is detachable from the actuator bracket housing, making it adaptable for handling different miniature optical components.

A new hybrid-type microgripper was developed that uses integrated force sensor to control the gripping force for handling micro objects (Park and Moon, 2003). The microgripper is composed of a piezoelectric multilayer bender for actuating the gripper fingers. The microgripper is referred to as a hybrid microgripper because it is composed of two main components: micro fingertips fabricated using micromachining technology to integrate a very sensitive force sensor measuring the gripping force, and piezoelectric gripper finger actuators that are capable of large gripping forces and moving strokes.

Design, fabrication, and calibration of a piezoelectric polymer-based sensorized microgripper was reported by another researcher (Kim *et al.*, 2004). EDM was employed to fabricate the super elastic alloy-based microgripper. It was experimentally tested to show the improvement in mechanical performance. For integration of force sensor in the microgripper, the sensor design based on the piezoelectric polymer polyvinylidene fluoride (PVDF) film and fabrication process was presented. The calibration and

performance test of the force-sensor-integrated microgripper was experimentally carried out. The force-sensor-integrated microgripper is applied to fine alignment tasks of micro opto-electrical components.

1.2.1.2 Microgrippers based on electrostatic actuation

The driving principle of electrostatic microactuators is based on electrostatic force created by applying voltage across two miniaturized capacitor plates that are separated by an air gap. The two most well known designs are the lateral comb drive (Tang *et al.*, 1992) and the rotary micromotor (Fan *et al.*, 1989). A successful microgripper design based on electrostatically driven microactuator was presented and tested to grip various microscopic objects like blood cells, protozoa *etc.* (Kim *et al.*, 1992).

1.2.1.3 Microgrippers based on thermal actuation

Thermal microactuators are based on the principle of material deformation that is generated by the application of heat to the material structure. The most commonly used thermal microactuators are bimorph (Keller *et al.*, 1995) and they are used for developing microgrippers with high-aspect ratio structure. In this work, the peizo resistor for gripping force measurement is integrated into the microgripper device.

Another work with two-finger bimorph microgripper was presented (Greitmann and Buser, 1996). Each finger is constructed by bimorph elements consisting of thin silicon film as the base layer, silicon nitride as the protecting layer, and thick aluminum film as the top layer. A long silicon cantilever that is attached to a support chip forms each finger.

1.2.1.4 Microgrippers based on shape memory alloys (SMA)

Recent progress in engineering material development enabled microgripper realization based on shape memory effect. SMA microgripper design consists of Ni-Ti-Cu thin films served as the main material for actuation (Lee *et al.*, 2000). The silicon fabrication process is used to fabricate the device. Also a flexural link based microgripper which is actuated by shape memory wire and integrated with micro joint design to provide the required amplification for the grasping motion has been reported (Troisfontaine *et al.*, 1997).

1.2.2 Microgrippers based on manufacturing processes

Several fabrication technologies have been commonly used to produce complex MEMS structures, devices and systems. However, most of these fabrication methods are mainly derived from the conventional Integrated Circuit (IC) manufacturing processes. As MEMS technology is foreseen as enabling techniques in the near future, many novel fabrication methods are continuously being developed in the recent years, such as LIGA technique, DRIE (Deep Reactive Ion Etching), micromolding (Hexsil), micro-electro-discharge-machining (μ -EDM) or wire EDM and precision machining. In the past decade, several researchers have attempted to use the above mentioned fabrication processes to realize the microgripper devices. A combination of surface and bulk silicon micromachining techniques have been widely used to fabricate the microgrippers. On the other hand, a titanium gripper fabricated by combination of EDM and etching process was also presented (Thornell *et al.*, 1995). A polysilicon microgripper was realized by the Hexsil process developed at UC Berkeley (Keller and Howe, 1997).

1.2.3 Design methods for compliant flexure-hinge based gripper mechanisms

An atlas of 64 linkage type mechanisms for planar two-fingered robotic grippers were reported (Belfiore and Pennestri, 1997). These mechanisms have either one input or two inputs. All of these mechanisms have rotoidal and sliding pairs. Authors also presented the feasibility of these mechanisms.

Although piezoelectric devices can provide large output forces, extremely small displacement (only few microns) is not sufficient for most general engineering applications, for which much larger movement ranges are usually required. Therefore, the use of a flexure-hinged mechanical displacement amplifier is the most appropriate approach to magnify the output displacement of the piezoelectric stack actuators (Yu *et al.*, 2003). Some authors have extensively worked on compliant mechanisms and proposed a general design procedure (Ananthasuresh and Kota, 1995). Also an optimization method using topology optimization and FEA was used to design a compliant microgripper (Oh *et al.*, 2003).

1.2.4 Summary of study of various microgrippers

A review of available literature reveals that the research effort focused around microgripper development is mostly based on two major strategies. The first is design

based on different activation principles: by electrostatic, piezoelectric, thermal or shape memory effect. The second is microfabrication processes to construct the microgripper structure, such as IC based silicon processing, LIGA technique, micro EDM. Also some other new fabrication technologies are under development nowadays.

1.3 Formulation of thesis objectives

Generally, the MEMS microgrippers developed in the past can be broadly categorized into two major types. One is to separately integrate the actuation source and the finger part as a complete device. The other is to directly serve the entire actuation source as the finger part of microgripper. The structural configuration of both types may include the amplification mechanism and also the grasping finger arms (Ananthasuresh and Kota, 1995). Moreover, these microgrippers mostly emphasized on the various design requirements such as large working force capable of performing large opening displacements, fine structural rigidity and ease of manufacturing or compatibility with the well-developed microelectronics fabrication. However, very few studies have concerned with the initial stage considerations of design work of microgripper such as the structural design issues that may entirely govern the actuation behavior of a microgripper device. Most of the existing microgripper designs provide little information regarding the systematic procedure of structural design issue. Although numerous examples of compliant microgrippers for various applications have been demonstrated in literature, detailed study of design methodology, including design method and rules, are too varied and diverse to be shown as a unified design procedure.

The main objective of this thesis is to present a new concept in the design of a microgripper based on a biologically-inspired approach. Biological creatures like crustaceans have interesting gripping mechanisms (Mariappan *et al.*, 2000) and implementing them in real devices can enhance the compliance and applicability of microgrippers for several applications (e.g. biological sample handling, precision assembly, microoptics manipulation etc.). A systematic design procedure including modelling, prototype fabrication and performance evaluation for a planar two-fingered gripping mechanism inspired from the mechanism of a crab's claw is presented in this work. The design scope considers the compliant monolithic design; the work presents the relationship between the mechanical motion of the conventional rigid macro-mechanism

and that of the micro compliant mechanism in terms of their kinematical behaviour. The compliant microgripper employs a linear expansion element as a prismatic joint (sliding joint), while its gripping part involves individual revolute joints (hinges).

One of the major drawbacks of the miniature grippers seen in literature is its inability to grip both soft and hard objects. A new approach to the design of compliant microgrippers is therefore desired. Interestingly, biological creatures like arthropods (e.g. crabs, lobsters, ants etc) regulate their stiffness in their joints quite easily without much sensory information (Dollar, 2001). Therefore, study of arthropods grasping mechanism and the related bio-inspired design is a very promising approach for developing miniature grippers to operate in unstructured environment (i.e. when the object stiffness is not known).

Biological creatures make effective use of equivalent mechanisms through agonist-antagonistic activation of joints (Mariappan *et al.*, 2000). These actuation methods when applied to compliant mechanism offer a new design strategy for microgrippers. This approach is presented in this thesis with a holistic design perspective for mechanisms and applications.

The sub-objectives of the thesis and various tasks thereof are subsequently defined as follows:

A. Bio-inspired design of microgripper

- i. To study and develop new compliant microgripping mechanisms with variable stiffness in the joints inspired from arthropods specifically crustaceans like crabs, lobsters etc.
- ii. To investigate the feasibility of combining micro compliant mechanisms with conceptual regular macromechanism design to develop a compliant microgripper for microassembly and biological applications.
- iii. To develop a systematic design procedure for designing planar two fingered microgripper based on the bio-inspired actuation.
- iv. To optimize design of the microgrippers for overcoming various constraints in operation and manufacturing.

B. Modelling of microgripper

- i. To develop a dynamic model of bio-inspired agonistic-antagonistic equivalent single piezo and dual piezo actuated microgripper and to study and analyse the dynamic performance of the design.
- ii. To simulate the model for predicting the dynamics of the microgripper mechanism.
- iii. Develop control schemes to be used with the model for microgripper tip displacement and gripping force control.

C. Manufacturing of microgripper

- i. To fabricate microgrippers with a suitable micro manufacturing process from the design models of the microgrippers for various configurations (e.g. single degree of freedom (d.o.f.), 2 d.o.f. and 4 d.o.f. actuations).

D. Performance evaluation and testing of microgrippers

- i. Development of experimental setup for characterization, testing, demonstration and control of the microgrippers.
- ii. Implementation of a suitable vision based measurement system for microgripper.

1.4 Outline of the thesis

The organization of this thesis is as follows:

In Chapter 2 the working principle and the design procedure of a two-fingered gripper inspired by claws of a crab is discussed. A static kinematic model and subsequently equivalent flexure based mechanism and its pseudo-rigid-body-model (PRBM) was developed utilizing single and two linear multilayer stack piezoelectric actuators as actuation source. The output displacement obtained by the PRBM is validated using finite element analysis software package ANSYS. The crucial geometrical parameters of flexure hinge and microgripper dimensions, which greatly influence the working performance of the microgripper, are optimized using Genetic Algorithms (GA).

Chapter 3 discusses the dynamic modeling of the miniature gripper considering the system as a combination of mass-spring-damper. The mathematical model is then simulated using MATLAB/SIMULINK. A SIMMECHANICS model of the system is

developed for more flexibility and incorporating more complexity into the mechanism easily. Based on the SIMULINK model developed, a Proportional-Integral-Derivative (PID) controller is used for precise position and gripping force control.

Chapter 4 discusses the prototype manufacturing through wire-EDM process. The process principle, process parameters and different manufacturing errors are discussed in this chapter.

Chapter 5 discusses the performance evaluation of prototype microgrippers manufactured by wire-EDM process. This chapter discusses the displacement measurement using vision-based techniques with NI Vision and LABVIEW. Also PID control implementation for position control of microgripper is described.

Chapter 6 summarizes the work done so far and future plan and finally references are listed.