DESIGN AND REALIZATION OF A MICROASSEMBLY WORKSTATION

By

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ABSTRACT

With the miniaturization of products to the levels of micrometers and the recent developments in microsystem fabrication technologies, there is a great need for an assembly process for the formation of complex hybrid microsystems. Integration of microcomponents made up of different materials and manufactured using different micro fabrication techniques is still a primary challenge since some of the fundamental problems originating from the small size of parts to be manipulated, high precision necessity and specific problems of the microworld in that field are still not fully investigated.

In this thesis, design and development of an open-architecture and reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts is presented. The workstation is designed to be used as a research tool for investigation of the problems in microassembly. The development of such a workstation includes the design of: (i) a manipulation system consisting of motion stages providing necessary travel range and precision for the realization of assembly tasks, (ii) a vision system to visualize the microworld and the determination of the position and orientation of micro components to be assembled, (iii) a robust control system and necessary fixtures for the end effectors that allow easy change of manipulation tools and make the system ready for the desired task. In addition tele-operated and semi-automated assembly concepts are implemented.

The design is verified by implementing tasks in various ranges for micro-parts manipulation. The versatility of the workstation is demonstrated and high accuracy of positioning is shown.

MİKROMONTAJ İŞ İSTASYONU TASARIMI VE ÜRETİMİ

Emrah Deniz KUNT

EECS, Yüksek Lisans Tezi, 2006

Tez Danışmanı: Prof. Dr. Asif SABANOVIC

Anahtar Kelimeler: Mikromontaj, mikrosistem, mikromanipülasyon, mikromontaj iş istasyonu

ÖZET

Günümüzde üretilen ürünlerin mikrometre seviyelerine varan minyatürleştirilmeleriyle ve mikrosistem üretim teknolojisinde olan son zamanlardaki gelişmelerle, karmaşık melez mikrosistemler oluşturmak için gerekli olan montaj sürecine büyük bir ihtiyaç duyulmaktadır. Değişik materyallerden ve değişik mikroüretim teknolojileriyle üretilmiş mikro parçaların entegrasyonu; manipüle edilecek parçaların boyutlarının küçük olması, yüksek hassasiyet gereksinimi ve mikro dünyaya özel birtakım problemlerden kaynaklanan bazı ana sorunların henüz daha tam olarak incelenmemiş olmasından dolayı mikrosistem teknolojisinde halen en temel sorunlardan birini oluşturmaktadır.

Bu tezde, mikroüretim teknikleriyle üretilmiş parçaların verimli ve güvenilir bir şekilde montajlarının yapılması amaçlanılarak açık-mimarili ve yeniden yapılandırılabilir bir mikro montaj iş istasyonunun tasarımı ve uygulaması sunulmuştur. İş istasyonu, mikromontaj alanındaki problemlerin incelenebilmesine olanak sağlamak amacıyla bir araştırma aracı olarak tasarlanmıştır.

Bu tip bir iş istasyonunun geliştirilmesi şu tasarım süreçlerini içermektedir. (i) mikromontaj görevlerini gerçekleştirebilmek için gerekli olan hareket mesafesi ve hassasiyeti sağlayabilecek hareket platformlarını içeren bir manipülasyon sistemi, (ii) mikro dünyayı görselleştirmek ve montajı yapılacak mikro parçaların konumunu ve

yönelimlerini belirlemek için bir görü sistemi, (iii) Gürbüz bir kontrol sistemi ve sistemin tanımlanmış görevlere hazır olabilmesi için gerçekleştirilecek olan göreve uygun manipülasyon araçlarının kolaylıkla sisteme entegrasyonunu sağlamak için gerekli sonlandırıcı bağlama fikstürleri. Bunlara ek olarak tasarlanan mikro sistemde uzaktan komutalı ve yarı otomatik montaj kavramları da gerçekleştirilmiştir.

Tasarımın uygulanılabilirliği, mikro parçaların manipülasyonunu içeren çeşitli montaj görevlerinin gerçekleştirilmesiyle doğrulanmıştır. İş istasyonunun çok yönlülüğü yapılan deneylerle kanıtlanmış olup konumlandırmada yüksek hassasiyetlere ulaşıldığı gösterilmiştir.

"To people I love"

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AFM	Atomic Force Microscope
STM	Scanning Tunneling Microscope
SEM	Scanning Electron Microscope
CNT	Carbon Nanotube
PC	Personal Computer
CCD	Charge-Coupled Device
CAD	Computer-Aided Design
DOF	Degrees of Freedom
SMC	Sliding Mode Control
PZT	Lead Zirconium Titanate

1 INTRODUCTION

1.1 Background and Motivation

There is a great effort towards the miniaturization in the last few decades. We can see the effects of that trend in every aspect of our lives. From the laptops to the cellular phones, we always prefer the smallest one since the idea of “the smaller the better” has penetrated into our minds and one can be equipped with more gadgets as miniaturization goes further. Miniaturization process of mechanical components started with microfabricated sensors and was followed by microfabricated parts and microactuators. In recent years integration of micro components such as precision mechanisms, sensors, actuators and embedded electronic circuits into microsystems has become one of the most prominent research areas all over the world. When the micro components were first introduced, they were simple and could be naturally integrated directly into the product. However, developments in microsystem technology resulted in a large variety of micro components made from dissimilar materials and technologies. These miniaturized products use even smaller components, and in more and more cases they are micro components with sizes of components less than one millimeter. However, to miniaturize a product it is not sufficient to simply reduce the dimensions of that product. Many problems arise through the miniaturization process because of the scaling effects, manufacturing limitations and, as might be expected, assembly. The incompability of various materials and processing technologies of each individual component as well as the necessity of integration of these components in order to form a functional microstructure require a versatile assembly technology and development of specific processes, methods and machines.

The production of microsystems with many functionalities, components made of different materials require flexible, modular, accurate mechanisms, which can finely pick, orientate, move and release different types of objects at the desired location. In the presence of microparts, assembly is a key issue in the formation of a product since different functions require different materials within a product. In addition microassembly is the key for the development, modification and maintenance of hybrid microproducts.

Considering the relations between the production rate and the size of the parts to be assembled, as the assembled parts become smaller and smaller the production rate rapidly falls thus opening a vast domain of research in the micrometer size components assembly. (Figure 1-1) Due to the fact that the operator has no direct access to the micrometer size components and direct human handling of those components is not possible the need for automated micromanipulation and microassembly arises.

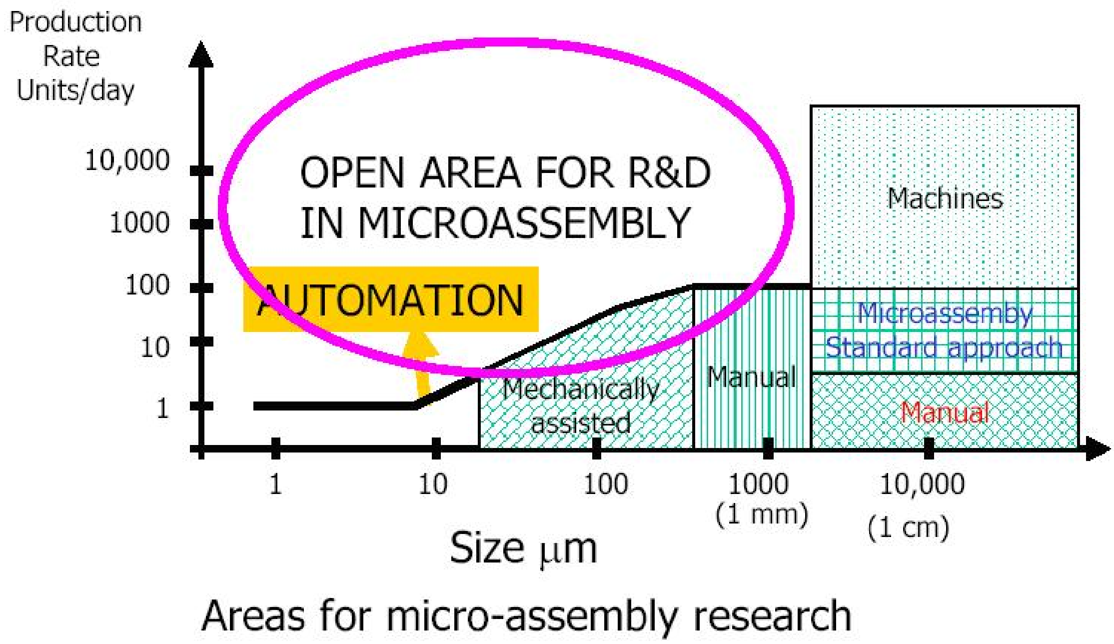


Figure 1-1 - Interrelations between areas of microassembly

For achieving high output and quality in microassembly tasks, it is necessary to develop a high-speed, repetitive and reliable open-architecture reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts. Since the human skills for handling are to be replaced by such an automated machine, micro scale manipulation tools which supersede the human hand in the micro domain, material properties of these tools and the microcomponents to be assembled gain significant importance. Microassembly, integration of components into complex microsystems, is still a primary challenge since some of the fundamental problems originating from the small size of parts to be manipulated, high precision necessity and specific problems of the microworld in that field are still not fully investigated.

1.2 Objectives

The main objective of this thesis is to develop a high-speed, repetitive and reliable open-architecture, reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts. The workstation will be used as a research tool in order to be able to provide solutions for the problems in microassembly.

Manipulation tools play the key role in microassembly operations. According to the task to be implemented and the parts to be manipulated, a special tool has to be used or developed since the concept of a universal gripper seems impossible. For that reason we propose a platform that allows the realization of different assembly tasks just by changing the manipulation tool in order to overcome the limitations of tools capability o performing only some specific tasks. For that reason it is designed in such a way that according to the task to be realized, the manipulation tools can be easily changed and the system will be ready for the predefined task. In that sense, manipulation tools such as microgrippers, AFM probes, micropipettes and any other tool can be the matter of choice for the workstation.

On the other hand, accuracy requirements for these operations are very high; therefore, precision and repeatability of such assembly systems must be in the micron to nanometer range for automatic assembly of millimeter and micron structures. Focusing on the high-precision necessity of such a microassembly platform, we aim to achieve motion control with nanometer accuracies.

1.3 Thesis Outline

The second chapter is intended to give an overview on microsystems integration and the existing microassembly systems and specifications.

In chapter 3, microassembly issue will be presented. Firstly focusing on what differences micro world brings into the picture differing from the macro world, requirements for designing a microassembly workstation will be discussed. These requirements will be presented for each subsystem building the whole system; manipulation, vision and control system.

Chapter 4 is intended for explaining the technical details of the components used in the design by clearly defining the reasons and ideas behind for choosing these components. With the defined necessities of the micro world, role of each component and selection criteria and some other solutions will be presented. This chapter will mostly deal with the hardware side of the design.

In chapter 5, system supervision is discussed in detail. Used control structure and methods for achieving desired precision in motion is presented. Following the control structure and methods, vision structure and visual feedback used in automated microassembly and the motion planning algorithms, as well as system calibration and prior-knowledge acquisition issues are described.

In chapter 6, experiments made by using different end effectors are presented. Semi-automated microassembly experiments will be introduced and results will be discussed. System will be evaluated according to the experimental results.

Chapter 7 concludes the thesis by pointing out the achievements and giving future motivations.

2 STATE OF THE ART IN MICROASSEMBLY

For the development of new materials and production of functional microstructures in microsystem technology, the necessity of joining of the microcomponents is inevitable. There are two different types of microsystems integration; monolithic and hybrid integration.

Monolithically integrated microsystems combine all functionalities of the system on a basis body. Techniques for monolithic integration have its origin from the microelectronics technology and are generally 2D processes. That kind of integration of microsystems provides reliable compact devices, however, causes high costs because of the sophisticated fabrication methods.

Hybrid microsystems consist of several components made of different materials by different manufacturing techniques. Each element of the system to be formed requires manipulation in order to form the complete structure. In contrast with the monolithic integration, hybrid microsystems integration allows the flexible combination of different types of components and provides the possibility to produce different types of devices. Additionally, hybrid integration has lower manufacturing costs.

However, high precision assembly of the components to form the desired microsystem must be realized which requires accurate positioning skills and high flexibility of the microassembly machine. There are no existing standard microassembly techniques so that the machines are generally designed for serving a specific task.

2.1 Types of Microassembly

According to the technique used, microassembly can be classified as shown in Figure 2-1. In addition to these techniques, there are some special approaches, however, a general classification is defined in the following sections.

2.1.1 Manual microassembly

Manual microassembly is the realization of assembly tasks by specially trained human operators where the need is to perform high-precision hand motions. For the manual microassembly there is a great need for visual aid by magnifying glasses or microscopes under which the operators carry out the assembly tasks by using special tools like tweezers. As a result of the small dimensions of the parts to be assembled, forces that can be applied without damaging to the parts are restricted. Manual assembly may result in varying product quality since the control of such small forces is hard and may lead to deformations of the parts. In addition, as the need for miniaturization increases, the mounting tolerances are becoming smaller and smaller which makes the manual assembly harder since the capabilities of the human becomes inadequate in that scale.

2.1.2 Tele – operated Microassembly

In tele-operated microassembly, motions of the human operator are transferred into the actuators by means of a man-machine interface. MMI having more number of degrees of freedom enables the control of the motion with the same number of DOF in the target space. Since the forces and the precision of motion necessary for realizing an assembly operation in the microworld should be too small and the human capabilities become inadequate for such motions with the increasing miniaturization, tele-operation makes it feasible to perform the operations remotely, not in contact with the environment. It allows the realization of the manipulation operations precisely by scaling the forces and the motions of the microworld to the macroworld and feeding them back to the human operator. That way, the operator can perform the operations similarly as in the macroworld and the task is realized by the micromanipulator system in the microworld. During those operations, the operator is guided through visual feedback and possibly with force feedback.

2.1.3 Automated Microassembly

Main issues related to the microassembly are the component handling, precision and the final product quality. Component handling difficulties, required submicron precision necessary for the quality of the product and the limits of human capabilities brings the necessity for an automated microassembly operation. Besides guaranteeing the required precision and repeatability, automation is necessary in the microassembly also for economic reasons since automation increases the quality of the product and the production rate which will reduce the cost.

Automatic microassembly can be divided into two categories

- Semi-automated Microassembly
- Fully-automated Microassembly

In semi-automatic microassembly, operator intervention is permitted but to a certain extent. The operator can define some parameters for the operation such as the pick-place positions or the assembly order of the components. The rest of the operation is executed automatically. In fully-automated microassembly, all the tasks and the parameters are predefined. With the aid of sensory feedbacks such as visual feedback, force sensors, etc. the assembly task is realized automatically.

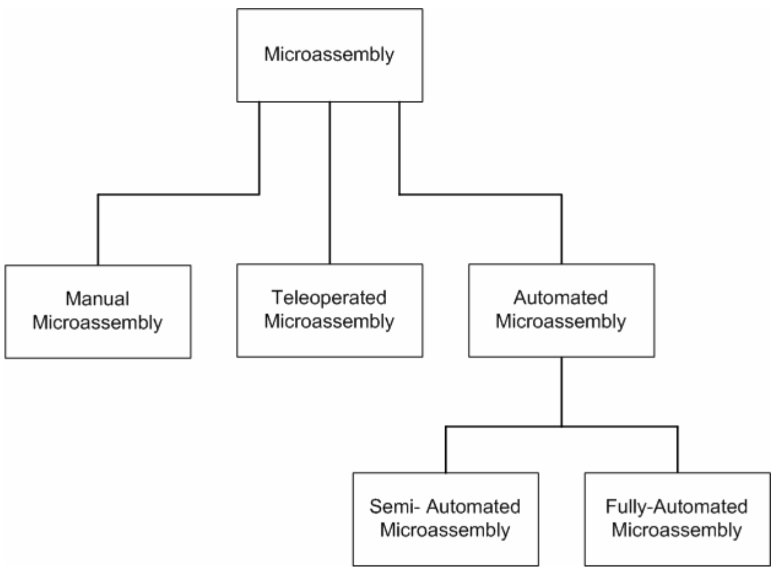


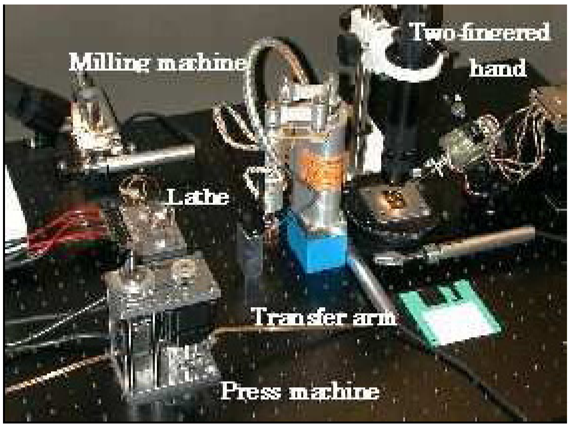
Figure 2-1 – Classification of Microassembly Techniques

2.2 Some Examples of Existing Microassembly Systems

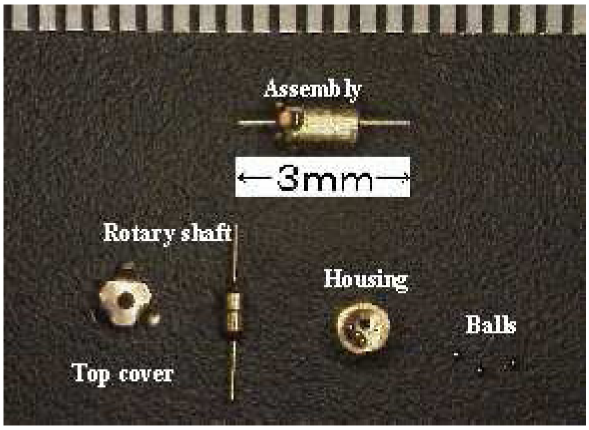
In the available literature many microassembly systems are presented but very few of them are actually full operational microsystems assembly stations. In most of the cases the presented systems are part of the research setups for providing facilities for the research in the manipulation of microparts. Some of the solutions representing the most common structure will be described in the rest of this section.

Desktop Machining Microfactory, MEL (Mechanical Engineering Laboratory) Laboratory, Japan

The MEL microfactory is the first prototype of desktop machining microfactory (Figure 2-2a), developed by the Mechanical Engineering Laboratory in the nineties. (Figure 2-2b) The desktop microfactory consists of machine tools such as a microlathe, a milling machine, a press machine, and assembly machines such as a transfer arm and a two-fingered hand. Miniature machine parts can be produced and assembled such as the fabrication and assembly of a ball bearing with an outer diameter of 0.9mm. [1]



(a) The first microfactory



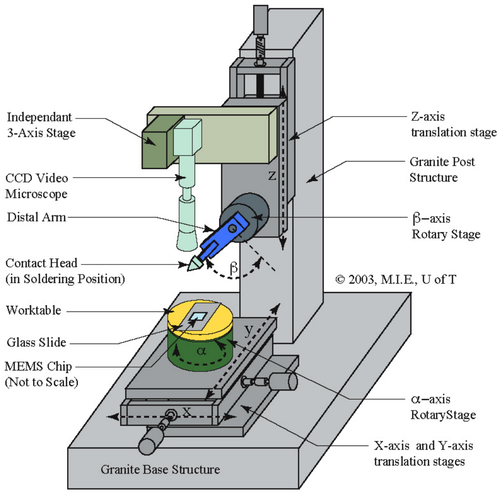
(b) Assembled ball bearing

Figure 2-2 – MEL Microfactory

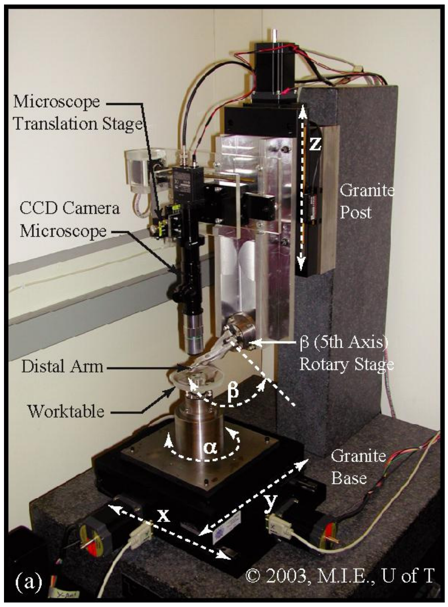
The Robotic Workstation (MJMP) – University of Toronto

The robotic workstation is designed with the objective of the development of a general, rather than an application specific, microassembly system. A five axis (*x, y, z, α, β*) robotic manipulator forms the basis of the microassembly system. (Figure 2-3)

Linear axes (x, y, z) are driven by five-phase stepper motors with 4000 steps for revolution allowing a linear step distance of 0.5 µm. Rotational axes (α, β) are driven by custom designed actuators with radial and axial runouts of less than 2 µm with resolution of 0.36º. There is also a 3-axis translation stage to allow the movement of the microscope independently of the MJMP. The system has the travel ranges of; 200mm in x and y axes, 150mm in the z axis and rotation range of 0 to 360 degrees in alpha axis and -50 to 50 degrees in the beta axis.



(a) Schematic Diagram



(b) Actual View

Figure 2-3 – Robotic Workstation (MJMP)

The MJMP (Manipulator and Joiner of Micro Parts) can be used as a tele-robotic system controlled by a human operator. The operator uses a joystick relying on the vision feedback from the microscope and the readouts from the linear encoder positions in order to control the system. The system can also work in automatic mode to the extent of locating the plane of the substrate chip and solder bonding to microgrippers. The described microassembly system has been used for the construction of out-of-plane microcoils. [2]

Considering the general micromanipulation, passive microgripper [3] proposed with this microassembly system is much less versatile than the actively controlled microgrippers as they are well suited for grasping irregular objects, in dynamic environments. Since this microgripper can only grasp and release objects that are adequately restrained, and that have specific geometries, micromanipulation possibilities are very limited.

OLYMPUS, Japan

Olympus microparts teleoperation system is developed (Figure 2-4) for intricate assembly of very small parts under a microscope. The applications are thought to be lying in areas requiring manual assistance, like microwelding and inspection. The system consists of three main components - a video microscope with a bifocal optical system, parallel-link micromanipulator with a miniaturized ultrasonic linear motor and an elastic hinge with bending deformation and parallel-link stage with six links driven by an ultrasonic linear motor having degrees of freedom in X, Y, Z and rotations in each axis. The operator is guided through a magnified image during the realization of the manipulation.

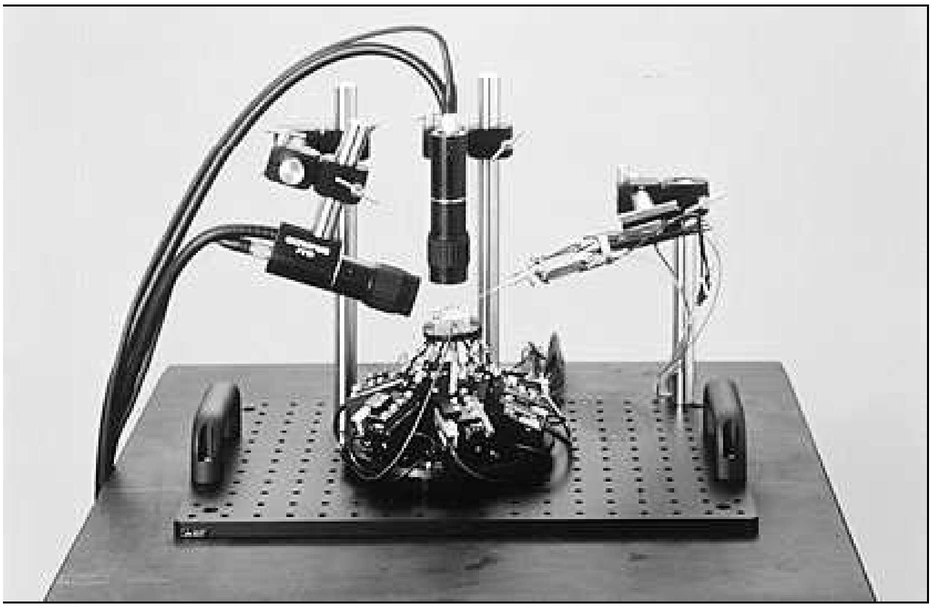


Figure 2-4 – Olympus teleoperated micromanipulation station

The Experimental Microfactory System, Seiko Instruments Inc.

The microfactory system consists of three units; that are a processing unit, an assembling unit and conveyance unit. The processing consists of a electrochemical machining device, micropumps and a recognition device. The resolution of the machining is about 20μm, the processing area 5x5mm^2 and the depth of the processing more than 300μm. The assembly unit is composed of two arms having seven degrees of freedom each axis driven by ultrasonic micromotors with 20μm accuracy, a precise stage with 0.5μm resolution for the assembly of microparts and several tools such as vacuum and electromagnetic chucks. The conveyance unit is constructed using a electromagnet microactuator array, each with size of 1mm^2. [4]

The microfactory is capable of making gear trains, which includes a gear of sub-millimeter in diameter. Production of the gears is made in the processing unit and then they are transported to the assembling unit by the conveyance system to be assembled by the microarms. Some other parts can be provided from the part-supply station to the assembling unit.

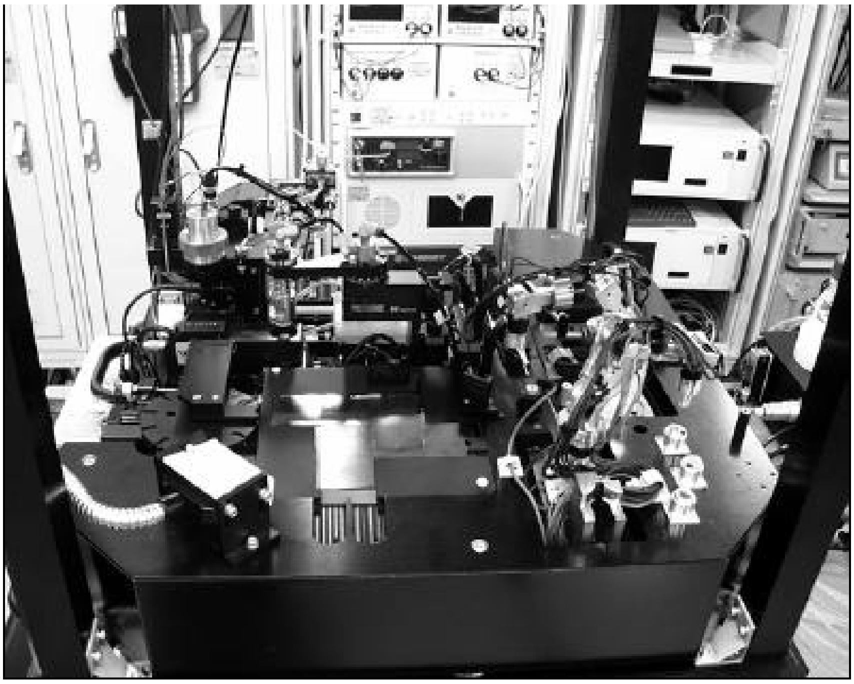


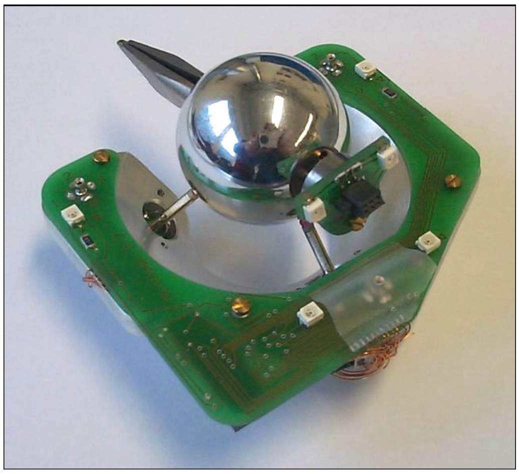
Figure 2-5 – Experimental Microfactory System

MINIMAN, University of Karlsruhe (TH)

A microassembly station based on flexible micromanipulation robots having both the transportation and manipulation skills has been developed throughout that project. Being controlled with the help of visual and force sensors, robots are able to move by tube-shaped multilayered piezo actuators and manipulate down to an accuracy of 10 nm.

Each robot has an integrated manipulation unit which can be equipped with different manipulation tools enabling the robot to perform several manipulation tasks under an optical microscope or within the vacuum chamber of a scanning electron microscope (SEM). The main advantage of such a micro-robot based microassembly station is that it provides flexibility since several robots can be delivered simultaneously cooperating to perform an assembly task. Also, robots can be specialized to perform different tasks by using different tools in order to realize more complex operations. [5], [6]

(a) Microassembly Station



(b) MINIMAN Micro-robot

Figure 2-6 – MINIMAN

Zyvex A100 Assembly System

Zyvex A100 Assembly System is a manipulation and assembly tool suitable to be used with either an electron or optical microscope for the assembly of microscale components. The system has the capability to assemble microscale components which have been manufactured from various MEMS manufacturing techniques in order to form complex MEMS structures.

The assembly system is equipped with two positioners used to grasp, move, test, and position microscale components. One of the positioners has three degrees of freedom (x, y, z) and the other has four (x, y, z, Ø y). There is also a sample stage having the ability to move in three degrees of freedom (x, y, Ø) which further aids manipulation and positioning for assembly tasks. The positioners have 100 nm resolution in x, y, and z axes and 3.5 μradians resolution in Ø on the 4 DOF positioner. The sample stage has a resolution of 100 nm in x and y axes and 3 μradians in Ø rotational axis.

Zyvex also offers microgrippers and microgripper end effectors for the manipulation of the microscale objects.

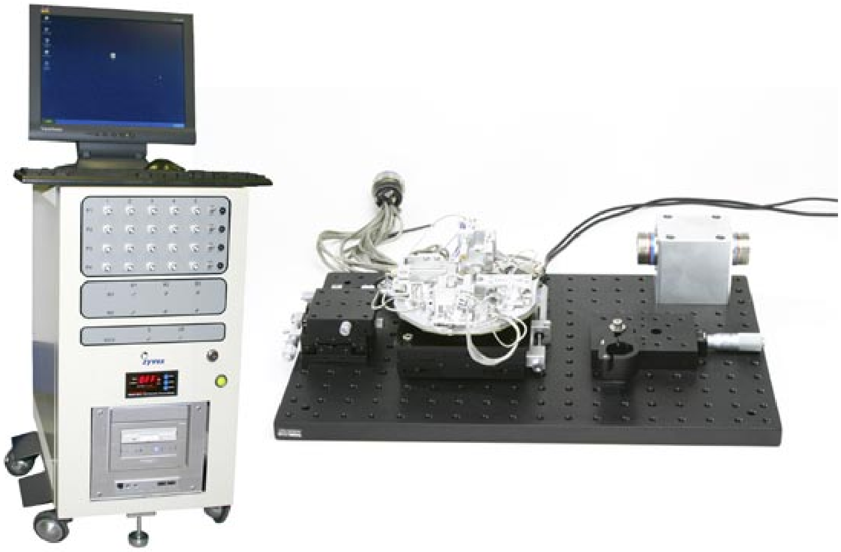


Figure 2-7 – Zyvex A100

3 DESIGN REQUIREMENTS

3.1 Introduction

This chapter deals with the requirements for the design of a microassembly workstation and the specifications of the system. When compared with the assembly in the macro world, necessary requirements for assembly in micro world show significant differences. The main difference between the assembly in the macro and microworld is the positional accuracy required for the assembly machines. Since the size of the parts to be positioned becomes smaller, precision of motion should also become better to assemble the parts accurately. For the robotic manipulators in the macroworld a precision of few microns is typical, however, in the microworld submicron precision is necessary. Positioning at the microscale becomes considerably more difficult since accurate sensing of the true output is more difficult, and link flexibility can induce residual structural vibrations.

Visualization becomes a more significant issue in the micro world as there are limitations such as orientation of the microscopes, magnification and depth of field. The microscopes limit the ability to directly see the objects to be manipulated. High magnification, necessary for imaging the microworld, restricts the field of view to a very small area causing the lack of global information about the object. At high magnification rates, depth of field becomes a problem as the limited depth of field obstructs the clear view of non-planar objects and the moving structures. Another problem is that the working distance limits manipulation operations. The number of degrees of freedom may also become a drawback since there may be occlusions as a result of the complicated end effector structure.

Another issue that has great significance in micromanipulation is the effect of force scaling. While the size of the objects become smaller, inertial forces scale down faster than adhesive forces as the inertial forces depend on the volume of the object and adhesive forces depend on the surface of the object. As a result of the effect of adhesive forces releasing the object after gripping becomes a great problem. The effect of adhesive forces should be carefully considered for a robust micromanipulation as it brings limitations to manipulation capabilities such as preventing the motion of the object.

Assembly Scale	**Mesoscale**	**Microscale**	**Nanoscale**
Assembly Attribute	Easy	Difficult	Very Difficult
Velocity	Cm/s or mm/s	µm/s or mm/s	Very slow nm/s or µm/s
Force sensing and force control	Easy, necessary to avoid part damage and improve manipulability.	Difficult, the range of forces could be as low as µm/N.	Difficult, AFM used to measure force.
Dominant forces	Gravity, friction	Surface forces (stiction, friction, electrostatic, Van der Waals)	Molecular, atomic forces
Throughput	Serial assembly provides adequate throughput	Serial assembly usually not sufficient. Parallel manipulation methods preferred.	Parallel manipulation methods, or self assembly are necessary.
Vision	Easy	Difficult (Expensive optics)	Impossible in visible wavelengths. SEM, TEM are used.

Figure 3-1 – The features of meso, micro and nanoscale assembly systems [7]

Differences between the assembly in macro and micro world forms the basic requirements for the design of a microassembly workstation which can be defined as speed, repetitiveness and reliability. As the system is defined as an open architecture and reconfigurable system – both hardware and software – the system is designed in such a way that it can adapt easily to different applications. So that flexibility comes out as another design requirement for the workstation.

3.2 Desired System Specifications and Requirements

The objective of the project is to develop advanced inspection and handling system for mini/micro products and component manipulation and assembly. Due to its open architecture – both hardware and software – workstation should easily adapt to many different applications. Further improvements towards higher accuracies and higher automation will be possible. At the same time workstation could be used as an experimental system for further experimenting in automated micromanipulation, microassembly and development of high precision systems.

Considering the issues defined in section 3.1, microassembly workstation should have the following requirements to operate with a good performance;

- A manipulation system with high accuracy at levels of nanometers for the precise handling of the micro parts.
- Robust control system design is of great interest in the microassembly. Modeling and control, especially vision assisted control, become more critical in microassembly as the accuracy requirements increase and the size of parts decreases.
- For the determination of the position and orientation of microparts, a sophisticated measuring system is needed such as an optical microscope for guidance in assembly of microparts.

3.3 Design Constraints

Design of a multiscale assembly system represents a complex problem with close interplay of many scientific fields and engineering disciplines. Some of the fundamental problems in the field of microassembly is still not fully investigated thus the microassembly workstation is designed to be used as a research equipment. That brings the necessity of an open architecture, both hardware and software, design of the microassembly workstation which will allow easy adaptation to research tasks.

Qualitative design considerations for multiscale assembly systems are listed below;

- Mechanical structure of the microassembly workstation is a challenging issue. Miniaturization requires development of a whole range of new miniature servo systems and measurement systems with very high accuracy and repeatability.
- A modular design of both the hardware and the software of the assembly system is an important design consideration for the scalability issues.

- Coarse-fine positioning based on considerations of accuracy, range, bandwidth and compliance. Positioning errors from of the coarse positioning system need to be compensated by the fine positioning system.
- Robust control system design is of great interest in the microassembly. Modeling and control especially vision assisted control, become more critical in microassembly as the accuracy requirements increase and the size of parts decreases.
- The assembly system should be designed and evaluated through directly measurable outputs of the assembly task. Specifications for the assembly system should not be based solely on the part size and tolerance. This consideration alone will lead to significant equipment cost savings.
- Measurement of position and orientation of microparts is a complicated task that requires sophisticated measuring system. Usage of optical microscopes for assembly of the components of a few micrometers and a possibility to obtain stereo image of an object with submicron accuracy is still a challenge.
- The problem of manipulation under microscope is stemming from the loss of eye-hand coordination and the limited dexterity of the manipulator and grippers. The mechatronics man-machine interfaces are becoming a very important part of the overall assembly system.

3.3.1 Micromanipulation System

Manipulation system should allow the positioning of the end effector with very high accuracy. According to the complexity of the manipulation tasks, the manipulator system should have necessary number of the degrees of freedom. With translational degrees of freedom in x, y and z coordinates, system will be capable of executing simple pick and place tasks and some 2D tasks such as pushing, pulling type of assembly tasks. To be able to implement more complex assembly tasks and to provide the system to adapt to any kind of assembly process, a rotational degree of freedom about the z axis will be required for the manipulator system.

In addition to the necessity of high resolution for the manipulator system, it should also have the capability to scan a wide area as the microparts may be scattered over the substrate. To be able to handle and gather the parts the manipulation system should have the necessary travel range to access the microparts dispersed on different areas of the substrate. In addition to cover a large workspace area, coarse positioning stages should have enough accuracy in order to bring it into the range of motion of the fine positioning system. According to the information from the vision system, fine positioning is performed by the fine positioning stages with an order of magnitude better than coarse positioning stages. Since the workstation contains multiple degrees of freedom consisting of translation and rotation, great attention has to be paid to the manipulator kinematics which is influenced by the order in which the microstages are assembled. In particular, if the distance from rotation centers to the microgripper is significant, it will amplify the manipulator positioning error. Moving across scales from meso to micro can be accomplished with a coarse-fine positioning scheme provided that the accuracy, bandwidth, and compliance of the coarse positioning system are smaller than the range, bandwidth, and compliance of the fine positioning system. Essentially, positioning errors from of the coarse manipulator have to be compensated by the fine positioning system.

3.3.2 Control System

The micro assembly workstation will serve the purpose of manipulating micron and sub micron sized modules, and assembling them to build complex but small sized machines or modules thereof. This section focuses on the design methods for the implementation of control system aspects of the project. The system can be made up of the following modules:

- Positioning stages with different type of actuation mechanisms
- Manipulation tools (e.g. microgrippers)
- Vision system with cameras and an optical microscope which has actuated focusing and zooming features
- Man-machine interface consisting of devices that relay concise information to the user including a haptic device for information exchange.
- Main control computer as the computing engine running in real-time, processing the data coming from various parts of the system and producing reference values for the modules.

- Real-time communication network to provide the connectivity between the modules.
- Non-real time communication network to communicate between parts of the system where occasional late arrival of data can be tolerated. (e.g. connection between the main control computer and the haptic device.)

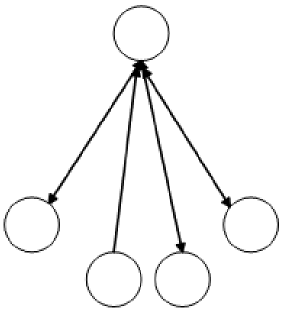
The modules of the system listed above should be configured in such a way that they can operate independently of each other. In order to provide the functioning of the whole system, all modules must be coordinated. For the coordination of the modules, there are several ways to implement the data processing and the control system.

The traditional method is the “Centralized Approach” in which a powerful computer is placed at the center of the system and sensors, actuators and other modules are connected to that computer. Main advantage of the centralized system is the simplicity. Since all modules are connected to the central computer, all the information is concentrated in one place which makes it fast to access for real-time operations. On the other hand, the system cannot be easily modified, it is hard to modify as any modification brings the necessity of both hardware and software changes. Also the scalability of the system is limited with the capacity of the central computer. CPU would need to be fast to provide the necessary computation power.

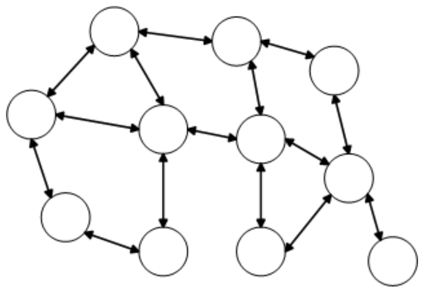
The opposite of the “Centralized Approach” is to have each module implement its own set of functions and exchange the minimum information required among each other, which is called “Decentralized Approach”. In this configuration, each module is working autonomously while exchanging data with the other modules. In that configuration data transfer is reduced as a result of the autonomy of the modules. However, the system is hard to manage as the functionality of the system depends on the cooperative behavior of each module which makes it a very difficult problem to guarantee the stability of the whole system.

Another method is to a have hierarchical structure in which the fast control loops and simple operations are done locally by the modules and the computations regarding the whole system are done centrally by the main computer. This is called “Distributed Approach”. Considering for the realization of the microassembly workstation, each module is treated as a separate system getting a reference input from the main computer and sends the sensor and other data to the main computer. The rest of the low level tasks are realized within each module. The main control computer deals with the supervision and control of the overall system, man machine interface and other tasks, and generates references for the modules. In order to connect the system units together, an internal real-time communication network is used. Man machine interface is the only module which does not require real-time communication as a result of the nature of the human interaction.

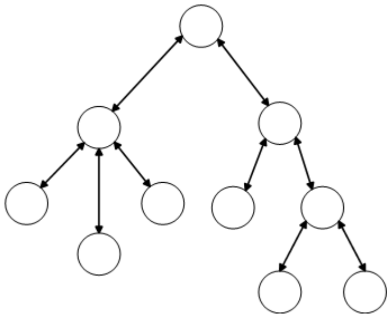
Centralized and distributed approaches are the suitable ones for the realization of the control system of the microassembly workstation.



a) Centralized Approach



b) Decentralized Approach



c) Hierarchical Approach

Figure 3-2 – Control System Approaches

3.3.3 Vision System

In the micro domain, position and orientation of the parts to be assembled with respect to each other and the manipulation tool can be determined using a vision system. An effective vision system is necessary to visualize the micro domain for recognizing the geometries and position of 3D microparts, path generation for the micromanipulator and providing the necessary position feedback. Application of different vision technologies depends on the size of the parts to be manipulated. The assembly task for the microassembly workstation is defined in the micrometer domain, so that optical microscope and contact manipulation are suitable solutions for the vision system. (Figure 3-3)

Scanning tunneling microscope (STM) is regarded as the manipulation tool for handling a single atom in the atomic scale world. However, STM can be used only to handle objects with atomic scales. In the intermediate region of 1 nanometer and 1 micrometer, where neither manipulation under STM nor optical microscope is applicable, manipulation technology such as handling (pick and place), assembling and machining are in early stage of development and scanning electron microscopes (SEM) are candidates for this region.

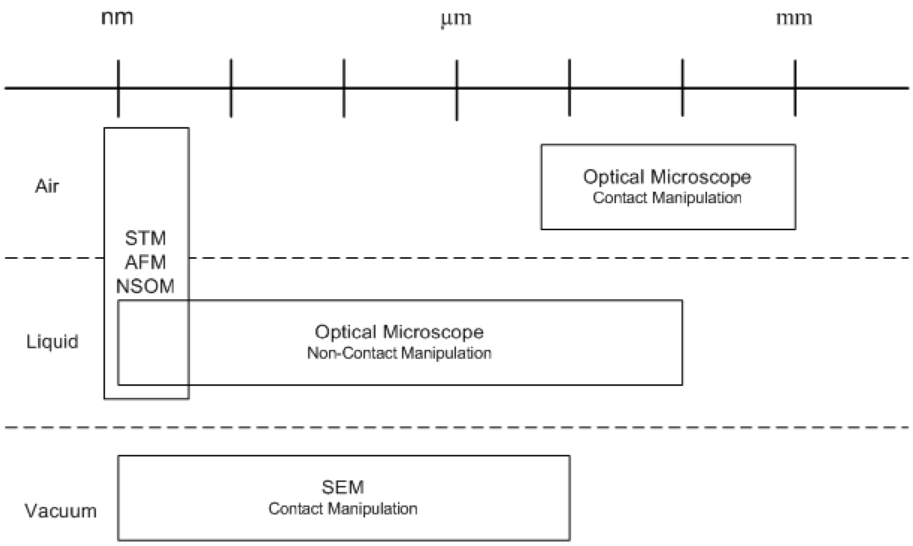


Figure 3-3 - The selection of the vision system and gripper according to the size of the manipulated object and the media

For the vision system selection for the visualization of microworld and providing relative position feedback, some specifications should be considered carefully. These specifications include;

- Magnification is the measure of the difference in size between the object and the image. According the object size to be assembled, magnification of the microscope should be selected in such a way that the objects can be visualized clearly to identify the object geometries.
- Resolution is one of the most important features for the vision system. The measurement of the ability of an optical system to distinguish, detect and record physical details of the object and reproduce these to the image. The resolution of an optical microscope can be characterized by a modulation transfer function (MTF), which is a measurement of the microscope's ability to transfer contrast from the specimen to the intermediate image plane at a specific resolution. Resolution of the vision system determines the lower limit of the object size to be manipulated and it is important in the sense that it allows the determination of the object geometries in a precise manner.

- Working Distance is the distance between the object and lens system. It is important that the working distance of the vision system should allow the manipulation of the objects for assembly purposes simultaneously with the imaging system. Working distance should be large enough for allowing the motion of the manipulator to be able to realize the assembly tasks.
- Depth of Field is the amount of distance that allows the maintenance of acceptable image without refocusing. A narrow depth of field leads to precise focusing for the vision system. However, for 3D assembly tasks, it may become a problem as the focused image distance will be small.
- Field of View is the visible area that can be seen by the vision system. As the magnification increases the field of view becomes smaller. The minimum and maximum values of the visible area provided by the vision system should be carefully considered according to the scale of the microassembly task. That brings the necessity of a variable zooming feature of the vision system in a wide range. High magnification provides detailed information for the objects and the handling. However, higher magnifications bring narrower field of view and limit the workspace. A vision system capable of having a coarse imaging and a fine imaging at the same time can be the optimum solution for the field of view problem. While obtaining the workspace data from the coarse image, detailed information about the object can be retrieved from the fine image.
- Illumination is a key issue for the vision system. As the assembly tasks require image processing algorithms for the detection of the parts to be manipulated and information about the geometries of these parts, the illumination should be considered carefully. For example, shadows can cause problems for extracting the exact shape of the parts which may cause the assembly tasks to fail.

3.3.4 Manipulation Tools

One of the most essential components of microassembly systems is the manipulation tools determining the manipulation capabilities of the whole system. Manipulation is the key operation for a microassembly workstation as the assembly can be realized by means of manipulation.

Manipulation can be defined as “the action of touching with the hands (or the skillful use of the hands) or by the use of mechanical means”.[8] Human hand is the gold standard of manipulation and in the macro world the characteristics of the human hand is imitated for the design of the end effectors. In the micro world the case is somewhat different. Differing from the macro world dexterity may become less important as a result of the difference tasks and environmental conditions. Visualization becomes a more significant issue in the micro world as there are limitations such as orientation of the microscopes, magnification and depth of field. The number of degrees of freedom may become a drawback since there may be occlusions as a result of the complicated end effector structure. In addition to these constraints, with existing microfabrication methods, producing and actuating those micro mechanisms is difficult.

Another issue that has great significance in micromanipulation is the effect of force scaling. While the size of the objects become smaller, inertial forces scale down faster than adhesive forces as the inertial forces depend on the volume of the object and adhesive forces depend on the surface of the object. As a result of the effect of adhesive forces releasing the object after gripping becomes a great problem. The effect of adhesive forces should be carefully considered for a robust micromanipulation as it brings limitations to manipulation capabilities such as preventing the motion of the object.

For the manipulation of the microparts such as picking, placing, pushing, etc., manipulation systems should be integrated with necessary end effectors which have the capability of performing these tasks. These end effectors must be appropriate for the handling of microparts as the forces other than gravity dominate due to scaling effects. They should be designed in such a way that the effects of surface related forces such as electrostatic, van der Waals and surface tension forces should be overcome to be able to realize the assembly task successfully.

For a better understanding of the necessities and requirements for the manipulation tools, one needs to grasp the physics of micromanipulation very well. In the following sections, the effect of force scaling, dominant forces in the micro scale and reduction techniques and finally particular solutions for micromanipulation will be covered.

3.3.4.1 Physics of Micromanipulation

With the miniaturization of the objects to be handled to micron sizes, attractive forces, such as van der Waals force, surface tension forces and electrostatic force between microobjects and the manipulator become dominant over the gravitational and inertial forces.

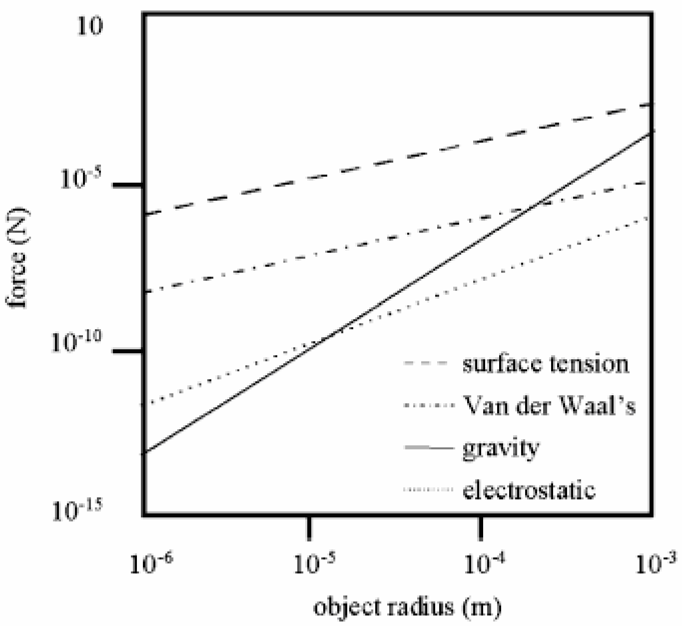


Figure 3-4 – Comparison of gravitational and adhesive forces [9]

These attractive forces depend on environmental conditions, such as humidity, temperature, surface condition, material, etc. For the manipulation of the microobjects, the physics in the micro world should be carefully considered. Thermal, optical, electrical, and magnetic effects will change or become dominant when the objects are miniaturized (Figure 3-4). Micro parts stick to the manipulator surface as a result of these attractive forces and the manipulation becomes a very challenging task. (Figure 3-5) When the manipulation takes place in open air condition, attractive forces present in the environment are van der Waals forces, surface tension forces and electrostatic forces.

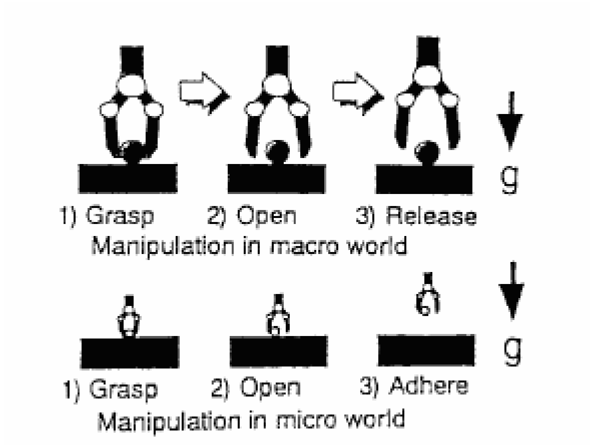


Figure 3-5 – Difference of Macro/Micromanipulation [10]

3.3.4.1.1 Van der Waals Forces

Van der Waals forces are the physical forces of attraction and repulsion existing between molecules. Van der Waals forces make varying contributions to the overall intermolecular force which can be classified as;

- The orientation effect (dipole - dipole);
- The induction effect (dipole – induced dipole);
- The dispersion effect or the London force, (induced dipole – induced dipole)

For most of the materials except special materials with strong polarity (water, ammonium, etc.) dispersion effect is dominant. The dispersion force is also called the London force and it is generated based on the instantaneous dipole generation when the two atoms get closer. The interactive energy between atoms from the London's theory;

$$\varepsilon = -\frac{\Lambda}{z^6} \qquad (3\text{-}1)$$

where Λ is a constant and z is the distance between the atoms. The interactive force between the two spheres based on the interactive energy between atoms by integrating the whole area (Figure 3-6) we derive the equation;

$$E_{vdw} = -\frac{H}{6}\left[\frac{2r_1r_2}{R^2-(r_1+r_2)^2} + \frac{2r_1r_2}{R^2-(r_1-r_2)^2} + \ln\frac{R^2-(r_1+r_2)^2}{R^2-(r_1-r_2)^2}\right] \qquad (3\text{-}2)$$

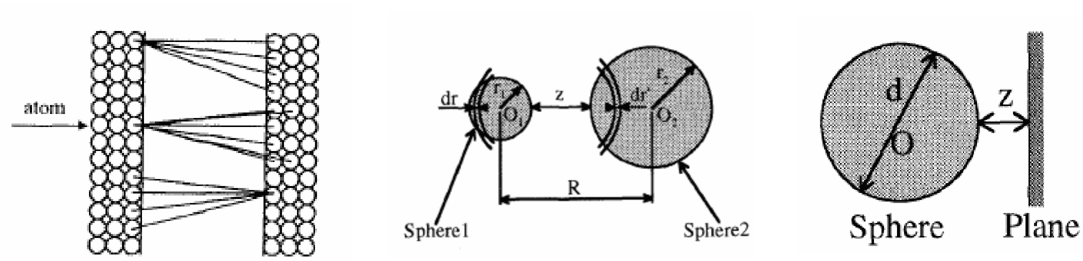
$$H = n^2\pi^2\Lambda$$

where H is the Hamaker constant. Taking r_2 infinite, van der Waals interactive energy and force between a sphere and plane can be calculated as (Figure 3-6):

$$E_{vdw} = -\frac{H}{6}\left[\frac{d}{2z} + \frac{d}{2(z+d)} + \ln\frac{d}{z+d}\right]$$

$$F_{vdw} = \frac{H}{6}\left[\frac{d}{2z^2} + \frac{d}{2(z+d)^2} - \frac{1}{z} + \ln\frac{1}{z+d}\right] \qquad (3\text{-}3)$$

where $d = 2r$.



(a) Van der Waals force (b) Two spheres (c) Sphere and plane

Figure 3-6 – Van der Waals Forces [11]

3.3.4.1.2 Surface Tension Forces

In a humid environment or when the surface is hydrophilic, a layer of adsorbed moisture may be present between the spherical object and the surface forming a large capillary force. (Figure 3-7) The effect of the surface tension force and capillary force is modeled as follows;

$$F_t = \pi R_2^{\,2}\gamma\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + 2\pi R_2\gamma \qquad (3\text{-}4)$$

where, γ is surface tension force. Here, if R_2 is small enough compared with d, equation above is approximated as follows.

$$F_t = \pi\gamma d \tag{3-5}$$

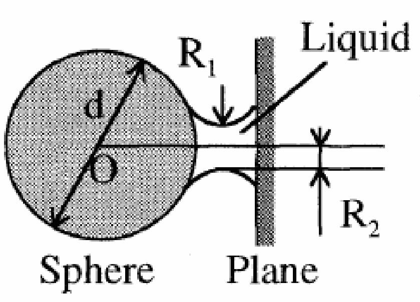


Figure 3-7 – Force caused by absorbed moisture layer [11]

3.3.4.1.3 Electrostatic Forces

Electrostatic forces arise from charge generation or transfer during contact. They can be classified into three types:

- Electrostatic force caused by contact charge of bodies following uncharged bodies

$$F_{ce} = \frac{1}{2}\pi\varepsilon_0 \frac{V_c^{\,2}}{Z^2}\left[\frac{Hkd^2}{32z^2}\left(1+\frac{H^2k^2d}{108z^7}\right)\right]^{2/3} \tag{3-6}$$

where, ε_0 is dielectric constant, V_c is contact voltage difference, z is distance, H is Hamaker constant, k is elastic constant characterized by Young's modulus and Poisson's ratio. d is reduced diameter defined as follows;

$$d = \frac{d_1 d_2}{d_1 + d_2} \tag{3-7}$$

where, d_1 and d_2 is the diameter of each sphere.

- Electrostatic force between charged body and uncharged body. Considering a charged sphere with diameter d and an uncharged wall, electrostatic force between these bodies can be written as (Figure 3-8);

$$F_e = \frac{\pi}{4\varepsilon_0} \cdot \frac{\varepsilon - \varepsilon_0}{\varepsilon + \varepsilon_0} d^2 \sigma^2 \qquad (3\text{-}8)$$

where, ε is dielectric constant of the wall, σ is electric charge density of the surface.

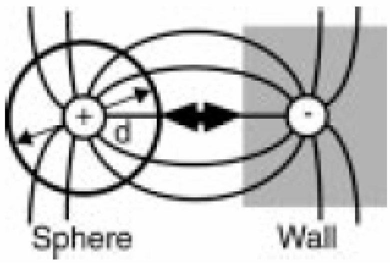


Figure 3-8 – Electrostatic force between a charged body and an uncharged body

- Electrostatic force between the charged bodies. If the distance z is small enough compared with reduced diameter d, it is written as follows.

$$F_e = \frac{\pi \sigma_1 \sigma_2 d^2}{\varepsilon_0} \qquad (3\text{-}9)$$

where, σ_1, σ_2 is electric charge density of each sphere.

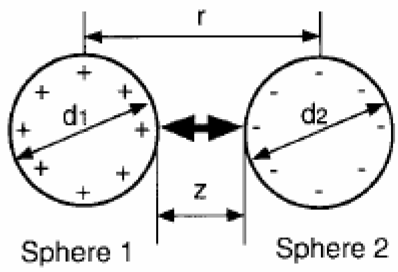


Figure 3-9 – Electrostatic force between two charged bodies [10]

In the micromanipulation simple stick and remove motion is preferable. To control or use stick/ remove motion the attractive forces which becomes important for that kind of motion in micro world must be reduced. Research on reducing the effects of attractive forces is promoted [10], [12]. Some of the strategies for reducing the attractive forces are defined in the following section.

3.3.4.1.4 Reduction and Overcoming of Adhesive Force Effects

For the reduction of the sticking effects in micromanipulation, the effects of surface forces can be reduced by an adapted choice of the manipulation parameters. In order to reduce the effects of Van der Waals forces, it is suggested to:

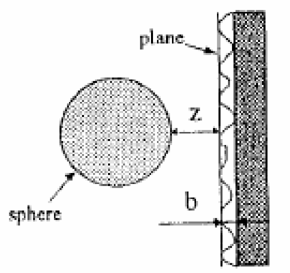
- Change Material and Coating Different Material [11]

Van der Waals force depends on the Hamaker constant so that changing the material surface coating or choosing a suitable material, Hamaker constant results in the change of the Hamaker constant causing the Van der Waals force to change. When the gap between two bodies is filled with the different material, the Hamaker constant is written as follows;

$$H_{123} = (\sqrt{H_1} - \sqrt{H_3})(\sqrt{H_2} - \sqrt{H_3}) \tag{3-10}$$

where H_1, H_2 is the Hamaker constant of each body and H_3 is that of the sandwiched body. If the non-charged material which has low Hamaker constant is coated on the surface, van der Waals force as well as electrostatic force is reduced.

- Increase Surface Roughness [11], [12], [13], [14]



Minimizing the contact area reduces the van der Waals force so that the roughness of the surface directly affects the van der Waals force. Van der Waals force is calculated as follows with the surface roughness of b;

$$F_{vdwb} = (\frac{z}{z + b/2})^2 F_{vdw} \tag{3-11}$$

Figure 3-10 – Rough surface and sphere with smooth surface [11]

A microendeffector with micropyramids (sharply edged projections) on the end effector surface can reduce the Van der Waals force by reducing the contact surface and electrostatic force as the sharp electrodes are effective to generate the high electric field.[10]

The liquid bridge force due to the capillary condensation of water when the humidity of the atmosphere around the two contacting surfaces is high. For the reduction of surface tension forces thermal treatment and hydrophobic treatment are effective. For the thermal and hydrophobic treatment in order to reduce the surface tension effects;

- Number of contact points can be reduced
- Hydrophobic coatings can be used [11]
- Micromanipulation can be handled in liquid environment [15], [16]
- In air Si and metals can be easily covered by hydrophilic native oxide layer which can be overcome by working under vacuum.

For the reduction of electrostatic forces;

- Conductive materials can be used for manipulation purposes. [12]
- Manipulation can be realized in vacuum environment without O_2 so that the effects of the insulation layers can be neglected as the objects to be handled and the manipulation tool surfaces can be covered with native oxides which are a good insulation layer.
- Materials with a small contact potential difference can be used.[12]

On the other hand several solutions are proposed in order to overcome the sticking effects. However these techniques are just practical solutions which cannot result from an integrated approach. Some of these proposed solutions are;

- Using a large probe for picking the micropart by using the effects of the surface forces and using a smaller probe for releasing. [17], [18]
- Using vibrations to perform the release task [19]
- Accelerating the manipulation tool with a high acceleration which can overcome the sticking force to the component. [20]
- Using a vacuum gripper and injecting gas to push the object [17], [18]
- Gluing the part to the substrate on the right place [21]
- Destruction of the gripping mechanism. For instance, with a gripper using the surface tension force to pick an object, the object can be released by heating the gripper and evaporating the adhesive liquid. Another example is the ice microgripper described in [22].

3.3.4.2 Particular Solutions

There are relatively few manipulation tools available on the market; however research on new designs is growing with several types of tools with different gripping principles in the research institutes. Some particular solutions for manipulation and their working principles are defined in the following sections. (Figure 3-11)

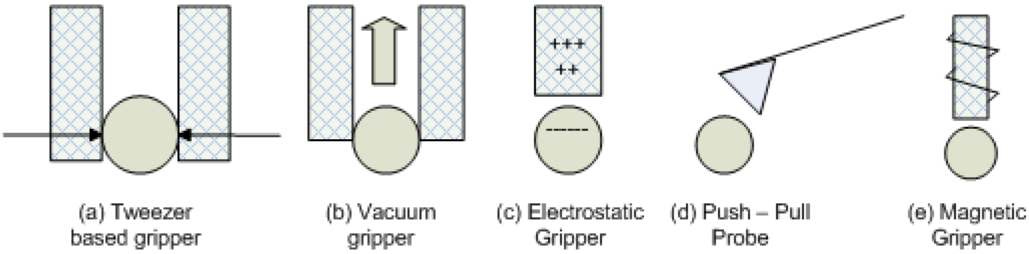


Figure 3-11 – Working Principles for Manipulation

3.3.4.2.1 AFM Probes as Micromanipulation Tools

The AFM (Atomic Force Microscope) measures the ultrasmall interaction forces (less than 1 nN) present between the tip and surface by measuring the motion of a very flexible cantilever with an ultrasmall mass. The tip may be dragged across the surface, or may vibrate as it moves. The interaction force will depend on the nature of the sample, the probe tip and the distance between them.

The movement of the tip or sample is performed by an extremely precise positioning device made from piezo-electric ceramics, most often in the form of a PZT tube scanner. The sharp tip of the flexible cantilever is brought in contact with the sample with that positioning device. As the sample moves under the tip features on the sample surface causes the cantilever to deflect in the vertical and lateral directions. A diode laser is focused onto the back of a reflective cantilever. As the tip scans the surface of the sample, moving up and down with the contour of the surface, the laser beam is deflected off the attached cantilever to a position-sensitive photodetector consisting of two photodiodes. The difference between the two photodiode signals indicates the position of the laser spot on the detector which is a sensitive measure of the deflection of the cantilever as the cantilever deflections are proportional to the difference signal. Since the Cantilever obeys Hooke's Law ($F = -k.x$, where k is a constant and depends on the material and dimensions of the cantilever and d is the displacement of the cantilever.) for small displacements, the interaction force between the tip and the sample can be found. (Figure 3-12)

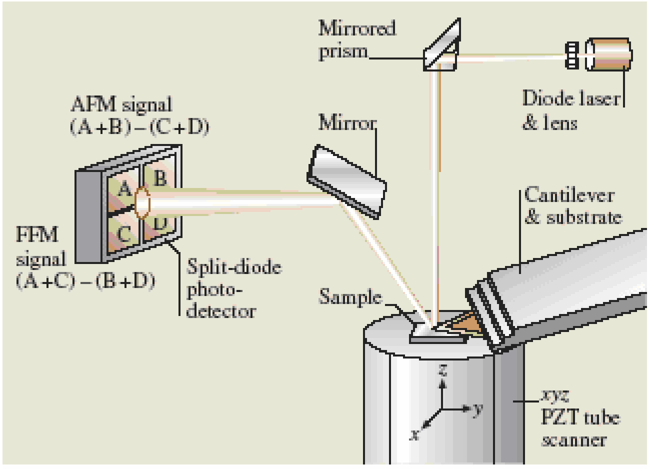


Figure 3-12 – AFM structure

Probes are the key components in the operation of an AFM. An AFM probe is a micro fabricated silicon or silicon nitride cantilever with a sharp tip at its end. For high vertical and lateral resolutions at small forces less than 0.1 nN, low spring constant is required for an AFM probe. At the same time, in order to minimize the sensitivity of the probe to vibration noise a high resonant frequency from 10 to 100 kHz is necessary. This requires a spring with extremely low vertical spring constant from 0.05 to 1N/m with a low mass of 1 ng.

With the problem of micromanipulation which can be defined as the manipulation; pushing, pulling, indenting, etc, of micrometer size objects with micrometer size end effector with micrometer precision, AFM also became popular as a simple manipulation tool. It gives the opportunity to realize both imaging and manipulating with the same tool. However, imaging with the AFM is offline so that during the manipulation operation unexpected problems can not be detected. Because of this problem optical microscope imaging can be added to the system which can give real-time visual feedback. As the AFM is working with the principle of force feedback, during the pushing operation real-time force feedback can be utilized and with the characterization of the force, fragility of the particles and probes can be reduced resulting in a more robust manipulation operation. The force feedback can be utilized by the AFM photodiode system described above and by using piezoresistive cantilevers [23], [24]. Manipulation of micro particles without utilizing the force feedback by using only visual feedback is also realized in [25].

Using AFM probes simple 2D tasks can be realized. Research on using AFM probes as manipulators has been a hot topic for the recent ten years. As examples of these tasks, micro particle pushing [23] and indenting [26] can be given. 3D manipulation can also be realized such as manipulations of CNTs with single probe. [27], [28], [29], [30]

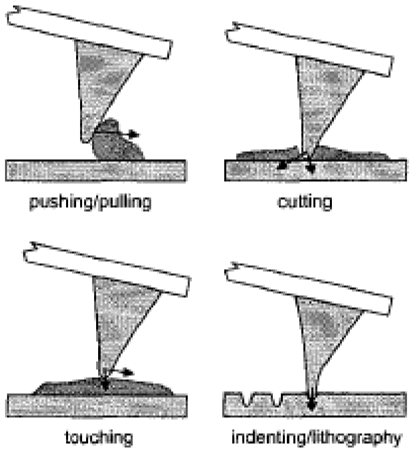


Figure 3-13 - Possible Manipulation Tasks using AFM probe as a manipulation tool [31]

3.3.4.2.2 Microgrippers

For the necessity of 3D manipulation tasks such as pick place operations of the micro parts, manipulators which can realize these tasks become necessary. As the field of micromanipulation has been a hot topic and the needs are growing for the assembly of micromechanical parts, handling of biological cells and samples for testing or characterizing and surgery, research on solving the problem of micromanipulation is growing with different designs of microgrippers with different working principles.

- Electrostatic Microgrippers

Working principle of these devices depend on the coulomb forces present between two charged plates, subject to a difference of potential. [32] reported a microgripper which has one inner electrode and two outer electrodes gripping the micro objects with the electrostatic force and releasing with the backwards motion of the inner electrode with electrothermal actuation breaking the electrostatic field. [33] proposed a polysilicon microgripper with the structure made up of electrostatic comb drives that has the finger opening and closing of 10 μm and generating a force of 104nN at 50V.

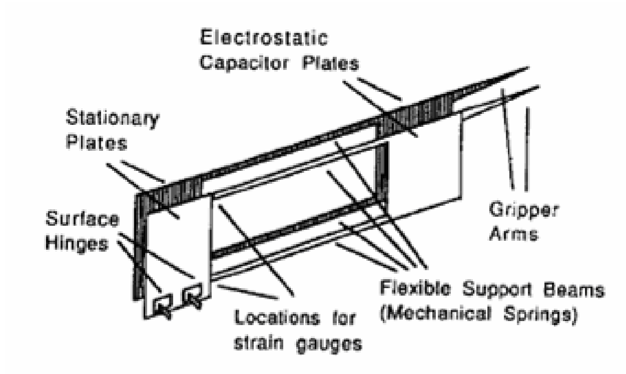


Figure 3-14 - A typical Parallel Plate Electrostatic Gripper [34]

- Thermal Microgrippers

Thermal actuation is another principle for actuating microgrippers. The actuation principle is based on the difference between the thermal properties of two materials or the difference of temperature between two regions of a material. The actuator consists of two electrically conducting and connecting arms. According to the width, resistance and heat dissipation differences between these two arms, the thinner arm (hot arm) has a higher temperature and as a result of the thermal expansion the tip bends laterally towards the thick-flexure arm (cold arm) side [35], [36], [37]. Material used in this type of microgrippers should be conductive because of the electrical nature of this actuator.

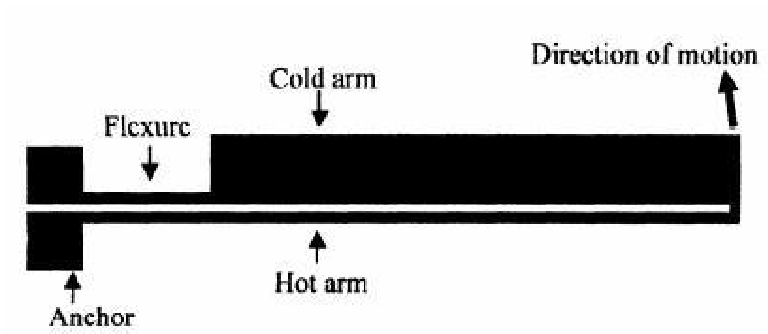


Figure 3-15 – Thermal Actuation Mechanism

- Piezoelectric Microgrippers

Piezoelectricity principle is used as the actuation principle for this kind of microgrippers. There is a great interest in that kind of actuation as the piezoelectricity offers several advantages such as great speed and high precision. On the other hand piezoelectric microgrippers are limited in actuation strokes which bring the necessity of amplifying mechanisms that causes a reduction in the actuation forces (Microgrippers with compliant structures actuated by piezoelectric actuators) [38], [39]. However, the reduced gripping force still remains sufficient to handle microobjects. Another limitation is that the inherent hysteresis and creep which makes the control of the piezoelectric actuator difficult. [40], [41] proposed a control method for hysteresis compensation for the microgripper with the structure of piezoelectric bimorphs based on the deformation of two beams independent of each other mechanically.

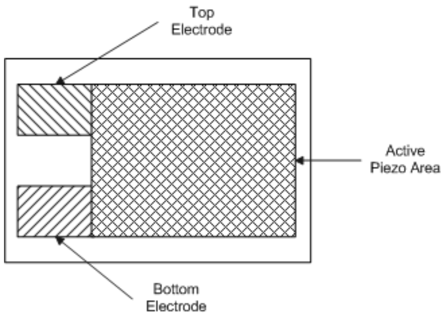


Figure 3-16 – Piezoelectric Film Pattern

- Vacuum Microgrippers

This kind of grippers use the pressure difference between the atmosphere and the vacuum generated inside the gripper to pick up the microparts. Releasing of the particles do not possess so much problems due to the thin tube employed and the absence of sealing which reduces the contact surface between the microparts and the gripper and relatively adhesive forces. However, during gripping operation parts picked may undergo slight displacements. [42]

- Magnetic Microgrippers

The gripping force comes from the magnetic field generated by magnets. For the actuation permanent magnets, electromagnets or superconducting magnets can be used. However, the use electromagnetism is limited for the materials with high electrical conductivity. [43], [44]

3.4 Conclusion

As described in the previous subsections, the action of micromanipulation is very complex and possessing several problems because of the adhesive forces, complicating the pick and place tasks. Requirements for the microgrippers differ from the conventional grippers not only for the size of the particles to be manipulated but also for the required gripping forces. As a result of that for the design of micromanipulation tools, it is not possible to just miniaturize the existing manipulation tools in the macro domain. According to the tasks to be realized and parts to be manipulated in the micro domain, a specific manipulation tool is necessary which can perform not only gripping but also releasing of the particles.

We aim to design a microassembly workstation that can allow execution of different assembly tasks which brings the necessity of using different sizes and types of end effectors. For that reason, the workstation is designed in such a way that it has the necessary fixtures and tool exchange devices to allow the use of different end effectors for different assembly tasks.

4 DESIGN AND IMPLEMENTATION

4.1 Introduction

This chapter is intended for explanation of hardware design and implementation of the microassembly workstation. In order to setup an open-architecture and reconfigurable microassembly workstation with the necessary specifications, issues related to the selection of the system components, detailed mechanical design concepts and the configuration of the components will be discussed.

In the following sections, the whole system will be examined in details as well as subsystems of: (i) manipulation, (ii) control, (iii) vision and (iv) end effectors. End-effectors are not included in the manipulation subsystem as detailed information will be given for possible solutions. Specific requirements for each subsystem will be introduced and realization of each system will be presented. Finally, configuration of the whole system from these subsystems will be presented.

4.2 Configuration of the Whole System

For targeting a precise, flexible and robust microassembly workstation, the system should be configured in such a way that the final system will be as simple as possible and highly efficient. In that sense, every moving component of the workstation should be placed according to the design considerations discussed in chapter 3.

The overall structure of the workstation is presented in Figure 4-1. The system has the following main components:

1. Manipulation System consists of the gripper manipulator and the sample stages, providing the motion necessary for the manipulation operations.

    a. Gripper manipulator consists of coarse and fine positioning stages providing necessary travel range and the accuracy for the manipulation stages mounted on the fine positioning stages.
    b. Sample Stages and provide the usage of the substrate surface more effectively by moving the different regions of the substrate into field of view.
2. Control System is the main control unit of the system consisting of a PC and a controller board embedded into the PC.
3. Vision System can be examined in two parts;
    a. Optical System consisting of a stereoscopic optical microscope, CCD cameras mounted on the microscope and an autofocusing control unit. The automatic zoom and the autofocusing motion units are mounted on the microscope and the control is realized from the vision computer.
    b. Illumination System is configured to provide backlighting by means of a mirror system using a fiber illuminator as the light source.
4. End effectors and necessary fixtures are used interchangeably in the system. Microgrippers and probes can be the matter of choice and necessary fixtures are designed to be easily integrated to the system.
5. The whole system is placed onto an actively controlled damping table in order to get rid of environmental vibrations.

The system has more than ten degrees of freedom and there is a little space for manipulation operations below the microscope lens and the surface where the microparticles are deposited. Within this space the working range of the motion stages must be carefully considered for not to allow any collision between these components and fixturing operation must be realized accordingly. Sample stages which will be defined in section 4.3 are placed beneath the microscope objective so that by the movement of these stages the region of interest on the glass substrate can be changed in order to bring the workpieces into the field of view of the microscope. Fine and coarse stages are placed next to the microscope and fine stage is equipped with necessary mounts for the manipulation tools. For the manipulation tool to be able to reach the field of view of the microscope and realize the manipulation operations within the field of view an arm structure is produced and tools are attached to the end of this arm. That mount is designed in a way that the tool tip can be tilted just by adjusting manually and enhanced by a manual rotation axis for the sake of removing the tool safely.

The whole system configuration is shown in Figure 4-2.

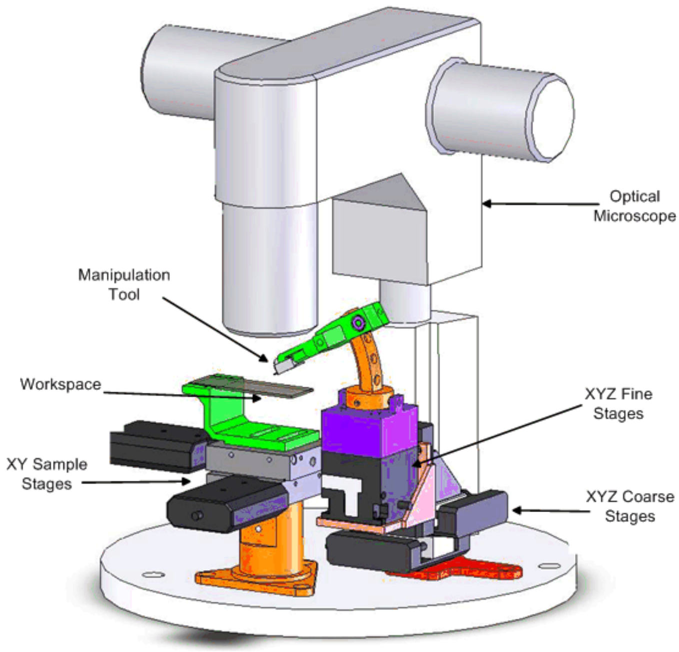


Figure 4-1 – Microassembly Workstation

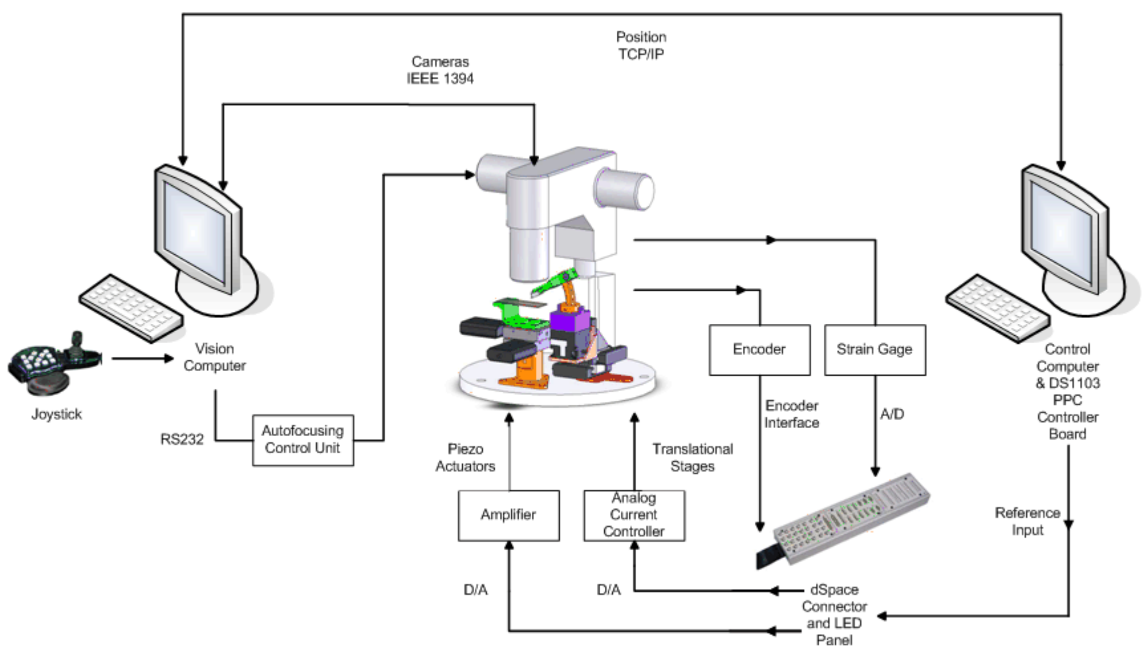


Figure 4-2 – Configuration of the Whole System

In the following sections the detailed description of each subsystem will be presented.

4.3 Manipulation System

For the implementation of the manipulation system, desired system specifications and requirements are discussed in section 3.3.1. The manipulator system consists of a coarse positioning and a fine positioning stage. Coarse positioning stage covers a large workspace area while providing enough positional accuracy to bring it into the range of motion of the fine positioning stages. According to the information extracted from the vision system, objects to be manipulated or the manipulation tool is moved into the visible area of the microscope and the final positioning is made by the fine positioning stage with high accuracy.

The coarse positioning stages should have enough travel distance to cover the necessary workspace area while having enough accuracy smaller than 10 micrometers. For the coarse positioning system, we proposed a Cartesian motion system with degrees of freedom in x, y and z. According to the configuration of the whole system, a workspace of at least 15 mm in x, y and z axes are required. The accuracy of the coarse stages is important as we aim to have nanometer scale accuracies. For the selection of the coarse stages, travel range, accuracy and the speed are considered. Size of the positioning stages is also another concern for the sake of design to be compact.

According to the specifications described above, PI M-111.1DG motorized translational stages are chosen for the coarse positioning system. (Figure 4-3) These stages provide ultra-high resolution with the travel range of 15 mm in a compact package. Motion is actuated by a backlash compensated leadscrew/nut system and gearhead. A high resolution encoder with resolution of 0.007 µm per count is integrated to the DC motor. Minimum incremental motion of the translational stages is 50 nanometers with speeds up to 1.5 mm/sec.

Figure 4-3 – Motorized Translational Stage, Image Courtesy of PI Gmbh

As an alternative to the M-111.1DG stages, M-105.10 translational stages with motor drive upgrades (M-232.17) is proposed. (Figure 4-4) These translational stages with the integrated high-resolution, closed-loop DC-Mike actuators have a travel range of 17 mm and with encoder design resolution of 0.007 μm per count. Minimum incremental motion of the translational stages is 50 nanometers with speeds up to 2.5 mm/sec.

Figure 4-4 - M-105.10 translational stages with motor drive upgrades (M-232.17)

Fulfilling the specifications defined for the coarse positioning system and being more compact, M-111.1DG motorized translational stages are used for the Cartesian xyz coarse motion system.

For the manipulation system, it is decided to use a combination xyz of coarse motion and xyz fine motion. Fine positioning stages should have the accuracy (10 nm) with an order of magnitude better than the coarse motion stage to be able to realize more precise motion. Requirements for the fine positioning stages can be defined as; submicrometer resolution, workspace of hundreds of micrometers, compact size and high speed of response. Piezo actuators offer high precision in the range of a few nanometers. These actuators can also handle high loads and move very fast. On the other hand, they have limited travel ranges and the piezoelectric actuators suffer from hysteresis and drift since the former one can cause not only positioning error but also instability.

Since the specifications determined for the fine positioning motion can be provided by the piezo actuators, PI P-611.3S NanoCube® multi-axis piezo-nanopositioning system is selected to drive the fine motion. (Figure 4-5) NanoCube® has travel range of 100 μm in the xyz axes with 1 nm resolution and settling times of only a few milliseconds.

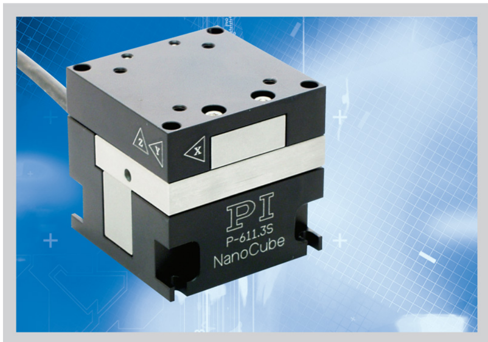


Figure 4-5 - Nanocube® XYZ Piezo Nanopositioning System

CAD Drawing of the combined structure of the manipulation system is shown in Figure 4-6.

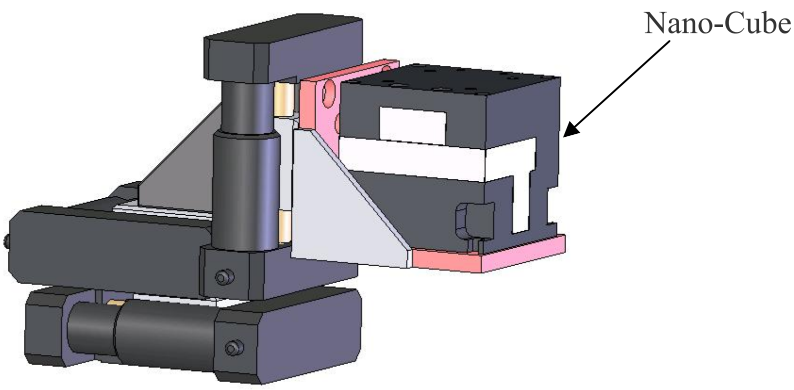


Figure 4-6 – CAD model of the manipulation system

In addition to the manipulation stages with the configuration of coarse and fine positioning with orthogonal axes of x, y and z, there are two translational stages with the xy configuration in the system. These stages are configured to be sample stages as they are moving the substrate under the microscope in order to provide the usage of the sample glass area efficiently without limited only by the area which is in the field of view. These sample stages is added to the manipulation system as they make the manipulation possible by moving the micro particles into the field of view. For the sample stages PI M-105.10 translational stages with motor drive upgrades (M-232.17) which are stated above are used.

In order to control the stages those are defined in section 4.3 precisely, a low cost high resolution controller board is designed. Motor driver with the lowest power available in the market is 20W and the translational stages used in the system are equipped with 2W DC motors. Using a 20W motor driver in current control mode for a 2W motor causes great loss of resolution which also affects the resolution of the position control. As a result of that, a high resolution driver is designed by using TDA2040 20W Hi-Fi Power Audio Amplifier as a classical op-amp mode to control the output current on a resistor by measuring the voltage on it. By simply adjusting the suitable resistance value used in the driver, the problem of resolution can be solved. Circuit schematic of the driver is shown in Figure 4-7.

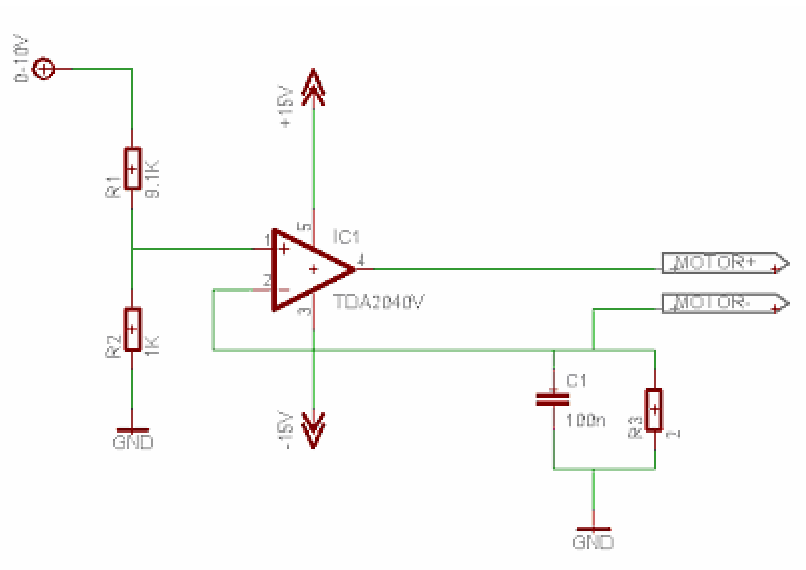


Figure 4-7 – Current Controller Circuit

4.4 Control System

Necessary number of degrees of freedom for the flexibility and possibility to realize different assembly tasks is defined in section 3.3.1. The control system should have the capacity for the real-time control of all axes simultaneously. Implementing the centralized structure, a main control computer, giving reference values and not possessing any direct sensor or actuator connections and a module control computer implementing a fast control loop by taking the reference values from the main control computer is necessary. A high performance personal computer (PC) is configured as the main control computer. Some requirements for the module control computer are ease of programming, modification and expansion, standalone operation, network connectivity, and possibility of remote diagnostics and debugging. For the module control computer a dSpace 1103 card satisfying the computational power necessary to solve control issues for all DOF is selected. The card allows the implementation of the real-time data acquisition and feedback control with 16 bit A/D and D/A converters and interfaces for connecting incremental encoders.

4.5 Vision System

In section 3.3.3 design necessities for the vision system of a microassembly workstation is defined in detail. Vision system is the sensor module of the whole configuration by allowing the monitoring the microworld as well as visually guiding the microassembly system. By using an optical microscope manipulation of micro particles with sizes from 1 µm to 1 mm can be executed. According to the design criteria, Nikon SMZ1500 Zoom Stereomicroscope is selected as the visualization tool for its workspace allowance, high magnification capabilities and high resolution optics. Specifications of the SMZ1500 are listed in Table 4-1.

Optical System	Parallel-optics zoom system
Total Magnification	1.5X – 675X (depends on the used eyepiece and objective)
Zoom Range	0.75X – 11.25X
Zoom Ratio	15:1
Illumination	Illuminator Light Source and Fiber Pair
Workspace	22 mm

Table 4-1 - Nikon SMZ1500 Microscope Specifications

Automatically adjustments of the zoom and focus are very important for the visual servoing capabilities of the overall microassembly system so that the microscope is equipped with a Z axis drive and controller (ASI – MFC 2000) with resolution of 0.05 μm for controlling the focus/Z position of the microscope stage. The microprocessor-controller MFC-2000 control unit provides RS232 communication with the host computer so that autofocusing can be managed from the computer.

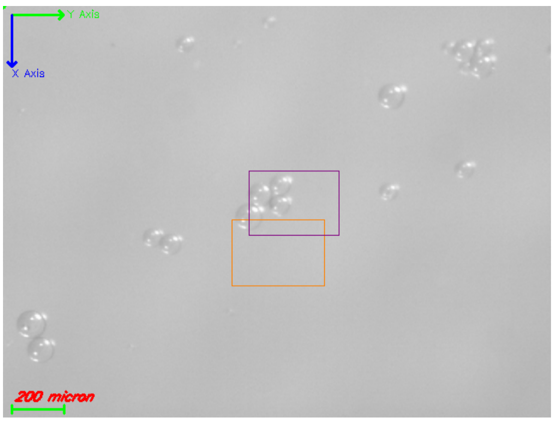
The vision system includes four high speed CCD cameras (100 fps) with resolution of 640x480. Two of them are installed to the eyepiece of the microscope for obtaining a stereo image and having the opportunity of applying stereo vision techniques. Another feature for the installation of the cameras to the eyepiece is to have an image with a higher magnification so that these cameras can be used for the fine imaging purposes. One of the cameras is installed to the camera path of the optical microscope for being used as the coarse imaging for the system and one of them is used as the side imaging to visualize the whole system.

The field of view of the coarse and fine views for different magnifications of the microscope is depicted in Table 4-2.

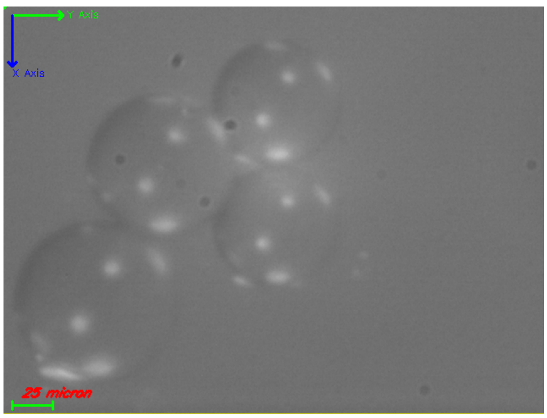
Magnification	Coarse Camera View (640 x 480 Image)	Fine Camera View (640 x 480 Image)
0.75×	5204.16μm × 3903.12μm	828.16μm × 621.12μm
1×	3939.84μm × 2954.88μm	610.56μm × 457.92μm
2×	1987.84μm × 1490.88μm	314.88μm × 236.16μm
3×	1354.49μm × 1015.87μm	209.92μm × 157.44μm
4×	983.68μm × 737.76μm	157.44μm × 118.08μm
5×	792.64μm × 594.48μm	140.16μm × 105.12μm
6×	658.24μm × 493.68μm	117.12μm × 87.84μm
7×	564.67μm × 423.50μm	101.12μm × 75.84μm
8×	492.86μm × 369.64μm	88.96μm × 66.72μm
9×	438.33μm × 328.75μm	81.6μm × 61.2μm
10×	395.84μm × 296.88μm	73.28μm × 54.96μm
11.25×	346.56μm × 259.92μm	64.32μm × 48.24μm

Table 4-2 – Field of View of Coarse and Fine Camera Views for Each Magnification

The most challenging part for the design and configuration of the vision system is the illumination system. At the very beginning the light source is used to illuminate the sample from the up by the fiber pairs. In that illumination microparticles to be manipulated are visualized in the captured images as transparent which make the detection of the particles by using image processing techniques very difficult. (See Figure 4-8)



(a) Coarse Image

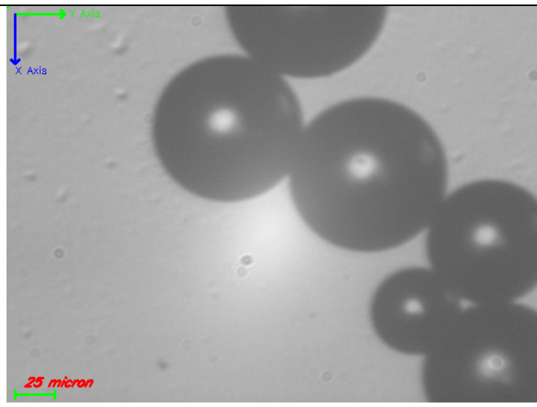


(b) Fine Image

Figure 4-8 – Images with top lighting

After experimentation with different optical microscopes with different illumination systems, most effective solution for the illumination is found to be backlight technique in which the samples are lightened from the bottom. To realize the backlighting technique for the system, the same fiber pair is used with a mirror inclined with an angle of 45º. Resulting images are shown in Figure 4-9.

(a) Coarse Image



(b) Fine Image

Figure 4-9 – Images with backlighting

Configuration of the vision system is shown in Figure 4-10.

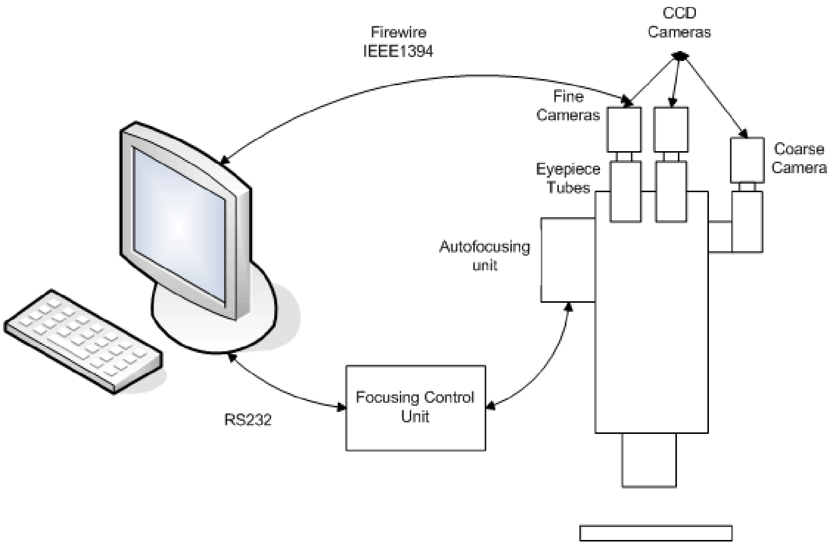


Figure 4-10 – Vision System

4.6 Manipulation Tools

Manipulation tools play the key role in microassembly as handling of the parts to be manipulated fully depends on the capability of these end effectors. Challenges about the micromanipulation are described in section 3.3.4.1. The problems concerning the manipulation in the micro world can be overcome by these end effectors for a successful manipulation task.

Main goal of the microassembly workstation is to be an open-architecture and reconfigurable platform that different assembly tasks can be realized just by changing the manipulation tool. For that reason it is designed in such a way that according to the task to be realized, the manipulation tools can be easily changed and the system will be ready for the predefined task. In that sense, manipulation tools such as microgrippers, AFM probes, micropipettes and any other tool can be the matter of choice for the workstation. (Figure 4-11)

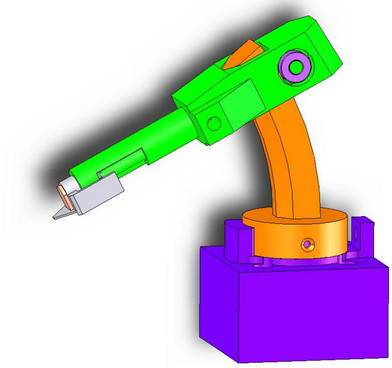


Figure 4-11 – Tool Holder

Unfortunately, there is not a wide range of choice of micromanipulation tools in the market as the microtechnology is still an immature research area all over the world. A few microgrippers are available in the market and suitable ones for our purposes are selected to be Zyvex Nanoeffector® Microgrippers and Nascatec Nanogrippers.

Zyvex Microgrippers are micromachined from single crystal silicon and driven by electrothermal micromachined actuators. Zyvex offers microgrippers with inside openings of 0 μm to 500 μm which allows the manipulation of microcomponents with sizes in that range. Gripper tip actuation motion up to 50 μm can be achieved with the compliant displacement amplification structures. In additional to these available microgripper interface and connectors ease the integration of the microgrippers to the workstation. (Figure 4-12) Specifications of the Zyvex Microgrippers are depicted in Table 4-3.

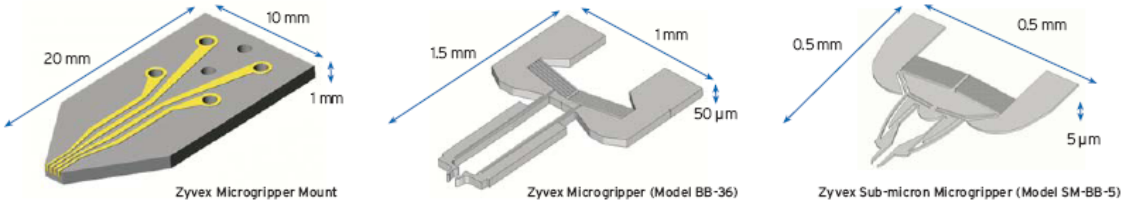


Figure 4-12 – BB and SM-BB series Zyvex Microgrippers

	Typical Specifications – BB Microgrippers	Typical Specifications – BB Microgrippers
Material	Single Crystal Silicon	Single Crystal Silicon
Powered Position	Open	Closed
Thickness	50 + 0.5 µm	5 ± 0.5 µm
Actuation	25 µm per arm	6 µm per arm
Max. gripping force	0.55 mN	0.21 mN
Max. mechanical potential	6.9×10^{-9} Joules	4.9×10^{-10} Joules
Allowable in-plane deflection	55 µm	9 µm
Out-of-plane stiffness	122 µN/ µm	2.2 µN/ µm
Allowable out-of-plane deflection	15 µm	25 µm
In-plane gripper arm stiffness	22 µN/ µm	27 µN/ µm
Peak driving voltage	10 Volts	6 Volts
Peak driving current	80 mA	10 mA

Table 4-3 – Zyvex Microgrippers and Technical Specifications

The Nascatec nanogripper is an electrostatically driven bulk silicone nano tweezers which can operate in standard atmosphere and in UHV conditions. Grippers with tweezer openings of 50 and 170 µm are available. Also grippers with tweezer openings down to 5 µm can be customized.

(a) SEM Picture (b) Gripper mounted on ceramic holder

Figure 4-13 – Nascatec Nanogripper

Microgrippers make it possible to realize 3D microassembly operations. With the available range of microgripper sizes it is possible to manipulate different objects with different sizes and features.

AFM probes become popular as manipulation tools for realizing simple 2D assembly tasks such as pushing, pulling, indenting, etc. Feasibility of the AFM probes as manipulation tools makes the AFM probes a matter of choice for the workstation.

AdvancedTEC™ Silicon-AFM-Probes offer real tip visibility from top by a tetrahedral tip that protrudes at the very end of the cantilever which prevents occlusion and makes it possible to use the probe with an optical microscope for realizing assembly tasks. (Figure 4-14) Even if the probe is tilted, the shape of the tip can still be visible from the top.

(a) Side View (b) 13° Tilted Probe

Figure 4-14 – ATEC-NC AFM Probe

The Active probe from Nano Devices is the first choice due to the fact that it has a PZT actuator –sensor so it can be used to sense the contact force. (Figure 4-15) The probe is micro-machined from bulk silicon with a piezoelectric film patterned along a portion of the micro-cantilever.

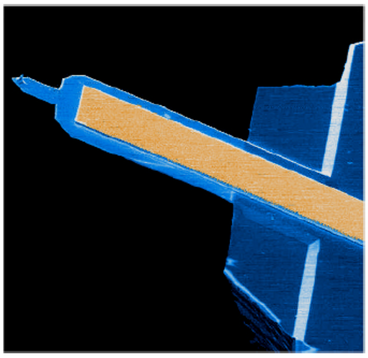
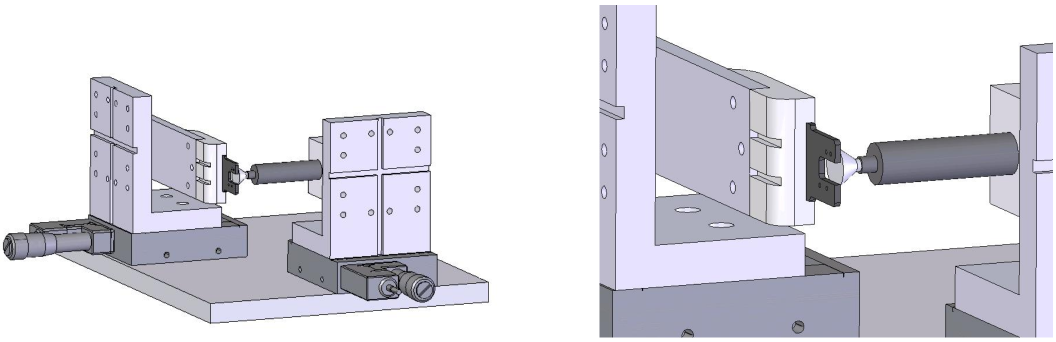


Figure 4-15 – AFM active probe

The feasibility of the active probe for manipulation while sensing the contact force is tested through an experimental setup. The actuation sensitivity of the probe is nominally 20nm/V with fundamental resonance frequency and operating resonance frequency of 50 and 200 kHz respectively. Experimental setup consists of a piezo stack actuator (Piezomechanik PSt150/5/60 VS10) with a maximum stroke of 80/60 μm. The tip of the piezo stack and the tip of the cantilever are aligned with the mechanical setup.



(a) CAD model of the setup (b) Closer view of the tips

Figure 4-16 - Force Feedback Setup

For the measurement, a non-inverting voltage amplifier circuit shown in Figure 4-17 is used. Piezo Actuator is controlled by a real time environment (dSpace 1102) and given sinusoidal references with different amplitudes and frequencies to analyze the behavior of the piezo film of the probe. The experiment is successful such that for given references with different amplitudes and frequencies, feedbacks measured from the piezo film are consistent. However, because of the capacitive behavior of the piezoelectric actuator, feedback can be taken only for dynamic forces which make it not suitable for force measurement during the manipulation.

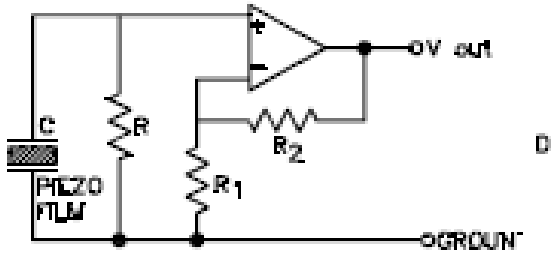


Figure 4-17 – Non-inverting Voltage Amplifier

In that sense, piezoresistive materials are more suitable for the manipulation operation. Piezo resistive cantilevers provided with strain gauges in full and half Wheatstone bridge configuration utilizes the force feedback also for constant forces which makes them a manipulator and a sensor simultaneously for the manipulation.

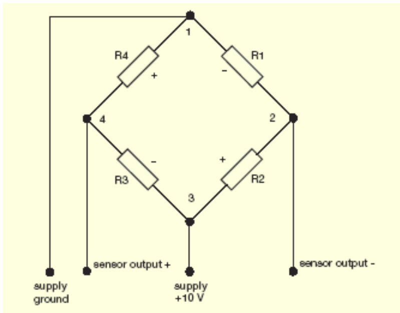


Figure 4-18 – Schematic of a Wheatstone Bridge

Unfortunately there is no available piezoresistive cantilevers in the market except Nascatec Piezo Cantilevers. These cantilevers are silicon based piezo cantilevers, with a Wheatstone Bridge (R=1.2kΩ-1.8kΩ) and symmetrical supply voltage: +/- (0.5…2V). (Figure 4-19)

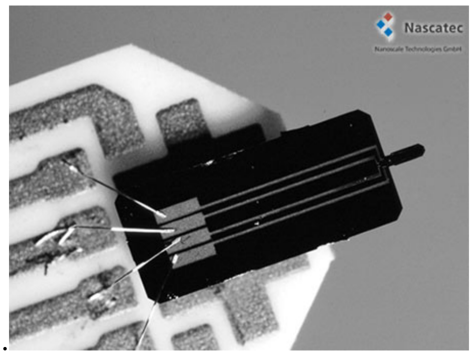
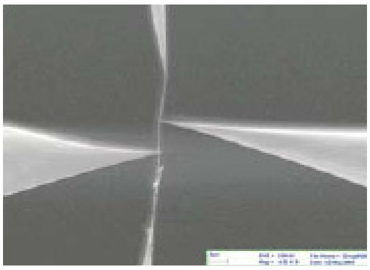
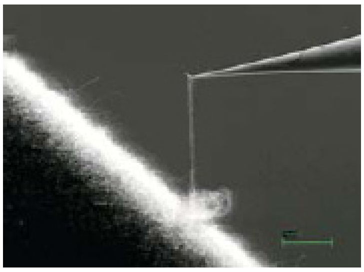


Figure 4-19 – Nascatec Piezo Cantilever

Zyvex Nanoeffector® Probes with tip radius less than 50 nm is another tool choice as they can be used for characterization of nanoscale materials and electronics, manipulation of nanoscale objects such as nanotubes and nanoparticles.



(a) Electrical characterization of a CNT bundle



(b) Probe pulling a nanotube from substrate

Figure 4-20 – Zyvex Tungsten Probes

4.7 The Workstation

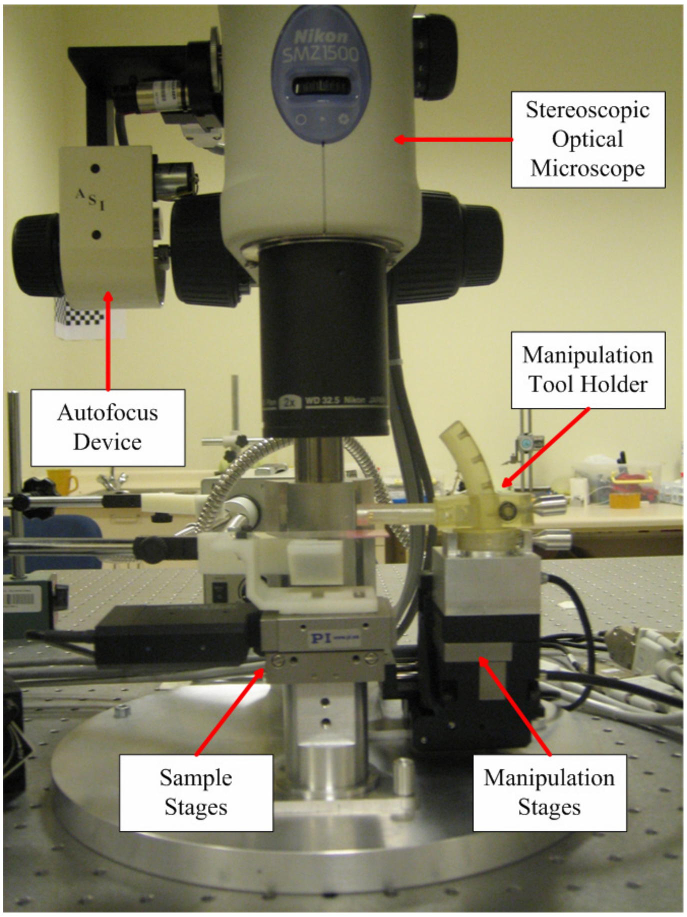


Figure 4-21 – Picture of the Whole System

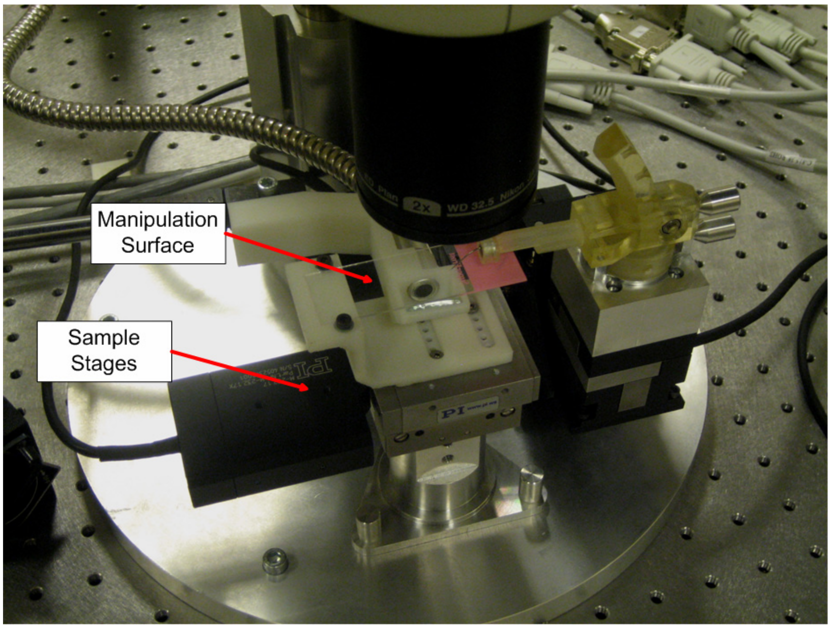


Figure 4-22 – Motion Stages

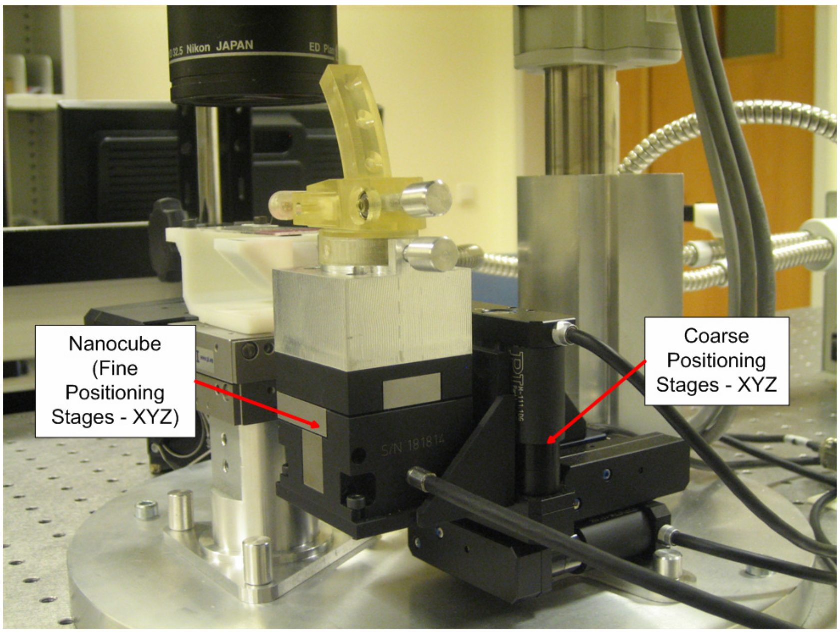


Figure 4-23 – Manipulation Stages

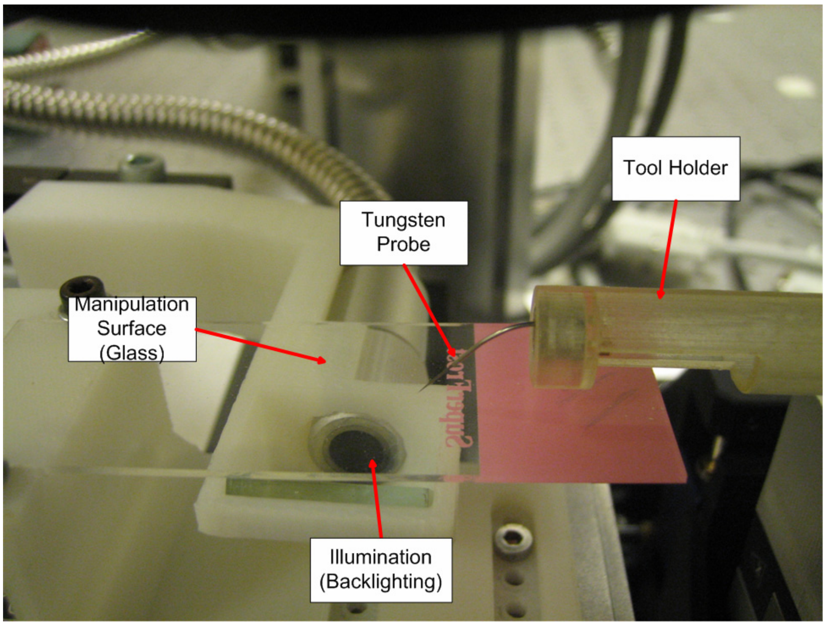


Figure 4-24 – Manipulation Tool

4.8 Conclusion

In this chapter, detailed design and implementation of the hardware part of the microassembly workstation is discussed by means of explaining each subsystem separately. Finally, the configuration of the subsystems in order to form the complete system is described.

Necessary design considerations are described in chapter 3. The system is designed in order to fulfill these requirements. The manipulation system consists of the coarse and fine positioning system for having the necessary travel range and the precision. However, rotational stages are missing which may be added to the system in order to increase the manipulation capabilities. The manipulation system is enhanced by the sample stages which increase the area of the sample surface.

For the vision system, main considerations are the magnification, workspace and the field of view. Selected microscope (Nikon - SMZ1500) has sufficient magnification (Table 4-1) for the visualization of the microworld and the field of view (Table 4-2) with the changing magnification range. In addition, the workspace of 22 mm allows the manipulation system enough free space.

5 SYSTEM SUPERVISION AND CONTROL

5.1 Introduction

In this chapter, supervision and control issues of the microassembly workstation will be presented. System architecture will be discussed by dividing it into parts and each of the part will be explained in detail. Motion control structure and methods used for achieving high accuracy of motion are discussed in details. Some theoretical background on method will be given in the motion control subsection. Vision structure and visual feedback for the microassembly tasks and the image processing algorithms will be presented. Finally, system calibration and the prior-knowledge acquisition issues such as autofocusing will be described.

5.2 Overall Structure

Motion control is the basis for the microassembly workstation since the precision and accuracy of the assembly tasks mostly depend on the control performance. Main considerations of the system supervision and control are related to the motion control and image processing. In order to achieve high accuracies for the motion, control method needs to be considered carefully. Vision system along with local feedbacks from other sensors supplies the external sensory feedback for the motion control unit. By using some image processing techniques, position of parts to be manipulated and the manipulation tools with respect to each other, which are necessary for the implementation of automated assembly tasks, are extracted. As the motion units operate according to the feedback supplied by visual information, vision system must be very precise for the sake of realization of the assembly tasks. In tele-operated tasks, only the mapping has great significance since the user defines the motion. However, for the automated tasks vision system gains significant importance as it gives the reference for motion according to the extracted position information.

5.3 Motion Control

In this section control structure used in the implementation of the control system and the control method that is used to achieve high accuracies in the microassembly will be discussed. Results will be shown with supportive graphs both for the translational stages equipped with DC motors and piezo stages.

The microassembly workstation falls in the group of fully actuated mechanical systems in which the number of actuators is equal to the number of the primary masses. The actuators used in the system are either electrical machines or PZT actuators. ,

The complexity and nonlinear dynamics of motion control systems along with high-performance operation require complex, often nonlinear control system design, to fully exploit system capabilities. Basic goal for motion control systems is to achieve smooth stable motion in the presence of unstructured environment (another system being in motion or stationary) with which plant in motion can be in contact.

Possible control system approaches are defined in section 3.3.2. For the microassembly workstation, control system is configured as in the centralized approach. A personal computer (PC) hosting the DS1103 board forms the central control unit of the system and all sensors, actuators and other devices in the system are connected to the central control unit. Centralized approach with the defined central control unit is used in the system as it allows for rapid control prototyping.

Main control structure is shown in Figure 5-1. The DS1103 card is equipped with D/A converters from which the control inputs are fed to the drivers and then the actuators, A/D converters for the strain gage outputs from the piezo stages, incremental encoder interface for the sensory feedback from the encoders of the translational stages and digital I/O for the limit switches, etc.

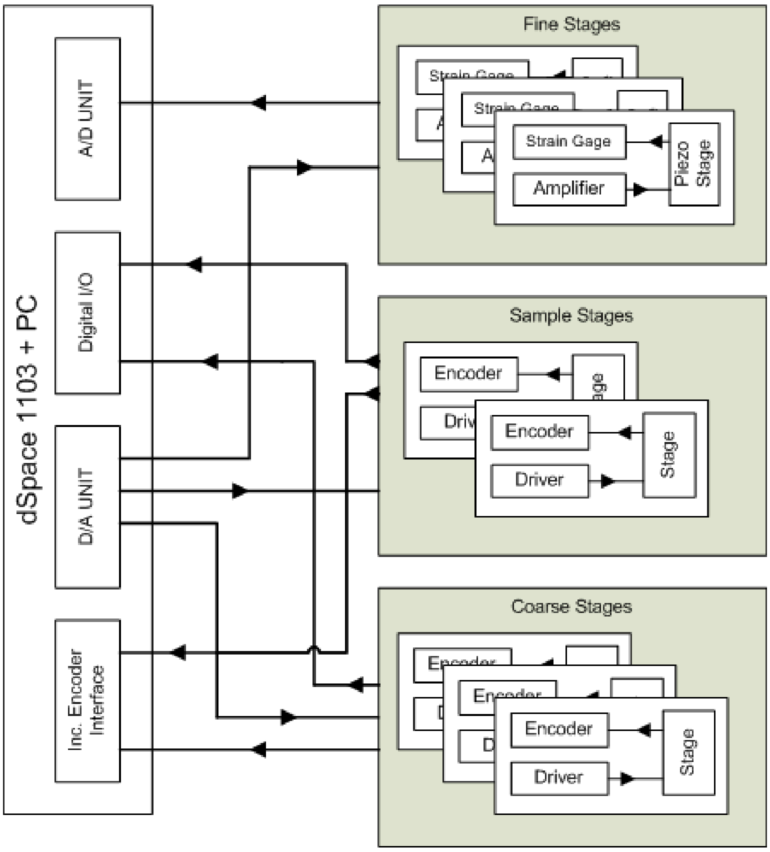


Figure 5-1 – Control System Architecture

The control algorithms employed in motion control are based on Sliding Mode Control (SMC) methods. The most salient feature of the Sliding Mode Control (SMC) is the possibility to constrain a system motion in selected manifold in the state space. Such motion in general results in a system performance that includes disturbance rejection and insensitivity to parameter variations [45]. The development of SMC has gone through oscillations with both very enthusiastic claims and the skepticism regarding the achieved results. In some cases researchers contributed to the confusion, especially in the case of so-called chattering phenomena, through incomplete analysis and design fixes [46], [47], [48], [49].

5.3.1 Control Methods

For the systems where high precision motion control is required, robustness of the control algorithm is the most crucial factor. Moreover, if the plant has high nonlinearities such as hysteresis in piezoactuators or friction, using a robust controller designed according to the nominal plant parameters and which rejects parameter uncertainties would be advantageous.

Variable structure control with sliding modes, frequently named as sliding mode control, is characterized by a discontinuous control action which changes structure upon reaching a set of predetermined switching surfaces. This control may result in a very robust system with its built-in disturbance rejection, which in turn implicitly compensates for the unmodeled dynamics, and thus provides a possibility for achieving high precision and fast response.

The advantageous features of the sliding mode control:

- The order of the motion can be reduced
- The motion equation of the sliding mode can be designed linear and homogenous, despite that the original system may be governed by nonlinear equations.
- The sliding mode does not depend on the process dynamics, but is determined by parameters selected by the designer.
- Once the sliding motion occurs, the system has invariant properties which make the motion independent of certain system parameter variations and disturbances. Thus the system performance can be completely determined by the dynamics of the sliding manifold.

The motivation of using SMC as the control algorithm for the system stems from the advantages stated above. In the following section, theoretical background for the SMC will be given over the control of the actuators existing in the system.

5.3.1.1 SMC of Piezo Stages

In order to achieve high position accuracy in the nano-scale and eliminate hysteresis which is the dominant nonlinear disturbance for the piezo stage, a robust controller is designed based on the assumption that the piezo stage can be modeled as a nominal linear lumped parameters (T_N, m_N, c_N, k_N) second order electromechanical system with voltage as the input and position as the output. The disturbance rejection is based on the concept of sliding mode observer which considers the total disturbance coming from the hysteresis and external force acting on the system. Thus the observer tries to estimate the lumped disturbance acting on the system.

A fairly accurate model was chosen [50] for the piezo stage due to its easiness for implementation and accuracy for estimating the actual behavior of these actuators. The piezo stage consists of a piezo drive with a flexure guided structure which is designed to possess zero stiction and friction. Moreover the flexure stages exhibit high stiffness, high load capacity and insensitive to shock and vibration. Figure 5-2 describes the overall electromechanical model [50] of a PZT actuator.

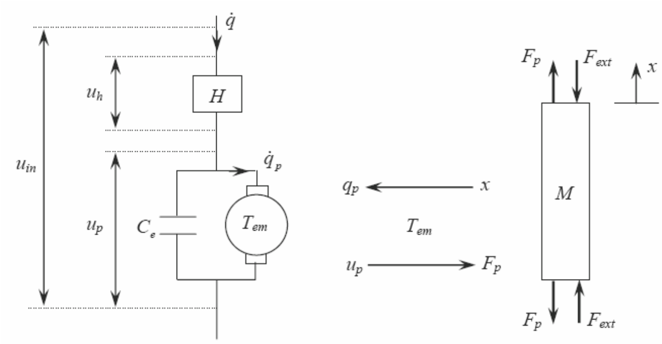


Figure 5-2 – Electromechanical model of a PZT actuator

The hysteresis and piezoelectric effects are separated. H Represents the hysteresis effect and u_h is the voltage due to this effect. The piezoelectric effect is represented by T_{em} which is an electromechanical transducer with transformer ratio T_{em}. The capacitance C_e represents the sum of the capacitances of the individual PZT wafers, which are electrically in parallel. The total current flowing through the circuit is $\dot{q}$. Furthermore, q may be seen as the total charge in the PZT actuator. The charge q_p is the transducer charge from the mechanical side. The voltage u_p is due to the Piezo effect. The total voltage over the PZT actuator is u_{in} , F_p is the transducer force from the electrical side, F_{ext} is the externally applied force, and the resulting elongation of the PZT actuator is denoted by x. The mechanical relation between Fp and x is denoted by M. Note that we have equal electrical and mechanical energy at the ports of interaction i.e. $u_p q_p = F_p x$.

The piezoelectric ceramic has elasticity modulus E, viscosity η, and mass density ρ. Furthermore, the geometric properties of the PZT actuator are length L and cross-sectional area A_p. Effective mass m_p, effective stiffness k_p and damping co-efficient c_p can be calculated as follows:

$$m_p = \rho A_p L \tag{5-1}$$

$$k_p = \frac{\rho A_p}{L} \tag{5-2}$$

$$c_p = \frac{\eta A_p}{L} \tag{5-3}$$

The complete electromechanical equations can be written as:

$$m_p \ddot{y} + c_p \dot{y} + k_p y = T_{em}(u_{in}(t) - H(y, u_{in})) - F_{ext} \tag{5-4}$$

Here y represents the displacement of the Piezo stage and $H(y, u_{in})$ denotes the non-linear hysteresis which is a function of y and u_{in}.

The equation (5-4) is rewritten in state-space form (5-5) for easiness of the derivation of the controller structure.

$$\begin{aligned} \dot{x}_1 &= \dot{y} = x_2 \\ \dot{x}_2 &= \ddot{y} = -\frac{k_p}{m_p}x_1 - \frac{c_p}{m_p}x_2 + \frac{T_{em}}{m_p}u_{in} - \frac{T_{em}}{m_p}H - \frac{F_{ext}}{m_p} \end{aligned} \tag{5-5}$$

The equation (5-5) can be written in more general form as shown below

$$\dot{x} = f(x, H, F_{ext}) + Bu_{in} \tag{5-6}$$

The aim is to drive the states of the system into the set S defined by

$$S = \{x : G(x^r - x) = \sigma(x, x^r) = 0\} \tag{5-7}$$

Here $G = \{\lambda \ 1\}$ with λ being a positive constant, x is the state vector $x^T = \{x_1 \ x_2\}$, x^r is the reference vector $(x^r)^T = \{x_1^r \ x_2^r\}$ and $\sigma(x, x^r)$ is the function defining sliding mode manifold.

The derivation of the controller structure with the proper selection of the Lyapunov function $V(\sigma)$, and an appropriate form of the derivates of the Lyapunov function, $\dot{V}(\sigma)$.

For SISO system such as (5-5), required to have motion in manifold (5-7), natural selection of the Lyapunov function candidate seems in the form

$$V(\sigma) = \frac{\sigma^2}{2} \tag{5-8}$$

Hence, the derivative of the Lyapunov function is

$$\dot{V}(\sigma) = \sigma\dot{\sigma} \tag{5-9}$$

In order to guarantee the asymptotic stability of the solution $\sigma(x, x^r) = 0$, the derivates of the Lyapunov function may be selected to be

$$\dot{V}(\sigma) = -D\sigma^2 \tag{5-10}$$

Here D is a positive constant. Hence, if the control can be determined from (5-9) and (5-10), the asymptotic stability of the solution (5-7) will be guaranteed since $V(\sigma) > 0$, $V(0) = 0$ and $\dot{V}(\sigma) < 0$, $\dot{V}(0) = 0$ .By combining (5-9) and (5-10) the following equation can be deduced

$$\sigma(\dot{\sigma} + D\sigma) = 0 \tag{5-11}$$

A solution for (5-11) is as follows

$$(\dot{\sigma} + D\sigma) = 0 \tag{5-12}$$

The derivative of the sliding function is as follows

$$\dot{\sigma} = G(\dot{x}^r - \dot{x}) = G\dot{x}^r - G\dot{x} \tag{5-13}$$

From equation (5-13) and using (5-6)

$$\dot{\sigma} = G\dot{x}^r - Gf - GBu(t) = GB\left(u_{eq} - u(t)\right) \tag{5-14}$$

After inserting (5-14) into (5-12) and the result is solved for the control

$$u(t) = u_{eq} + (GB)^{-1}D\sigma \tag{5-15}$$

It can be seen from (5-15) that u_{eq} are difficult to calculate. Using the fact that u_{eq} is a continuous function, (5-14) can be rewritten in discrete form using Euler's approximation,

$$\frac{\sigma((k+1)T_s) - \sigma(kT_s)}{T_s} = GB\left(u_{eq}(kT_s) - u(kT_s)\right) \tag{5-16}$$

Here T_s is the sampling time and $k = Z^+$ .It is also necessary to write (5-15) in the discrete form which results in

$$u(kT_s) = u_{eq}(kT_s) + (GB)^{-1} D\sigma(kT_s) \tag{5-17}$$

If equation (5-16) is solved for the equivalent control, the following is obtained

$$u_{eq}(kT_s) = u(kT_s) + (GB)^{-1} \left(\frac{\sigma((k+1)T_s) - \sigma(kT_s)}{T_s} \right) \tag{5-18}$$

Since the system is casual, and it is required to avoid the calculation of the predicted value for σ as control cannot be dependent on future value of σ .Since the equivalent control is a continuous function, the current value of the equivalent control can be approximated with the single-step backward value calculated from (5-18) as

$$\hat{u}_{eq_k} \cong u_{eq_{k-1}} = u_{k-1} + (GB)^{-1} \left(\frac{\sigma_k - \sigma_{k-1}}{T_s} \right) \tag{5-19}$$

Here $\hat{u}_{eq_k}$ (or $\hat{u}_{eq}(kT_s)$) is the estimate of the current value of the equivalent control. After inserting (5-19) into (5-17) and resulting in control structure as

$$u_k = u_{k-1} + (GBT_s)^{-1} \left((DT_s + 1)\sigma_k - \sigma_{k-1} \right) \tag{5-20}$$

The control structure (5-20) is suitable for implementation, since it requires measurement of the sliding mode function and the value of the control applied in the preceding step. Thus (5-20) is used as control structure as discrete sliding mode for Piezo actuation.

The observer structure is deduced based on the equation (5-4) under the assumption that all the plant parameters uncertainties, nonlinearities and external disturbances can be represented as a lumped disturbance. It is assumed that y is the displacement and it's measurable and similarly $u(t)$ is the input and also a measurable quantity.

$$\begin{aligned} m_p \ddot{y} + c_p \dot{y} + k_p y &= T_p u(t) - F_{dis} \\ F_{dis} &= T_p H + \Delta T(v_{in} + v_h) + \Delta m \ddot{y} + \Delta c \dot{y} + \Delta k y \end{aligned} \tag{5-21}$$

Here m_p , c_p , k_p and T_p are the nominal plant parameters while Δm , Δc , Δk and ΔT are the uncertainties associated with the plant parameters. Since y and $u(t)$ are measurable quantity, observer structure can be written in following form

$$m_p \ddot{\hat{y}} + c_p \dot{\hat{y}} + k_p \hat{y} = T_p u - T_p u_c \quad (5\text{-}22)$$

Here $\hat{y}$, $\dot{\hat{y}}$ and $\ddot{\hat{y}}$ are the position velocity and acceleration. u is the plant control is the control input u_c is the observer control input as shown in Figure 5-3.

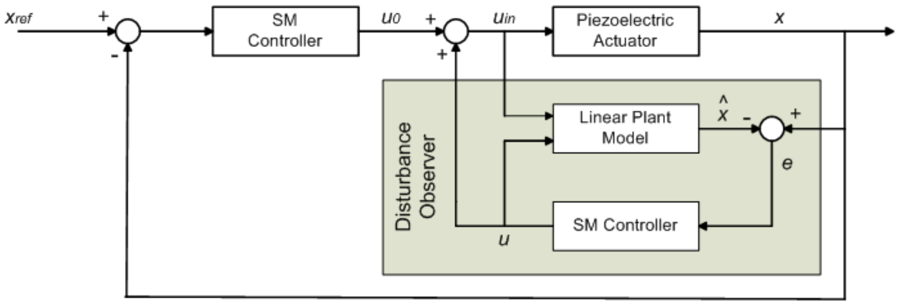


Figure 5-3 – Observer Implementation

If estimated position $\hat{y}$ can be forced to track y then total disturbance feed to the system. Again the SMC structure is used for deriving the observer controller whose sliding manifold is defined as:

$$\sigma_{obs} = \lambda_{obs}(y - \hat{y}) + (\dot{y} - \dot{\hat{y}}) \quad (5\text{-}23)$$

Here λ_{obs} is a positive constant. If σ_{obs} is forced to become zero then $\hat{y}$ should be forced to y. As described in the previous section from (5-12), with the same analogy it can be written as

$$\dot{\sigma}_{obs} + D_{obs}\sigma_{obs} = 0 \quad (5\text{-}24)$$

which guarantees $\sigma_{obs} \to 0$. By plugging the (5-23) into (5-24), the resulting equation is written as

$$\left(\ddot{y} - \ddot{\hat{y}}\right) + (\lambda_{obs} + D_{obs})\left(\dot{y} - \dot{\hat{y}}\right) + \lambda_{obs} D_{obs}\left(y - \hat{y}\right) = 0 \quad (5\text{-}25)$$

It can be seen that the transient of the closed-loop system are defined by the roots $-\lambda_{obs}$ and $-D_{obs}$. The same structure of the controller will be used in the observer as described in (5-20). From structure (5-22) it can be seen that the input matrix is given by

$$B_{obs} = \begin{bmatrix} 0 & -\frac{T_p}{m_p} \end{bmatrix}^T \tag{5-26}$$

The matrix G for this case is defined as

$$G = \left[\lambda_{obs} \;\; 1\right] \tag{5-27}$$

Thus, after some simplification the controller structure can be written as

$$u_{c_k} = u_{c_{k-1}} - \frac{m_p}{T_p}\left(D_{obs}\lambda_{obs_k} + \frac{\sigma_{obs_k} - \sigma_{obs_{k-1}}}{T_s} \right) \tag{5-28}$$

Here u_c is the compensated control input to the system. The positive feedback by input u_c forces the system to behave closely towards the ideal system having the nominal parameters. But in reality there is also some amount of difference between the real disturbance and estimated disturbances.

For the translational stages, discrete sliding mode control procedure is implemented. Differing from the control of the piezo stages, there is no implementation of disturbance observer since the response of stages is satisfying according to our criteria. The control structure for the translational stages is shown in Figure 5-4.

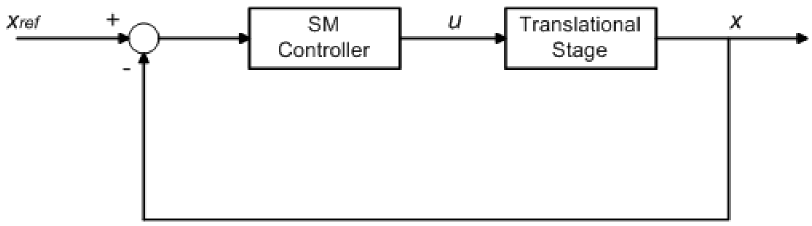


Figure 5-4 – Block Diagram of Translational Stage

5.3.2 System Details

In order to show the performance of the applied controller, the system is given a step input position reference with different magnitudes. The resulting responses are shown in Figure 5-7, Figure 5-6 and Figure 5-7.

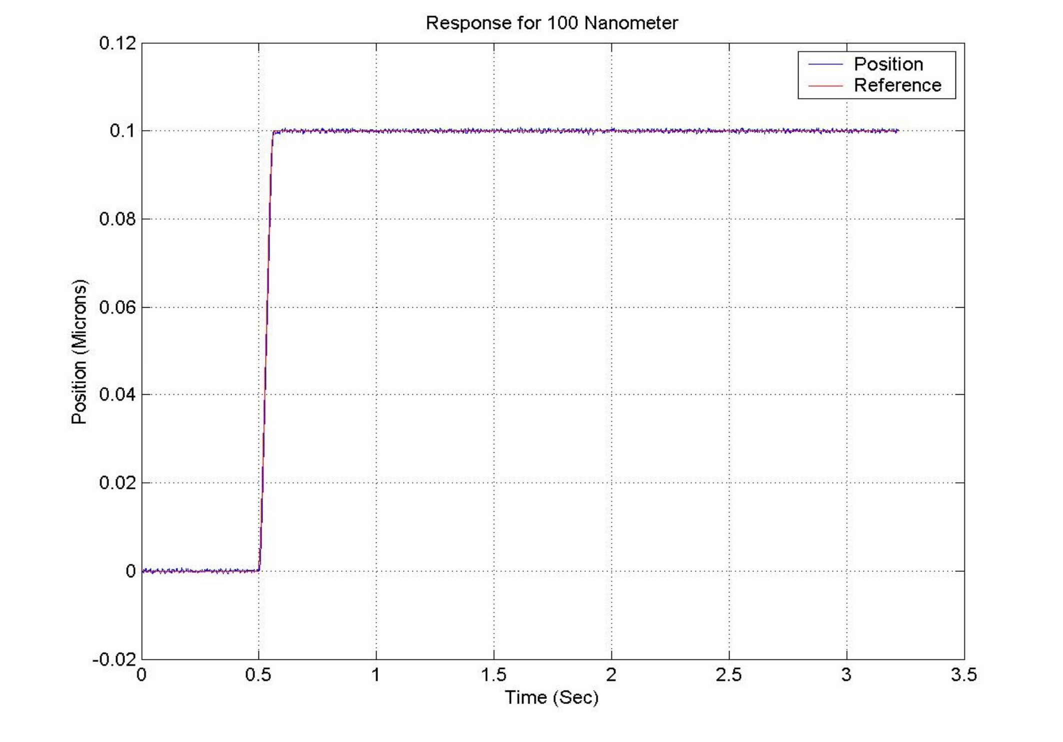


Figure 5-5 – Step response of piezo stage for 100 nm

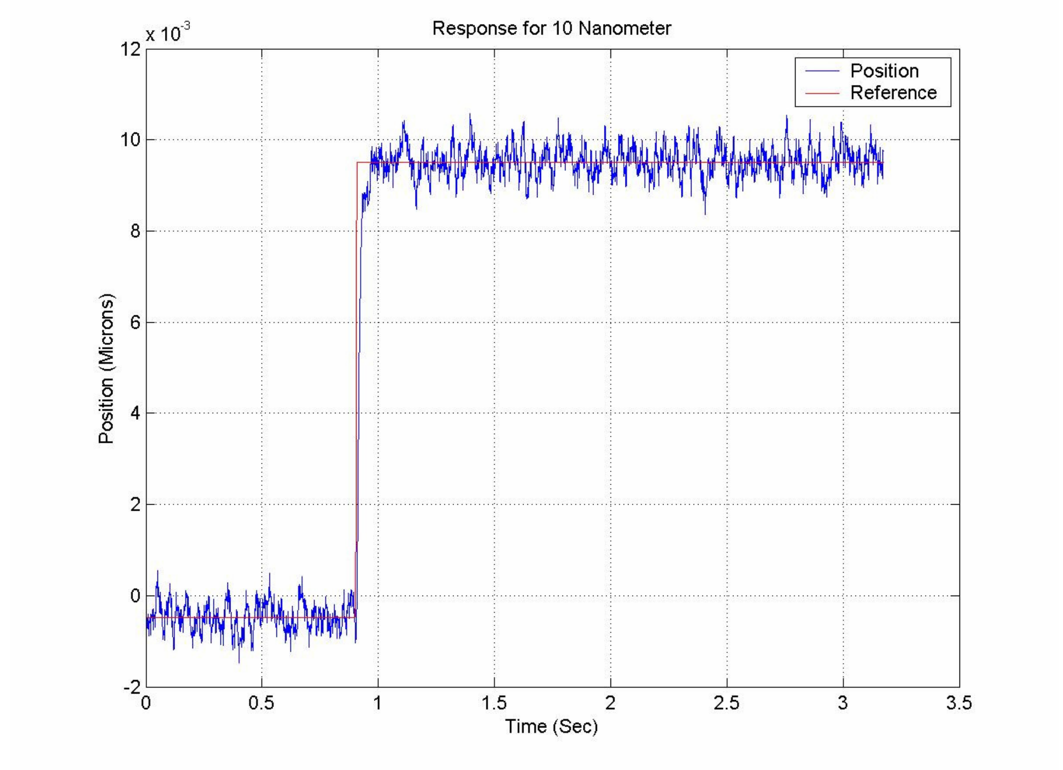


Figure 5-6 - Step response of piezo stage for 10 nm

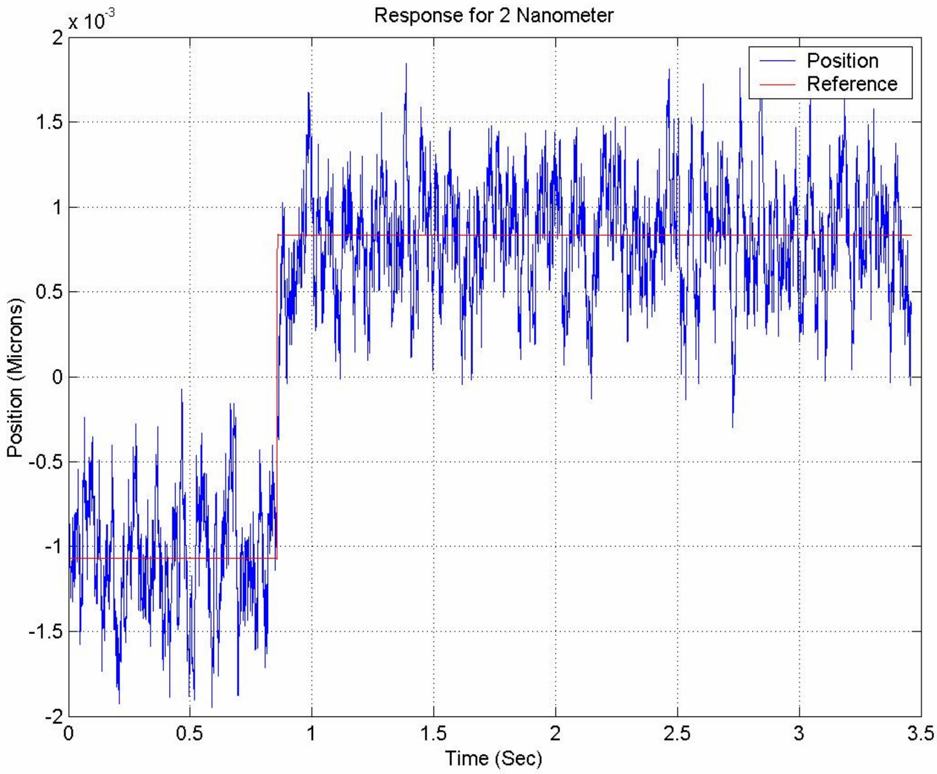


Figure 5-7 – Step response of piezo stage for 2 nm

As seen from the figures above, system is able to achieve the desired position with a fast rise time. However the system suffers from the noises belonging to high frequency range resulting from the measurement devices which affect the steady state of the system and forces an oscillatory behavior with maximum amplitude of 1-1.5 nanometer.

Step responses of the translational stages are shown in the following figures for 100, 10 and 1 microns respectively. As it can be seen from the figures that for the given position references, performance of the translational stages is satisfying since the responses are good but only suffering from a 0.007 microns oscillation representing the resolution of the encoder. That amount of error can be neglected in our case since it can be compensated by the fine translational stages.

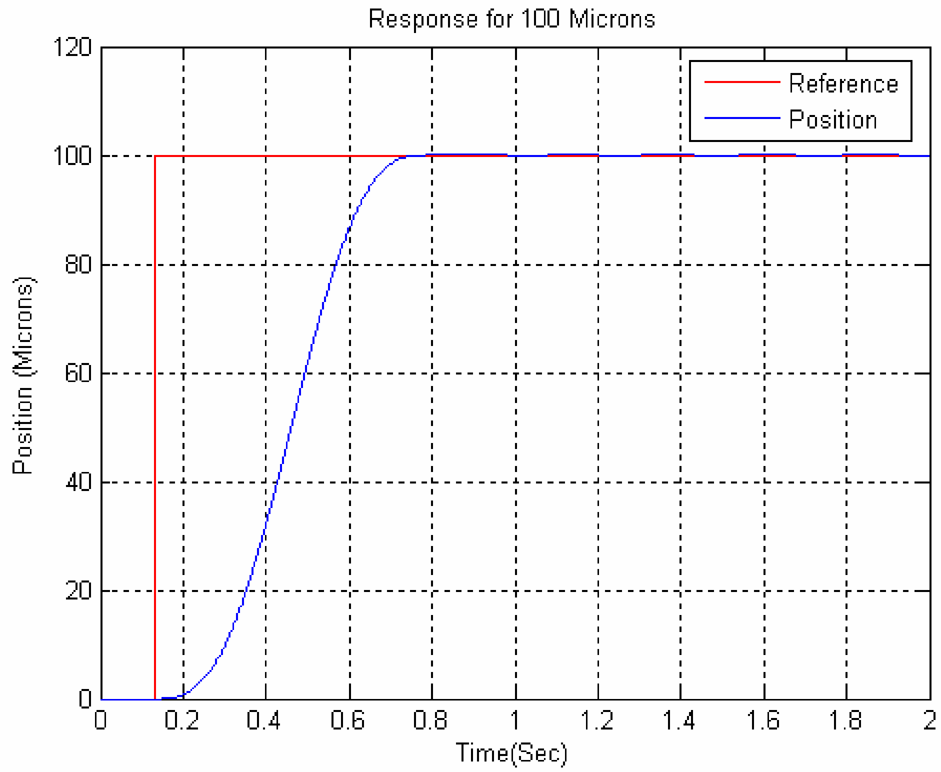


Figure 5-8 - Step response of translational stage for 100 µm

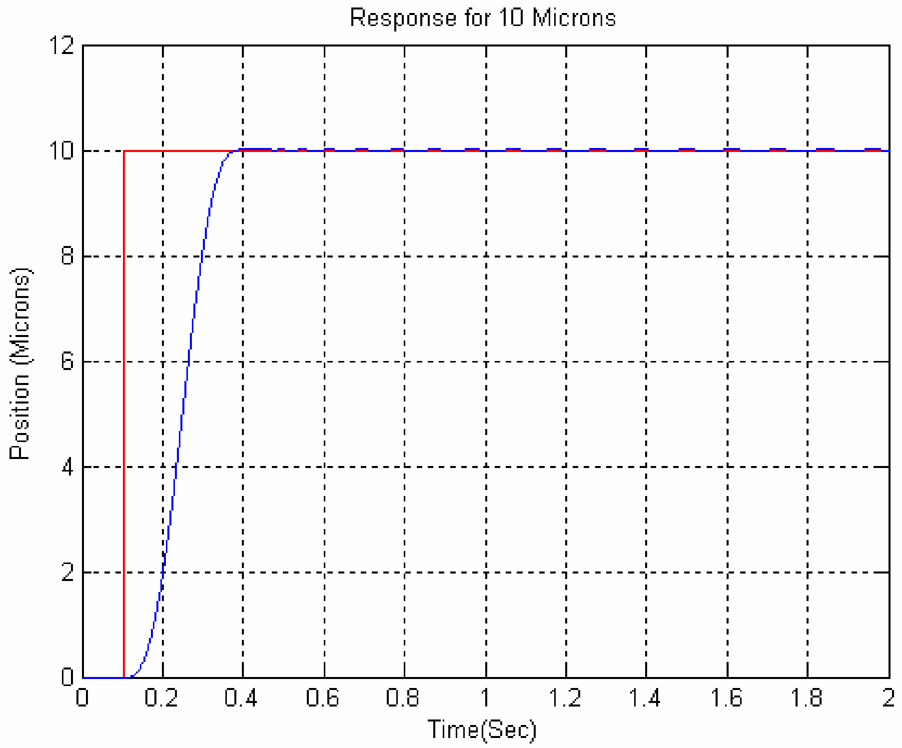


Figure 5-9 - - Step response of translational stage for 10 µm

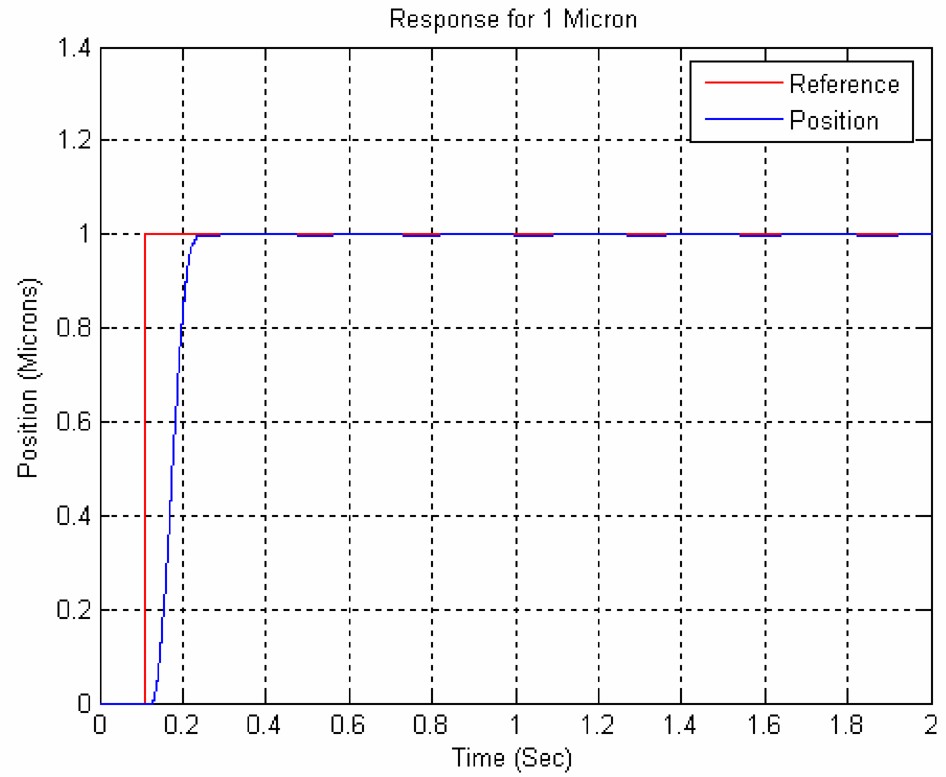


Figure 5-10 - Step response of translational stage for 1 µm

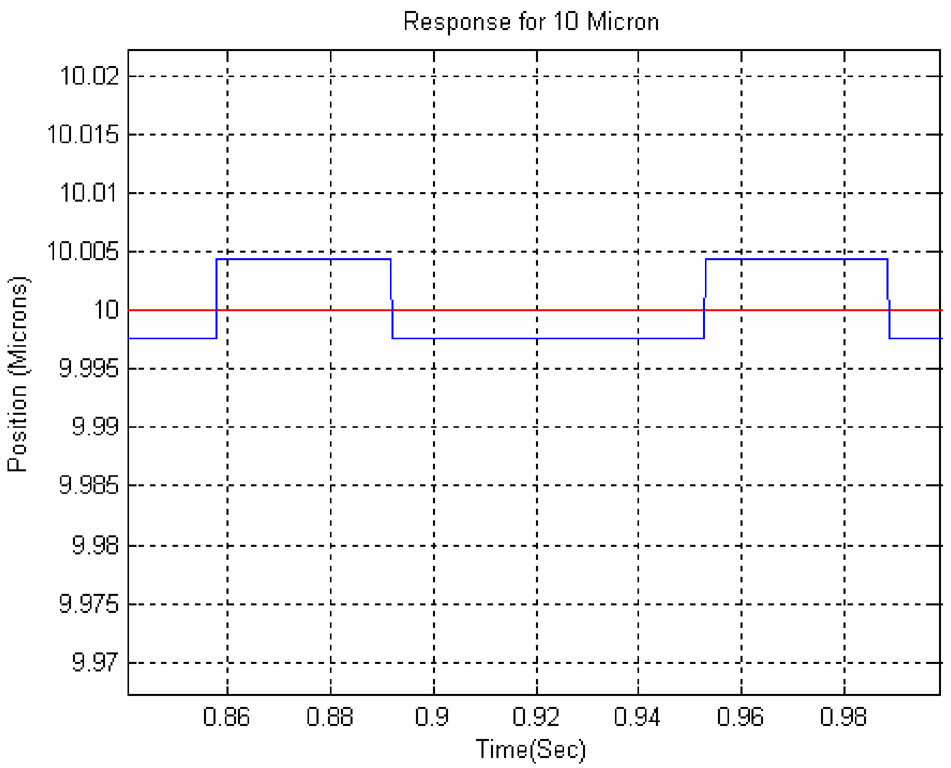


Figure 5-11 – One encoder pulse

Figure 5-12 depicts the reference velocity to be tracked by the five translational stages. The reference velocity is of a modified trapezoid-like type to provide an easy to follow second derivative continuous trajectory reference. The reference is generated such that it does not exceed a maximum velocity and acceleration limits for each axis. All the axes start and finalize their motion at the same time.

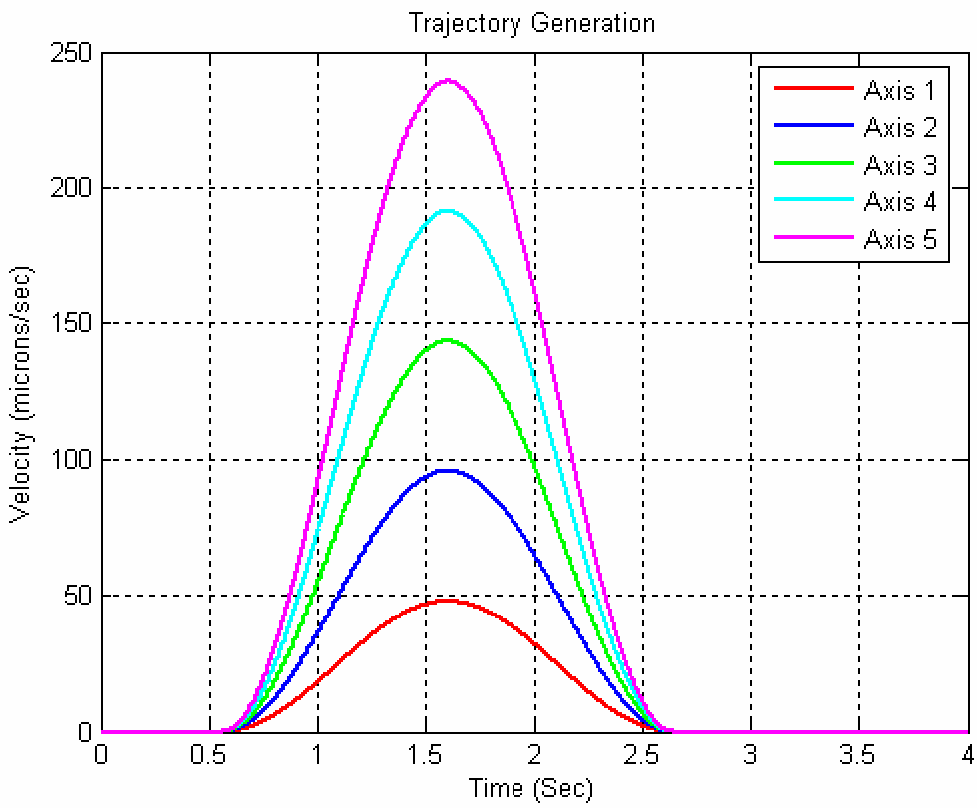


Figure 5-12 – Reference Generation

5.4 Vision System

The main functionality of the vision system in microworld is "making the invisible, visible". A vision interface for a microassembly workstation has great importance for the determination of the position and orientation of the parts to be assembled with respect to each other and the manipulation tool. That is the main necessity for automated microassembly tasks. The effectiveness of a vision system lies on recognizing the geometries and position of 3D microparts, path generation for the micromanipulator and providing the necessary position feedback. And these are possible by using image processing techniques.

Vision software is designed to provide the system or the user the clear visualization of the microworld and the position determination of the objects of interest. By this means it can be possible to realize any kind of assembly operation. Integrated with the hardware system, user interface designed for the vision system utilizes coarse and fine views of the workspace, enables autofocusing to provide clear images and determine the depth information. It also allows the realization of automated tasks with the utilization of visual feedback by determining the relative distances between the regions of interest and supplying the necessary information to the motion stages.

5.4.1 Vision Structure

The main functionality of the vision system is guiding the user for manipulation tasks and the extraction of positions from the images which are necessary for the implementation of automated assembly tasks. Typical tasks of position extraction for the microassembly process are determining the positions of the parts to be manipulated and the manipulation tool, pushing or gripping locations, etc.

The position determination process involves the following steps: segmentation of the captured images by thresholding, extraction of sharp contrast changes indicating the corners or edges of object boundaries existing in the image, identifying the objects and extracting necessary information. These steps will be defined in detail in the next section.

Additional to the position determination, there are some pre-processing issues related to the vision system. These pre-processing issues include procedures which are necessary to be completed before the implementation of the assembly tasks, necessary for the acquirement and determination of system parameters and the knowledge about the models of the objects to be identified. These procedures are autofocusing for the acquirement of a clear image necessary for the implementation of image processing algorithms and the depth information and the camera calibration for mapping the image space to real world coordinates. (Figure 5-13)

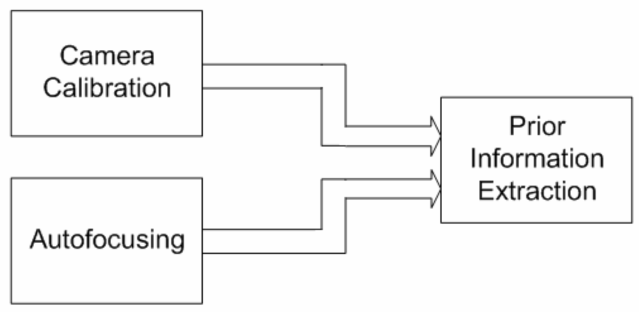


Figure 5-13 – Pre-processing procedures

In that context, the structure is as follows; firstly autofocusing is enabled to get the clear image for further processing, determination of the positions of necessary components is realized in image space in pixel coordinates. And finally, according to the parameters determined by mapping from image space to real world, necessary information is fed to the motion system in order to realize the assembly tasks. This structure is shown in Figure 5-14.

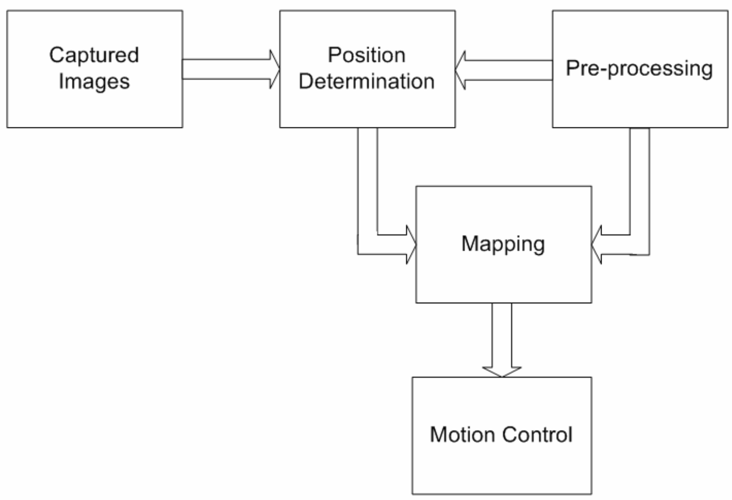


Figure 5-14 – Vision Structure

5.4.2 Visual Feedback

For the realization of micromanipulation and microassembly tasks, it is necessary to visualize and sense the environment. Position and orientation of microparticles with respect to each other and the manipulation tool can be defined by using a vision system. Since vision provides fast and contactless information extraction, it is suitable for visualizing the microworld and providing position and orientation data for the micromanipulation and microassembly tasks.

Visual feedback is provided by means of an optical microscope down to micron resolutions. For the teleoperated microassembly tasks, the operator relies on the online visual feedback supplied by the cameras integrated into the optical microscope. During the assembly, not only the visual feedback is provided for observing the situations of operation but also a readout display showing the linear encoder positions is supplied.

For the automated microassembly tasks, position and orientation information of specific manipulation tools or micro parts must be extracted by means of vision system. This information, named as visual features, is used as visual feedback in the control loop of the manipulation system. Thus, vision based control is attained.

5.4.3 Brief Description of Used Algorithms

Towards the determination of position and orientation of particles or the manipulation tool, in order to realize object recognition and tracking for the microassembly operation, it is necessary to distinguish some meaningful data to identify the objects which are called image features.

Feature extraction can be defined as a special form of reduction in dimensionality. It is one of the main issues in computer vision since the extracted features must be meaningful in the sense that they must be sufficient to describe the model and properties of the desired portions or shapes in the image. Figure 5-15 shows the selection of appropriate algorithms for feature extraction necessary for the realization of automated microassembly tasks.

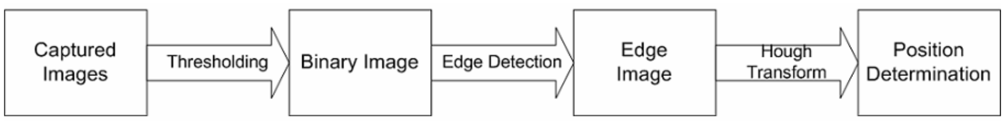


Figure 5-15 – Position Determination

Thresholding

For the separation of the regions of the image that corresponds to the interested objects from the regions that corresponds to the background, a segmentation process is necessary. The simple and suitable way of performing this segmentation is based on the different intensities in the back and foreground regions of the image. The main function of thresholding is to transform a greyscale image into a binary image having only the black and white levels of grayscale. In that sense, black pixels corresponds to the foreground and the white pixels correspond to the background of the image. ,

Thresholding operation requires a threshold value necessary for the segmentation of the image. That threshold value represents the boundary between the intensity of the pixels corresponding to the back and foreground regions of the image. Each pixel's intensity value is compared with the threshold value and pixels with the intensity higher than the threshold value are set to white and the others with less intensity are set to black. The threshold value determination is based on the histogram of the image which shows the occurrences of the each gray level on the image.

Predefinition of the threshold value may not be suitable in every case since the variations in the illumination can cause the requirement of different threshold values for the segmentation of the same scene. For that reason, an adaptive thresholding technique which changes the threshold value dynamically over each image is used for the sequence of images so as to attain a reliable segmentation.

Edge Detection

Edge detection is an important step for the feature extraction process. It refers to the process of detecting the sharp changes and discontinuities in an image. Edges characterize the boundary information of objects or regions in the image and are useful for segmentation and identification purposes. Edge detecting an image significantly reduces the amount of data and filters out useless information, while preserving the important structural properties in an image.

There are several edge detection operators in the literature; Roberts Cross, Prewitt, Sobel and Canny are the most common ones and based upon the first derivative of the intensity giving the gradient of the intensity. Roberts' Cross operator performs a simple 2-D spatial gradient measurement on an image so as to highlight regions of high spatial frequency corresponding to the edges. It is fast to compute since it uses a small kernel. However, using such a small kernel makes it very sensitive to noise and gives weak responses unless the edges are very sharp.

The Sobel operator works similarly to the Roberts' Cross operator but using a larger convolution kernel which makes it slower to compute. Using a larger kernel smoothes the image to a greater extent and makes it less sensitive to noise. Prewitt operator works in a similar way to Sobel operator but uses slightly different masks and the results are similar.

In our case, canny operator is used since it is the most commonly used edge detection method and known as the optimal edge detector. For the noise reduction, the image is first convolved with a Gaussian mask so that a noisy pixel lost its effect on the smoothed image. Canny also introduced the notion of non-maximum suppression, which means that edges are defined as points where the gradient magnitude assumes a maximum in the gradient direction. Then thresholding with hysteresis is used for the detection and linking the edges.

(a) Original Image (b) Canny Edge Image

Figure 5-16 – Edge Detection

Hough Transform

The Hough transform is a technique which is used for identifying the locations and orientations of particular shape within an image. Hough transform is mostly used for the detection of regular shapes such as lines, circles, ellipses, etc. since it requires the specification of the desired features in parametric form. The main advantage of the Hough transform technique is that it is tolerant of gaps in feature boundary descriptions and is relatively unaffected by image noise and its robustness and flexibility to model regular shapes.

Circle Detection

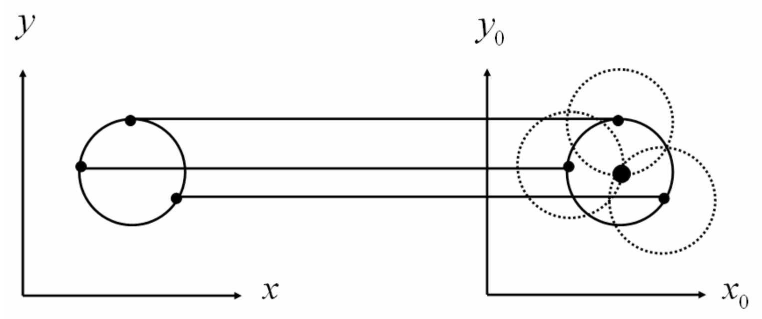


Figure 5-17 – Mapping for Circular Hough Transform

A circle with the center located at (x_o, y_o) and radius r can be represented as:

$$(x - x_0)^2 + (y - y_0)^2 - r^2 = 0 \tag{5-29}$$

The model has three parameters; two for the centre of the circle (x_0, y_0) and one for the radius r. The parametric equations for a circle in polar coordinates:

$$x_0 = x - r\cos\theta \tag{5-30}$$

$$y_0 = y - r\sin\theta \tag{5-31}$$

θ is the gradient angle determining the direction of the vector from the center of the circle to each edge point. Given the gradient angle θ at the edge points, $cos\theta$ and $sin\theta$ can be computed. The mapping for circular Hough transform is shown in Figure 2.6.

We are dealing with microspheres with different diameters for realizing the microassembly experiments in the microassembly workstation. For the detection of these particles, Hough circle transform is used and the results are shown in Figure 5-18. As it can be seen from the figures, the circular particles can be detected even if the particles are clustered resulting in missing contours.

(a) Separate Particles (b) Clustered Particles

Figure 5-18 – Hough Circle Transform for Microspheres

5.5 Autofocusing

Autofocusing is inevitable for an automated microassembly workstation. It is realized in order to extract the vertical position information for the assembly tasks. The vertical position information is necessary to be obtained in order to position the manipulation tools relatively to the parts to be manipulated. During microassembly operations, there is a need to focus on the different focal planes as a result of existing non-planar objects and different manipulation tools. Whether it is a 2D or 3D microassembly, autofocusing is needed. In 2D microassembly such as pushing, pulling, etc. the manipulation tool should be positioned to the pushing height, where the particle pushing point and the tip of the tool are in the same focal planes, before starting the assembly operation and that information should be computed automatically. In 3D assembly, focusing between different focal planes is necessary not only before the assembly process but also during the assembly.

Autofocusing systems can be classified as active and passive autofocusing systems. Active autofocusing relies on external sensors such as lasers and ultrasound devices and the depth information between the lens and the interested focal plane is measured by means of these devices. In passive autofocusing, image processing techniques are used to determine whether the object of interest is focused or not. [51]

In our case, a passive autofocusing technique is used based on normalized variance algorithm. Variations in gray level among image pixels in the image are computed by using this algorithm and the final output is normalized with the mean intensity of the image. This technique is demonstrated to be the best technique providing the best overall performance compared to the other autofocusing algorithms. [52]

Autofocusing operation is realized by using the autofocusing device which enables the motion of the lens of the microscope in z axis. First the microscope is moved to the home position along the z axis. Then it is moved downwards to a pre-defined height in order to speed up the process. Starting from that position, microscope is moved again downwards and the normal variance is calculated at each step. Using the first derivative of the normalized variances, local maximum values are calculated representing the interested focal planes. From the corresponding z values to the local maximum points, the vertical distance between each interested focal plane is then calculated.

5.6 Calibration of the System

In order to utilize visual feedback for the control of the assembly process, a mapping between image pixels coordinates and the real world coordinates. These parameters can be determined by means of camera calibration. In an optical system with a camera, a two dimensional projection image of the scene is formed on the image plane which causes the loss of depth information. To regain the 3D information, multiple views from a single camera, multiple cameras, or knowledge of the geometric relationship between several feature points on the target are necessary.

Necessary parameters essential for the mapping between image space and the real world includes the extrinsic and intrinsic parameters of the camera. Intrinsic parameters are the focal length, coordinates of the optical axis on the image plane and the pixel scaling factors. Extrinsic parameters denote the pose of the camera with respect to world coordinate frame. Camera calibration is the process of determining these parameters.

For an optical system including an optical microscope, calibration depending on the perspective projection type of image formation is not applicable since microscopy imaging provides only finite number of focal planes. As a result of that, an approximation of perspective projection by a linear scaled orthographic projection, so called scaled orthographic projection, is used. In order to establish a scaled orthographic projection, the coordinate systems of world and the camera frame must be aligned and the distance in the z axis should be known. These conditions are considered to be satisfied in our case since the z position can be obtained by autofocusing and the coordinate systems are aligned if small misalignments due to fixturing are neglected.

Using that model, image coordinates (*u, v*) of the corresponding world point coordinates (*x, y*) can be obtained from the equation;

$$\begin{bmatrix} u \\ v \end{bmatrix} = s \begin{bmatrix} x \\ y \end{bmatrix} \tag{5-32}$$

where *s* is a scale factor. [53] That fixed scale factor can be determined by using calibration patterns with known size and geometry.

Implementation of camera calibration for the microassembly workstation is as follows;

- For each magnification of the microscope, micropattern images are captured
- Edge detection is applied to each image
- Hough Line Transform is applied to the images in order to find the corner points of the patterns from the intersection of the detected lines.
- Since the results are not satisfactory, edge points having a certain amount of distance from each line found by Hough transform are determined and by point-to-line fitting, new line equations are determined.
- These points with the corresponding world coordinates are then used for the determination of the reduced camera calibration matrix.

Table 5-1 shows the resulting micrometer equivalent of a pixel for coarse and fine cameras at each magnification of the microscope.

µm/pixel Magnification	Coarse Image (x)	Coarse Image (y)	Fine Image (x)	Fine Image (y)
0.75 ×	8.1923	8.217	1.3806	1.3783
1×	6.1342	6.1399	1.0388	1.0404
2×	3.0859	3.0908	0.5242	0.5259
3×	2.0734	2.077	0.3548	0.3524
4×	1.54	1.5458	0.2661	0.2559
5×	1.2395	1.2375	0.2125	0.2147
6×	1.0229	1.023	0.1808	0.1814
7×	0.8789	0.8799	0.1486	0.1541
8×	0.7689	0.7698	0.129	0.1341
9×	0.6814	0.6815	0.1136	0.1087
10×	0.6143	0.6148	0.1042	0.1042
11.25×	0.5403	0.5429	0.0917	0.0934

Table 5-1 – µm equivalent of one pixel

5.7 Prior Knowledge Determination

There is a set of parameters which should be determined before starting the microassembly operations. These parameters are necessary within the cycle of the assembly process. Main modules for the prior information determination are the camera calibration for the mapping between the image space and the real world and autofocusing for the vertical position determination.

There are also other parameters so called model-based parameters [42] such as the data (size, shape, deviation in size, etc.) about the parts to be manipulated, and the assembly order when realizing an assembly of different components.

Allegro [42] classified the system parameters as the static system parameters determined before the assembly operation and the dynamic parameters initialized before the operation and updated during the assembly process.

For our microassembly workstation, static system parameters include;

- Mapping between the image space and the work space established by camera calibration (Section 5.6)
- Distance in order to bring the manipulation tool into the field of view realized by an homing procedure
- Depth information of the manipulation tool and the parts to be manipulated determined by autofocusing (Section 5.5)
- The illumination setting for different magnification values of the microscope

Dynamic system parameters include the positions of the motion stages, microscope settings and the progress information about the assembly process. Actual positions of the stages can be acquired from the internal sensory feedback.

5.8 CONCLUSION

In this chapter, issues related to the system supervision and control of the microassembly workstation is presented. The system is examined in two subsystems, motion control and the vision system. In the motion control part, system architecture is presented and the used control method, SMC, is explained over the control of piezo stages providing a robust system with its built-in disturbance rejection, which in turn implicitly compensates for the unmodeled dynamics, and thus provides a possibility for achieving high precision and fast response. Detailed results of the control structure are shown with the output graphs.

Vision structure is defined as an external sensory feedback for the assembly operations and used algorithms for image processing are explained briefly. Image processing techniques are used to detect and track the particles in order to give relative position information for the assembly tasks to be generated.

Camera calibration issue necessary for the mapping of 2D image coordinates to the 3D real world coordinates implemented in the project is described. Since for an optical system with an optical microscope, calibration depending on the perspective projection type of image formation is not applicable since microscopy imaging provides only finite number of focal planes. As a result of that, an approximation of perspective projection by a linear scaled orthographic projection, so called scaled orthographic projection, is used for the camera calibration.

For the determination of focal planes, a passive autofocusing technique is used based on normalized variance algorithm. According to the focal planes determined by the autofocusing, depth information between these focal planes corresponding to the tip of the manipulation tool and the particles is extracted and used as a parameter in the system.

Finally, prior information extraction issue is explained considering the parameters which should be determined before starting the microassembly operations and which are necessary within the cycle of the assembly process such as the model of the particles, mapping between the 2D image space and the world coordinates, depth information obtained by autofocusing, etc.

6 EXPERIMENTS AND RESULTS

6.1 Introduction

The microassembly workstation is designed in such a way that several experiments can be realized on the same platform just by changing the manipulation tool necessary for the defined microassembly task. The system modularity allows the possibility to employ different approaches of the microassembly defined in section 2.1; tele-operated, semi-automated and automated. By just choosing one of them the system becomes operational in that mode.

For the testing of the reliability of the system for different microassembly tasks, several experiments are implemented in different modes. These experiments will be defined in the following sections. Tele-operated microassembly is realized in two different ways; by giving commands on the screen with mouse clicks and by means of a joystick. Semi-automated microassembly involves the intervention of the operator to some extent. The operator just chooses the particle to be manipulated and the destination, the rest is executed automatically.

Experiments related to these two approaches and results will be shown in the following sections. System evaluation will be made according to the results achieved by the experiments and the chapter will be concluded with some discussion about the results of the experiments.

6.2 Tele-Operated Microassembly

6.2.1 Definition

In tele-operated systems, the hand motions of a human operator are transferred to the motion system by means of a man machine interface (MMI). Our system is configured to be used by a joystick giving commands to the X and Y axes of the manipulation stages. The operator can also give motion commands from the graphical user interface (GUI) by simply using the mouse and clicking on the screen to choose the home and destination points. Tele-operated system architecture is shown in Figure 6-1.

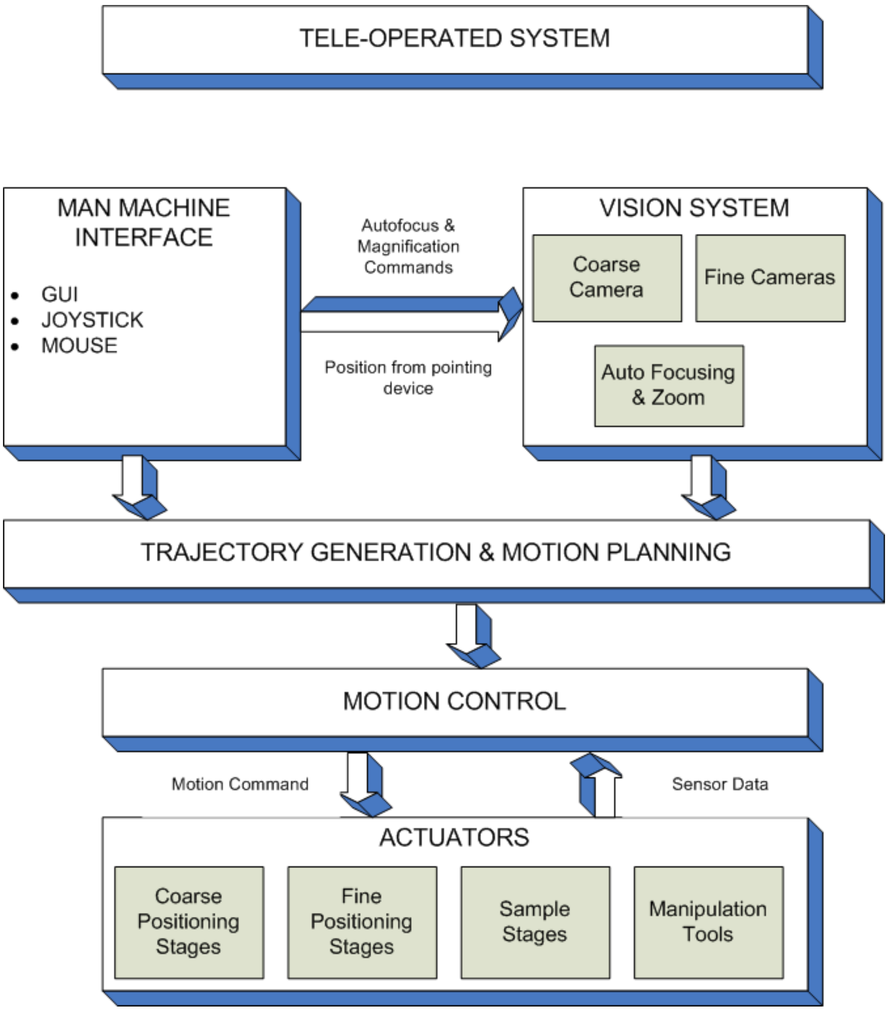


Figure 6-1 – Tele-operated System Architecture

By using the joystick, X and Y axes of the manipulation stages or the sample stages can be controlled. When using the microgripper as the gripping tool in the system, mostly the sample stages are given the commands of motion and the gripper is kept stable in the screen. So that, the particles are moved towards the gripper and by giving the open-close commands from the GUI the picking operation takes place. The procedure for manipulation operation with the microgripper by using joystick is summarized in Figure 6-2.

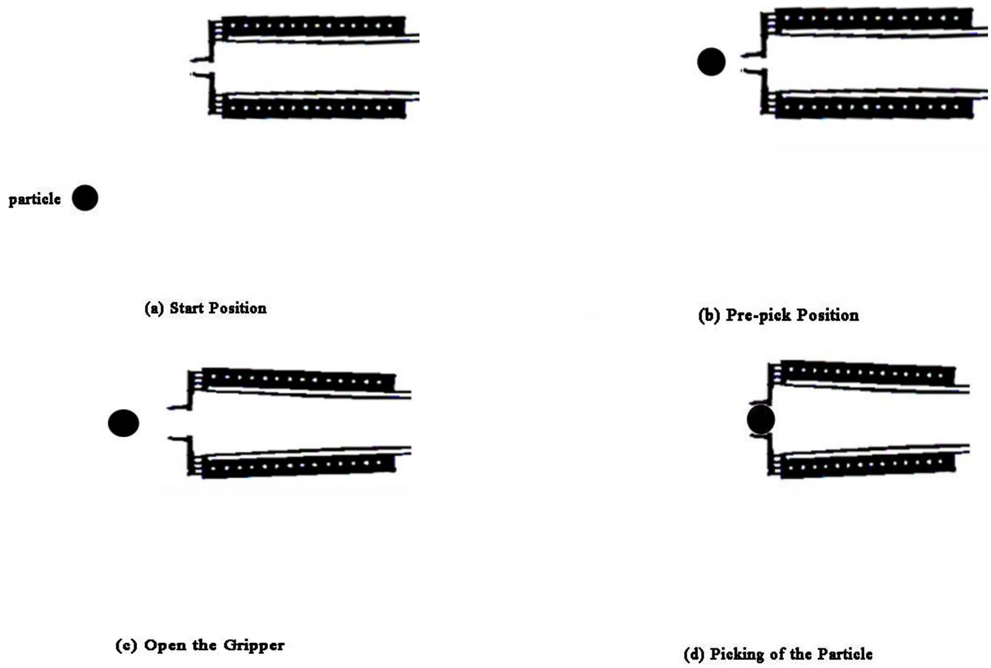


Figure 6-2 – Experiment Procedure (Joystick)

As it can be seen from Figure 6-2, the particle is first moved to the pre-pick point and then from a knob embedded into the GUI, the gripper is opened. Then the particle is moved inside the gripper and the gripper is closed. Then by moving the stages the particle is moved to the desired destination and placed.

By using the tungsten probe, the case is a little bit different since the particles are moved by pushing. During the pushing operation, the probe tip should point the center of the particle since the particle can roll around itself failing the pushing operation. Furthermore, if the distance determined for pushing operation is too much, the particle can also rolls around itself due to imperfections of the base surface and the particle shape, not touching the surface at one point, etc. Therefore, the operator should be trained to realize experiments by using the probe as the manipulator.

In the tele-operated system, mouse can be also used for giving motion commands to the manipulation system. Simply by mouse clicks on the screen, home and destination points are selected and the relative distance between these points are sent to the motion stages. So that the operator should first select the tip of the probe and the desired point for the probe to move.

If the desired points are predefined, there are some supportive features are added to the screen in order to guide the operator during the manipulation process. For the defined template, the lines between the center of the particles existing in the field of view and the desired locations are drawn. The extension of that line through the probe side is indicated with a point on the screen to guide the operator. The probe is first moved to that point and pushing operation is realized by giving the motion commands along the line. (Figure 6-3)

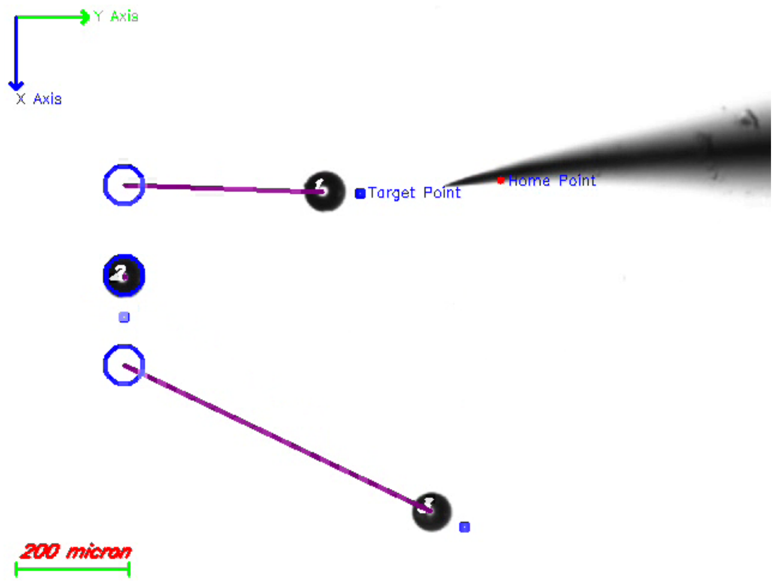
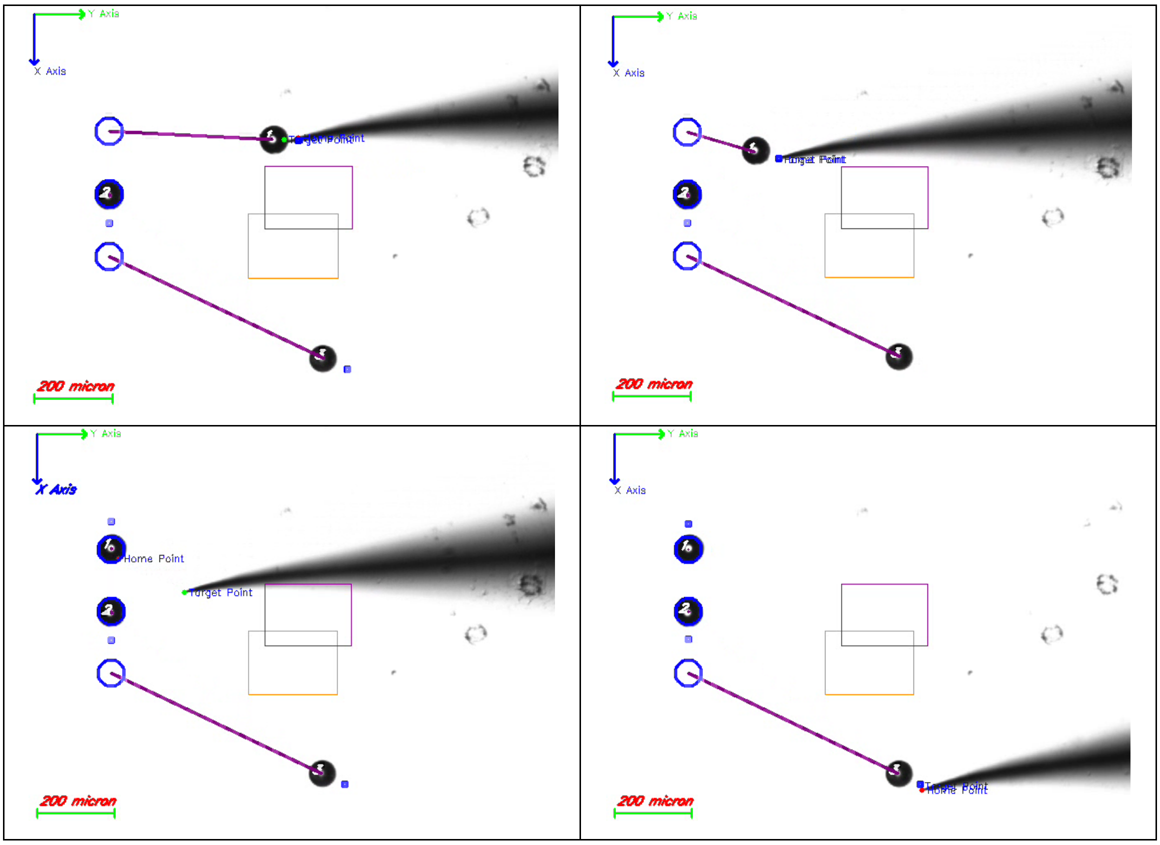


Figure 6-3 – Predefined Line Template

6.2.2 Implementation and Results



In this task, a predefined line template is formed in tele-operated mode. As there are three particles in the field of view, the line template consists of these three particles aligned vertically. Target positions of the particles are indicated with circles on the screen and the target position of each particle is determined according to the distance between the particle and the target position. Each particle is intended to be moved to the closest target point. In order to guide the operator, pushing points of each particle and the trajectory denoted by a line between the center of the microparticle and the target point are displayed on the screen. The operator, by simply clicking on the screen, moves the probe tip to the pushing point and then pushes the particle through the line to its target point. This process is repeated at each step.

6.3 Semi-Automated Microassembly

6.3.1 Definition of the Task

In semi-automated microassembly, the operator intervention to the assembly operation is limited. By this way, the tasks of the assembly procedure are commanded to the manipulation system one by one by the operator. The tasks are pre-programmed and the operator simply defines some of the parameters necessary for the assembly. The operator selects the particle to be manipulated and the destination point by simply clicking on the particle on the screen. The rest of the operation is managed automatically. Semi-automated system architecture is shown in Figure 6-4. After the handling of the initial steps by the operator, relative distance data calculated by the vision system is fed to the motion system while sensory feedback (position data) from the motion stages is sent back.

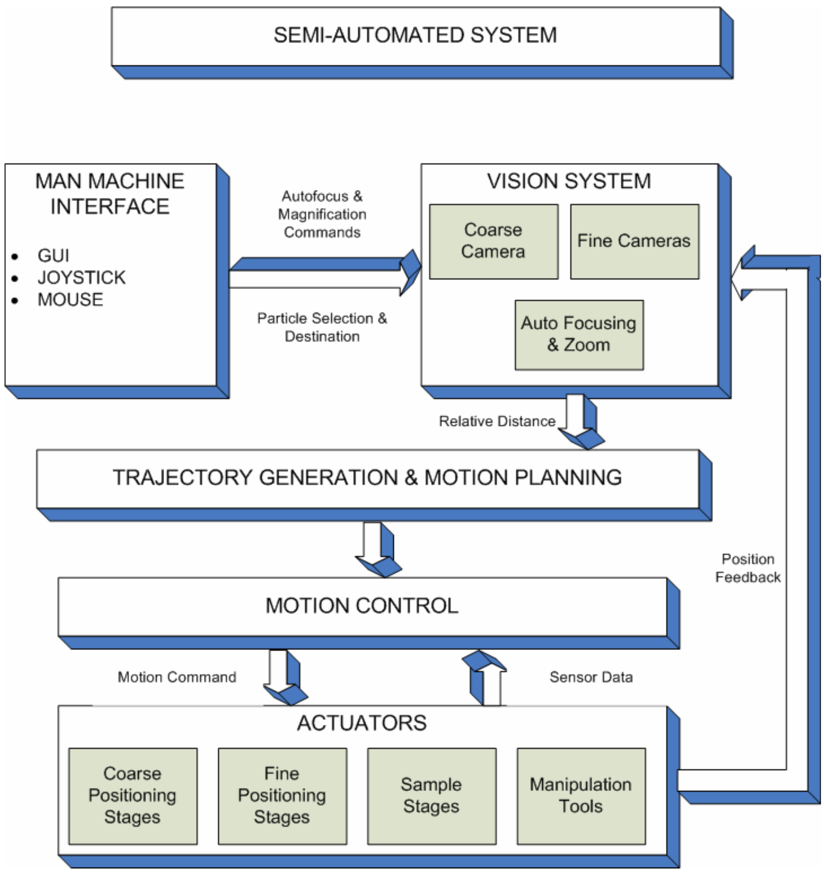


Figure 6-4 – Semi-Automated System Architecture

Using the sharp tungsten probe as the manipulation tool, the algorithm is explained in Table 6-1.

$INIT();$

$repeat$

$\quad \varepsilon, L_p, x_p, x_c \leftarrow UPDATE();$

$\quad MOVE(x_{pt}, x_p);$

$\quad PUSH(x_p, \varepsilon);$

$\quad RETRACT(\varepsilon);$

$until(x_c = x_g)$

Table 6-1– Semi-Automated Microassembly Algorithm

The system initialization includes the selection of the particle and the desired destination point, x_g. Center point of the selected particle x_c, line between x_c and x_g, step motion value for pushing the particle ε and the pushing point x_p are calculated. The tip of the probe, x_{pt}, is then moved to x_p. The probe is moved through L_p with a step motion of ε in order the push the particle. After the pushing operation the probe is retracted back with the same step motion size. These steps are repeated until the center of the selected particle coincides with the desired point. Figure 6-5 shows the semi-automated microassembly process for a single particle.

The most feasible trajectory for a particle to its target position by pushing is simply a line denoting the closest path to the destination. In that context, the operator should choose the suitable part to be pushed and the destination point considering the issue that the semi-automated assembly procedure does not include motion planning so that there exists nothing as an obstacle between the particle and the target point.

Throughout the experiments carried out in both tele-operated and semi-automated modes of the workstation, it is observed that the pushing operation should be realized gradually by pushing, retracting back and then pushing again. The reason for such an operation is that pushing for long distances causes the particle to roll around itself and the probe tip resulting in the failure of the pushing operation. Also there is the possibility of the particle stick to the probe as a result of that rolling. When the particles roll to the side of the probe the contact surface increases causing the particle stick to the probe which will fail the assembly process. As a result of that the semi-automated tasks are implemented in a step-wise manner. The probe is moved to the defined pushing position and then along the line trajectory determined the particle is pushed for a small amount and then the probe is retracted back.

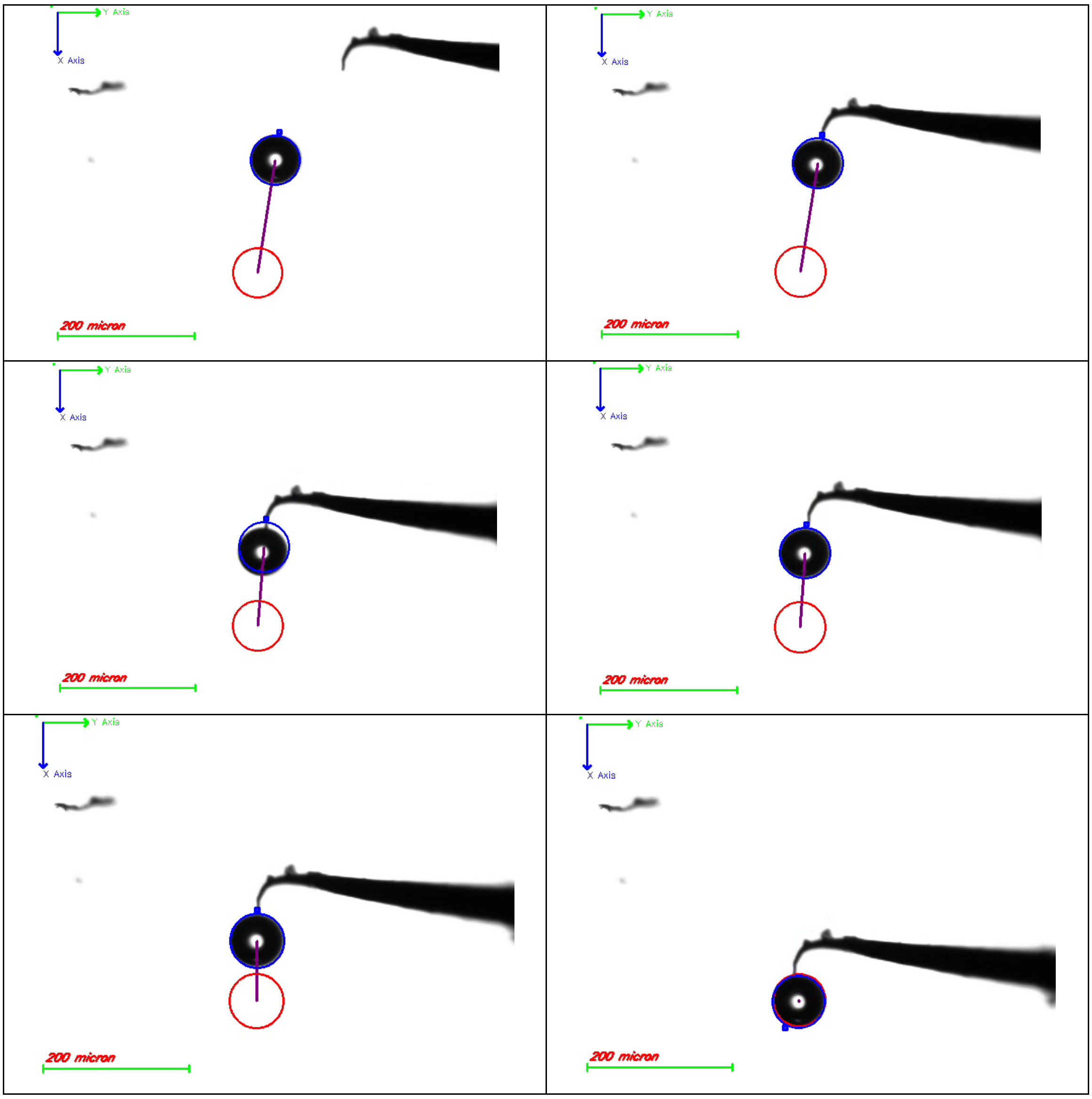
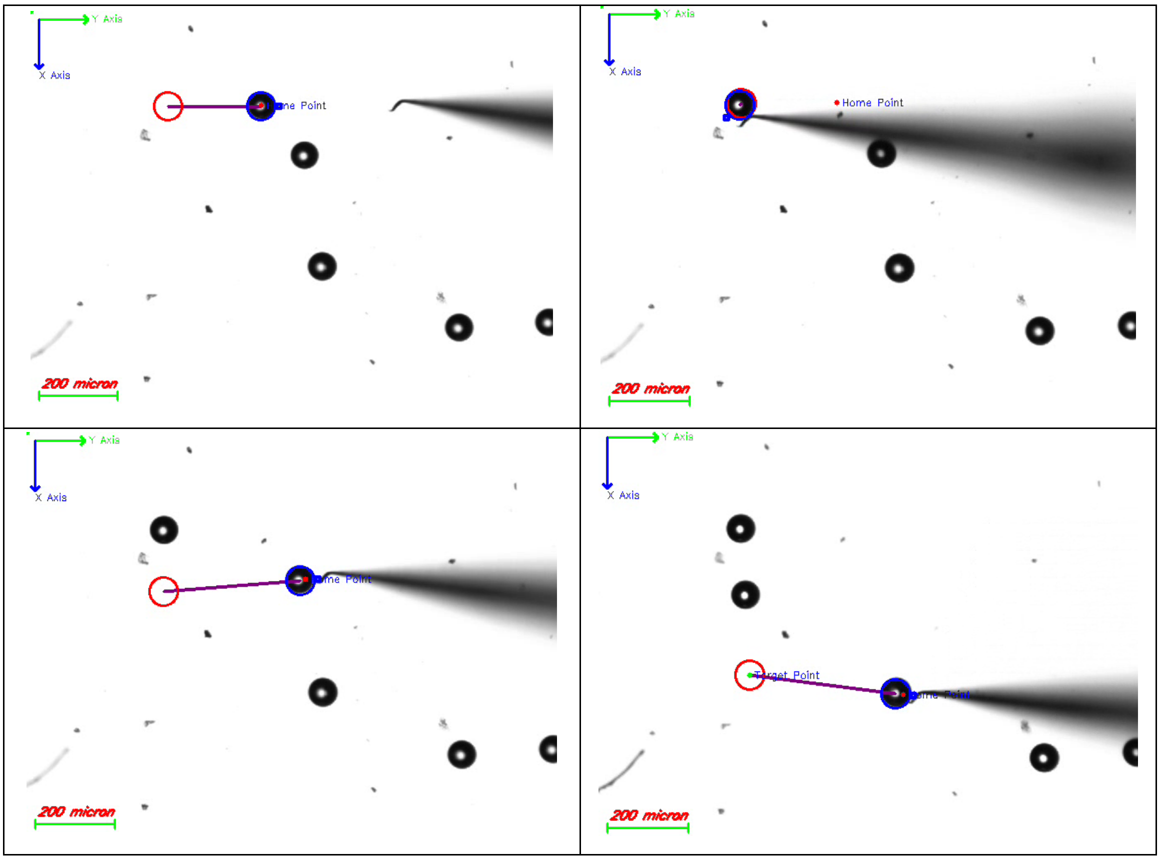


Figure 6-5 – Semi-Automated Microassembly

6.3.2 Microassembly Examples

Several semi-automated tasks are generated and implemented with the microassembly workstation. One of the main problems for the realization of the experiments is to find suitable microparticles to be used in the microassembly operations. In our experiments we used polystyrene microspheres with diameters of approximately 70 µm. By using these particles, some template formation experiments are realized by means of pushing with sharp tungsten probes and pick and place tasks with microgrippers.

A line formation experiment steps are shown in Figure 6-6. In that experiment, operator selects the particle and the destination point to where the particle will be moved at the end of the operation. This selection is made by the operator for every particle. After the manipulation of each particle to its destination, the probe returns back to the initial position and the new task is generated by the operator. The rest of each operation is executed automatically.



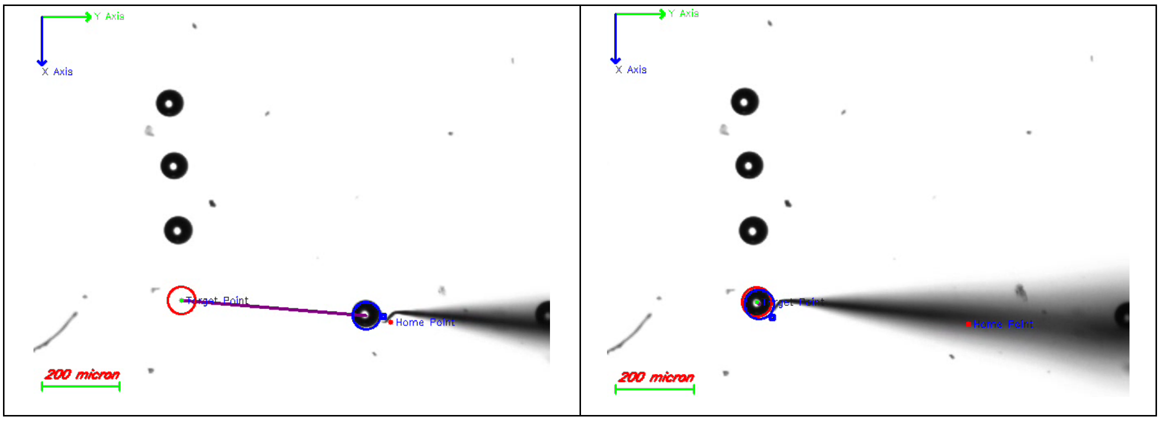


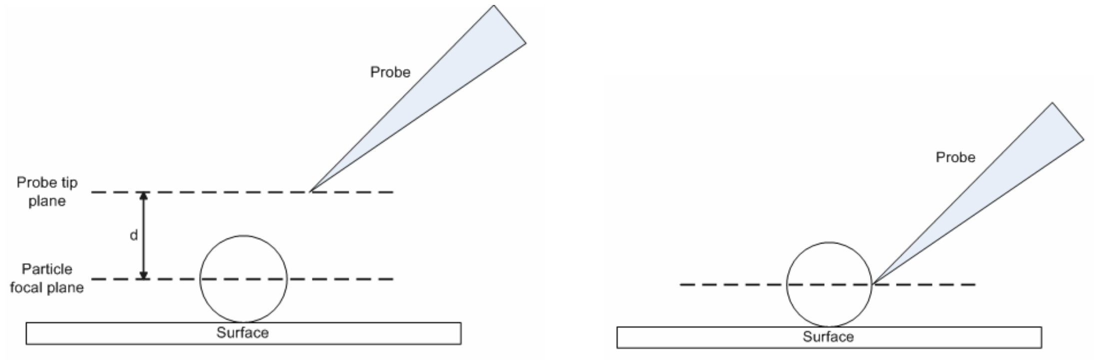
Figure 6-6 – Semi-Automated Line Formation

6.4 Results and Discussion

In the microassembly workstation, tele-operated and semi-automated microassembly concepts are implemented, and the validity of the approaches is demonstrated by implementing several experiments. These experiments show that the precision of the motion units and the vision system are sufficient enough to perform assembly tasks. The precision of the motion units is tested to be seven nanometers for the coarse motion stages and up to 1 nanometer for the fine stages.

However, there are several challenges regarding the manipulation operation like obtaining depth information, sticking problems and issues concerning sample preparation. These issues should be carefully considered for a successful assembly operation.

Before starting the manipulation of particles for the assembly task, the manipulation tool should be lowered to the level of the particle. The vertical distance between the tool tip and the particle center (Figure 6-7a) is determined by autofocusing described in Section 5.5. Since the probe is mounted with an angle, it is hard to focus on the sharp tip of the probe. The probe tip plane should be aligned with the particle center plane in order to realize the manipulation effectively. This vertical position adjustment should be realized very precisely. When the probe tip is below the center plane, the contact surface between the probe and the particle increases which causes the sticking of the particle to the probe. When the probe tip is above the center plane, the probe exerts a force towards the surface which will increase the friction between the particle and the surface. This may also cause a damage of the probe tip and imprecise positioning of the particles. In order to eliminate the forces complicating the manipulation, the probe tip must be aligned with the center plane of the particles very precisely. (Figure 6-7b) Vertical distance calculation results obtained by autofocusing are sometimes not precise since the tools are mounted with an angle which makes it difficult to determine the tip focal planes. For that reason, the system needs a more precise technique for the measurement of the vertical distance such as a laser sensor, etc.

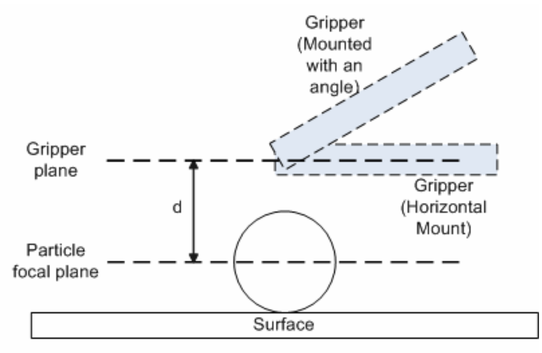


(a) Vertical distance between the probe tip and the particle center

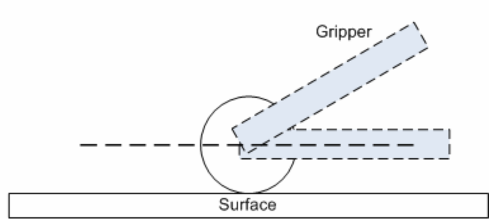
(b) Pushing position

Figure 6-7 – Vertical alignment of probe tip and the particle center plane

Same problems regarding the vertical alignment also exist for the microgripper when the gripper is mounted with an angle. In that case, middle plane of the microgripper must be aligned with the center plane of the particle. However, it is again difficult to focus on the tip plane of the gripper, since it is mounted in a tilted configuration. On the other hand, when the gripper is mounted parallel to the substrate surface, it is easier and more precise to determine the vertical distance. In this case, the gripper forms a planar surface which can be focused precisely and give better results. Two configurations are shown in Figure 6-8.



(a) Vertical distance between the probe tip and the particle center



(b) Picking position

Figure 6-8 - Vertical alignment of gripper and the particle center plane

Minimizing the contact surface is necessary to reduce the adhesive forces dominant in the microworld. In order to avoid the sticking effects, contact surface between the probe and the particle should be as small as possible. The optimum configuration for the pushing operation using sharp tungsten probes is depicted in Figure 6-9. In this configuration, the probe tip and the particle is in minimum contact providing an effective manipulation.

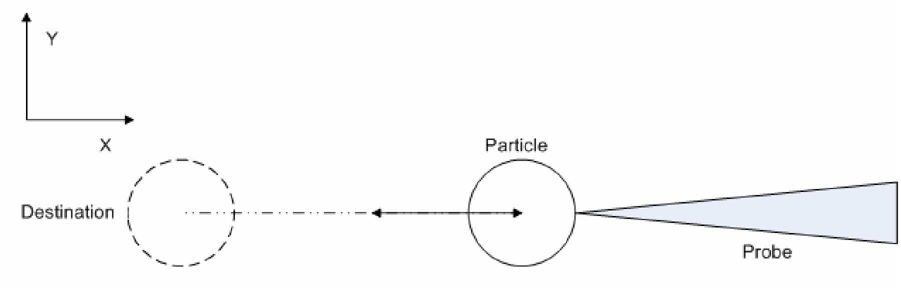


Figure 6-9 – Optimum pushing configuration

However, when the destination point is not selected in the same Y coordinate with the center of the particle, the particle needs to be pushed also in the Y axis which increases the contact surface. In that context, a rotational stage can be added to the system rotating the substrate which will allow the execution of the pushing operation only along the X axis. The case is explained in Figure 6-10. When the particle is desired to be moved to the *D1* or *D2*, by the aid of the rotational stage and compensation of X and Y sample stages, the substrate is rotated around the particle center axis with an angle between *LR* and *L1*, *L2.* Therefore, the optimum pushing configuration can be obtained. A rotational axis is also helpful for increasing the usable workspace of the substrate surface since the travel range of the motion stages are limited to some extent.

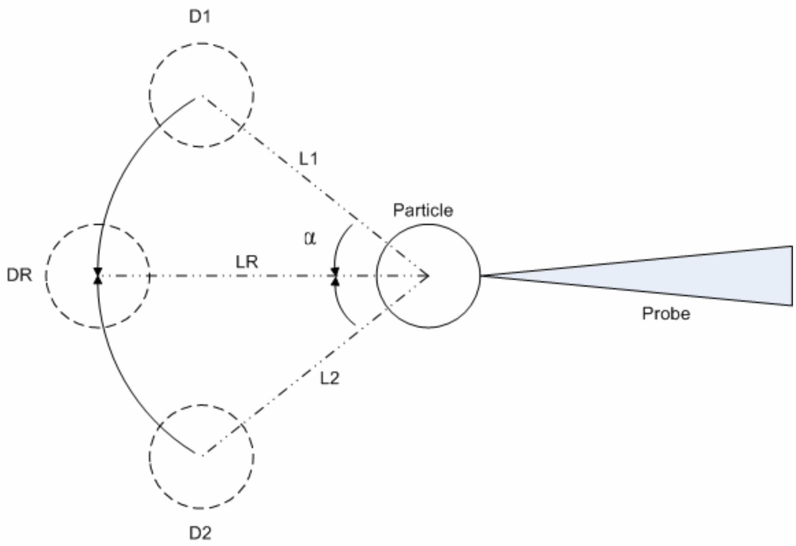


Figure 6-10 - Addition of a Rotational Axis

Sample preparation is also another main problem for the realization of the experiments. Particles used in the experiments are polystyrene microspheres having a diameter of approximately 70 micrometers. These particles are densely deposited in an aqueous solution and should be diluted to be used in the experiments. The dilution rate should be chosen carefully so that the particle concentration in the diluted solution will not be too much which will cause the aggregation of particles and not too little in order to have sufficient number of particles to manipulate. The solution is prepared using distilled water to prevent the contamination of unwanted substances on the substrate surface. While depositing the particles on the substrate surface, the water should be evaporated fully and quickly to prevent the aggregation of particles and remains of water between the particles and the surface.

Considering the experiments realized in the microassembly workstation, results are promising when precision, accuracy, reliability and repeatability issues are concerned. The efficiency of the system will be tested by implementing several assembly tasks and optimized according the results obtained from these experiments. With the attachments defined above, the system can operate effectively as a microassembly workstation for automated assembly tasks.

7 CONCLUSION

In this work, design and realization of an open-architecture and reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts is presented. Design necessities for an automated microassembly workstation are explained in detail and the realization of the system considering these necessities is demonstrated.

Microassembly process requires very high resolution actuators with good repeatability. For moving across scales from meso to micro and also to nano, a coarse-fine positioning scheme providing the necessary travel range and precision for microassembly tasks is implemented. Therefore, this scheme provides the compensation of positioning errors from of the coarse manipulator by the fine positioning system.

Same coarse-fine scheme is also implemented for the vision system. A stereoscopic microscope is equipped with a coarse imaging and a fine imaging at the same time. By the proposed scheme field of view problem is solved since while obtaining the workspace data from the coarse image, detailed information about the object can be retrieved from the fine image providing an effective system for microassembly tasks.

One of the main concerns for the design of the workstation is that it should allow realization of different assembly tasks just by changing the manipulation tool. The workstation is designed in such a way that according to the task to be realized, the manipulation tools can be easily changed and the system will be ready for the predefined task. In that sense, manipulation tools such as microgrippers, AFM probes, micropipettes and any other tool can be the matter of choice for the workstation.

The realized microassembly workstation represents an important step towards the automatic, autonomous assembly of micrometer-sized parts by means of sensory feedback. We demonstrated the functionality of the system on several experiments in different modes of operation, tele-operated and semi-automated. In tele-operated mode the operator controls the assembly process by means of a joystick or a mouse simply clicking on the screen to select the home and target positions of the manipulation tool. In semi-automated mode, the operator just selects the particle to be manipulated and the desired position. The rest of the operation is realized automatically using visual and position feedback. The results of the experiments are promising in the sense of precision, accuracy, reliability and repeatability. With the integration of motion planning algorithms, the system will have the ability to function in fully automated mode where there is no human intervention.

This project is the result of a team-work since there is a great amount of work done throughout the implementation of the project. The main motivation of this thesis is the realization of micromanipulation and microassembly tasks. However, the realization of these tasks involves every aspect of the design and realization of the microassembly workstation. As a result of that, I've contributed this project in every part defined in Chapter 4 and 5. The vision system and supervision is implemented by E. Doğan as a MSc. thesis. [54] My contribution mostly involves the mechanical design, electronics, motion control and implementation of the algorithms for the manipulation tasks.

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