Dissertation

A Contribution to Micro Manipulation (Handling and Assembly) in the Chamber of a Scanning Electron Microscope and under an Optical Microscope

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Dipl.-Ing. Aleksandra Cvetanovic
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Prof. Helmut Detter
Prof. Peter Kopacek

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To my husband, ***Andreja***
and to my parents, ***Mira*** *and* ***Nikola***

Aleksandra

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Abstract

The aim of this research work is to accelerate the micro manipulation proces and make it more efficient by using a novel protective cover for the micro components during micro assembly process, a visual system for prevention of collision between micro gripper and specimen holder during a micro manipulation procedure as well as by introducing an automation concept during micro assembly process.

Specifically, the first part of the dissertation discusses the development of a novel, protective cover for the micro components which are placed in the chamber of a scanning electron microscope (SEM). The problem that might occur during evacuation of the SEM chamber and, particularly at the beginning of the process, is that the micro components might be sucked into the vacuum pump and damage it. The protective cover prevents this from happening by covering the micro components during the evacuation of the chamber. The micro components being placed under the cover can neither be moved nor aspirated by the flow of air inside the chamber; during the moment of gripping and handling, the cover is opened and the micro component is available. Due to the facts that the micro components are not glued on the specimen holder the micro gripper does not have to separate them from the adhesive substance reducing the risk of damaging them. Additionally the micro components can be precisely positioned which enables the automated assembly process. An additional advantage of the presented system is that it is adaptable to standard specimen stages, it can be mounted without additional time, modification or expenses into the SEM chamber and it can be transformed into an automatic feeding system.

The second part of the dissertation considers the problem of a possible collision between the mounted micro gripper and the specimen holder. This might occur due to the fact that it is difficult to observe under a microscope the micro gripper's approach towards the micro component in the z-axis. The optical system consists of a micro camera with an infrared (IR) Light Emission Diode (LED) and magnification lenses, a mirror and a micrometer scale. It enables continuous monitoring of the micro gripper's approach to the micro object. The resolution limit is 20 μm. The accuracy that can be achieved with the described method depends on the micro camera's resolution and credibility. The micro camera has an integrated magnification of 20-40 X. The micro camera used in the first experiments had a resolution of 640x480 pixels and a mass of 20 g. The constraint on increasing accuracy is in the lack of micro-cameras which can be used in vacuum with a sufficient resolution. A video system can also be used under an optical microscope, without utilization of IR diodes and with a smaller adjustment to the workplace.

Finally the third part presents an analysis of the kinematics relationship in the SEM chamber in order to find an optimum path for manipulation and positioning of the micro components. In this chapter a method for reduction of the assembly time in the case that feeding of the components occurs both by translation motion of the stage (B) in the x and y direction and by rotation of the platform (P) with optimization of the trajectory in real-time is presented. The time reduction for a micro system which consists of ten components is almost 50%.

Chapter 1. Introduction

1.1 Problem definition and its relevance in todays context

A lot of advantages- increased reliability and portability, low power consumption, easy and massive deployment, easy maintenance and replacement, harmless for the environment, etc. - in a number of technical applications bring the miniaturization of single components or the whole systems. Nowadays the need for microsystems in mechanical engineering, automotive industry, communication technique as well as in medicine, aerotechnics, astronautics, process engineering, environment engineering is increasing.
Yet, manipulation and assembly tasks are still the limiting factor for a wider application of MEMS devices that are built by assembling of individual micro-components in spite of the vast amount of research being performed in these fields. [1-1] [1-2]
The purposes of micro manipulation operation present not only the micro assembly; the aim can be processing of structures for micro and nanofabrication, examination or alteration of the micro objects or biological cells, testing, etc. The manipulation in the micro scale does not mean the down scaling of well-known assembly techniques of the macro scale but different properties of the micro components have to be considered.
The handling and assembly of single micro components to complex micro systems present a complex operation which significantly influences the final production costs and quality.
The primary challenges originate from the small size of the components: the physics of micromanipulation is significantly different than the macro manipulation and has its own phenomena.
The demand for high precision in order to automate the micro manipulation process, the deficiency and imperfection of the manipulation tools and the equipment and absence of standardization hinder the way to the rapid expansion on the market of the hybrid MEMS.
High precision assembly processes make up a large proportion (up to 80 %) of the overall production costs. Therefore solutions for the flexible automation of handling and assembly processes capable of reducing cost and achieving proper production quality are needed, see Figure 1.1-1.

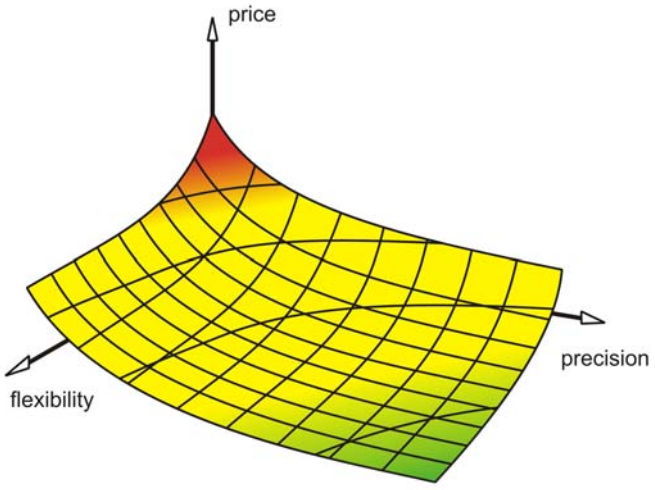

Figure 1.1-1: The dependence price-precision flexibility of the micro assembly systems

Even though nowadays micro manipulation technique suffer due to slow standardization and automation process, which is the main limitation, the potential for increasing the efficiency of micro manipulation; the potential is large and great progress in the field of micro technique

can be expected, in almost the same manner as the progress of micro electronic, a few decades ago.[1-3]
The main task in micro manipulation is making the operations with the micro components visible. The human eye, without the auxiliary tools, comes up against the physical limits very quickly. The resolution of the human eye is 0.1 to 0.2 mm and the objects that are smaller must be magnified, in order to be examined. The microscopes serve this purpose and in this thessis are particularly considered a conventional optical light microscope (OM) and scanning electron microscope (SEM). The consideration of the environment and the size of the object recommend the adequate microscope type, Figure 1.1 2.

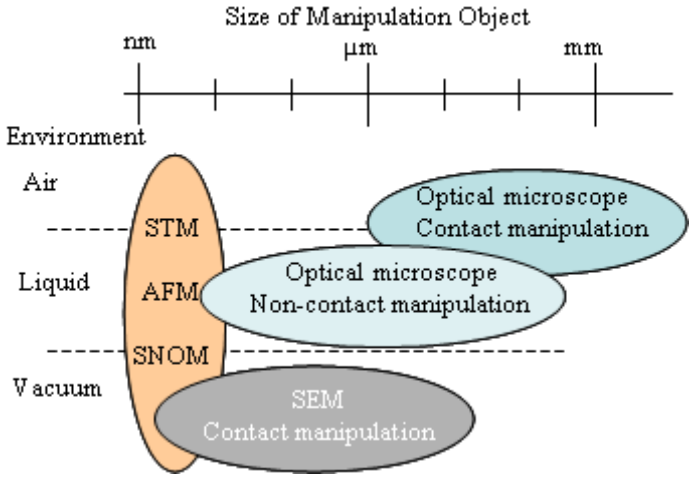

Figure 1.1-2: Visualisation of micromanipulation based on environment [1-4]

Nowadays an optical microscope is commonly used for manipulation in a range of a few hundred micrometers. Atomic Force Microscope and Scanning Tunnelling Microscope are used on an atomic scale. Scanning Electron Microscope techniques fill the gap for manipulation of objects in a range of a few tens of micrometers to a few hunderd of nanometers.
Even though their working principle is completely different, both can be used in micromanipulation and micro handling. As SEM offers incomparable better visualisation possibility than a conventional optical microscope it is important to continuously improve handling process in the chamber in order to get a reliable and efficient micromanipulation system.
These improvements have to lead to rapidly increased efficiency and reliability of the micro assembly process, reducing the costs and providing proper production quality.
The corresponding assembly systems must achieve accuracies in the range of several micrometres, increase the flexibility of the position and adjustment systems, improve the set-up process and meet the requirements of standardization. Figure 1.1-3 illustrates the assembly flow depending on the automation level, precision and microscope type; with increased automation level the micro assembly process can be more efficiently performed.

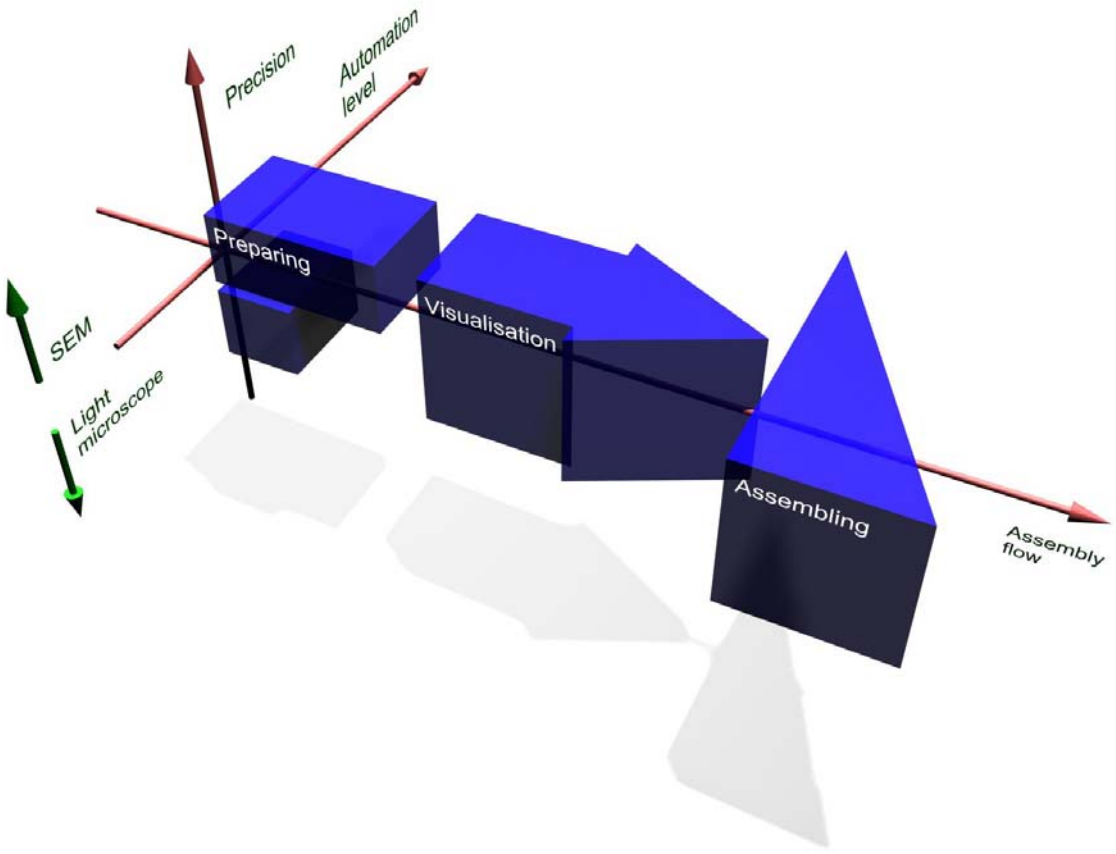

Figure 1.1-3: Assembly flow depending on microscope type and automation level

1.2 Main objectives of the dissertation

This dissertation contributes significantly to the research being performed worldwide in the field of micro handling and micro assembly. The improvement capabilities are addressed and executed in order to develop a more efficient micro manipulation system.
The research interests are primarily directed towards the analysis of the micro manipulation tasks in order to:

- Gain understanding of the micro world aspects with respect to the manipulation and handling operations both in a scanning electron microscope environment and under an optical microscope.
- Consider the visualisation task, since the microscope is necessary during the micro handling operation.
- Presenting the design and develop of a novel systems as it will be described bellow.
- Develop a concept for operations automation to make the micro manipulation procedure efficient and reliable. Considering the limitation of a human in the dexterous and reliable handling processes and in maintaining the yield over time, the automation of the micro manipulation process is a consequential step.

Chapter 2 and Chapter 3 are devoted to the description micro handling procedure, the state of the art and the effects and phenomena which occur in the micrometer scale. [1-9], [1-10], [1-11] [1-12]
In Chapter 4 the main characteristics and working principle of an optical microscope (OM) and a scanning electron microscope (SEM), with a detailed description of the performed micro manipulation procedure are discussed. [1-13] [1-14]

Chapter 5 solves the problem of a possible removal of the micro components which are positioned on the specimen holder inside the chamber of a scanning electron microscope due to the air flow during the evacuation of the chamber. In particular, one of the negative aspects of using the SEM in micro manipulation is the need for evacuation of the chamber. The process of vacuum generation is time consuming and the micro components might be moved from their place, or sucked in the vacuum pump, due to the produced air stream.
It is well known that the vacuum pumps, especially the turbo ones, which evacuate a SEM chamber, are highly sensitive to foreign object damage. This is one of the reasons why the micro components are glued on the specimen holder in the SEM chamber. On the other hand, the micro grippers that have to pick, lift and place the micro components in a desired system (position, orientation) are very fragile. They can not overcome the adhesive force of the glue and remove the micro component from the specimen holder.
A novel protective cover was developed to protect the micro components and enable the usage of a finest micro gripper during the pick-up tasks. After the pump phase the protective cover can be opened and the micro manipulation operation can be accomplished. The novel protective cover for micro components is developed, applied and evaluated.

Chapter 6 presents an innovative visual system for collision prevention during micro manipulation, i.e. during the phase where a micro gripper is approaching the micro component. A particularly problematic operation during a micro manipulation process performed in both microscopes is the micro griper approach to the micro components, because the microscopes enable only plain view, in x-y plain, and the distance estimation from the micro gripper to the micro componentin the z direction is very limited. [1-5][1-6] Since the micro gripers are very fragile, they break after collision with the holder. A design of the monitoring concept and its development, which offers continous z-axis monitoring and detection of the height of the micro gripper in relation to the micro component or specimen holder which is suitable for both types of microscopes, is presented.
It is based on the mirror principle and teleoperated visual control of the micro manipulation procedure. A necessity was the continuous monitoring of the relation between the micro gripper and the micro components. Currently a resolution of 20 μm is achieved; a nanometer resolution is not required, because the prevention of the collision occurs promptly, due to the quick interpretation of the visual information by the operator. It brings an optimal cost-performance ratio, and wide area of application.
The presented system configuration is mounted as a module in a conventional SEM, using standard tools, and does not influence its proper operation. During micro handling with this system specific skills are not required and the micro manipulation is simple and safe.

An automation concept in the chamber of the SEM is presented and evaluated in Chapter 7. [1-7] [1-8] [1-15] [1-16] The further development of the micro system technique will crucially depend on the accessibility of efficient automated assembly systems. This dissertation meets the need for automation, considering the simplest way to automate a micro manipulation process in the SEM chamber.
In this chapter a method for reducing the assembly time in the case that feeding of the components occurs both by translation motion of the stage in the x and y direction and by rotation of the platform with optimization of the trajectory in the real-time is presented. The time reduction for a micro system consists of ten components is almost 50%. This is a novel approach, efficient and implementable in any standard scanning electron microscope.
Figure 1.2-1 presents a micro manipulation area and a vision of development, from manual micro manipulation systems to the full automated and from precision in the μm range to precision in the nm range.

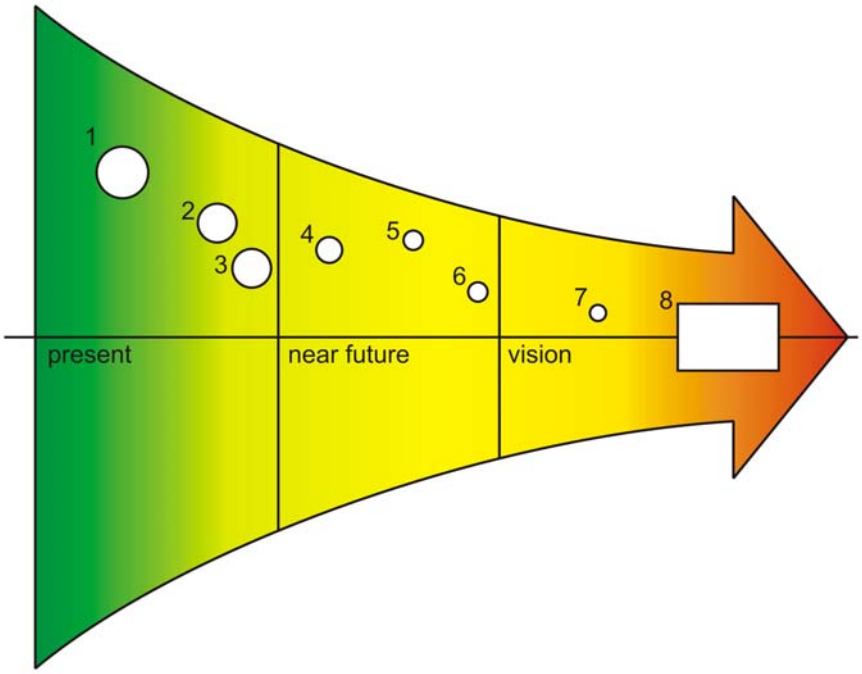

Figure 1.2-1: Micro manipulation systems: 1, 2, 3-work in research of micro phenomena, 3, 4, 5-different concepts of the micro manipulation system and system for collision prevention 7, 8-towards full-automated micro and nano manipulation systems

1.3 Configuration of the micro manipulation system used during the work

The basic equipment used during the work:
SEM examinations were performed with a Philips XL-40 (see Figure 1.3-1 and Figure 1.3-2 and equipped with a La B6 cathode; under optimum conditions, this microscope is capable of a 3 nm resolution.

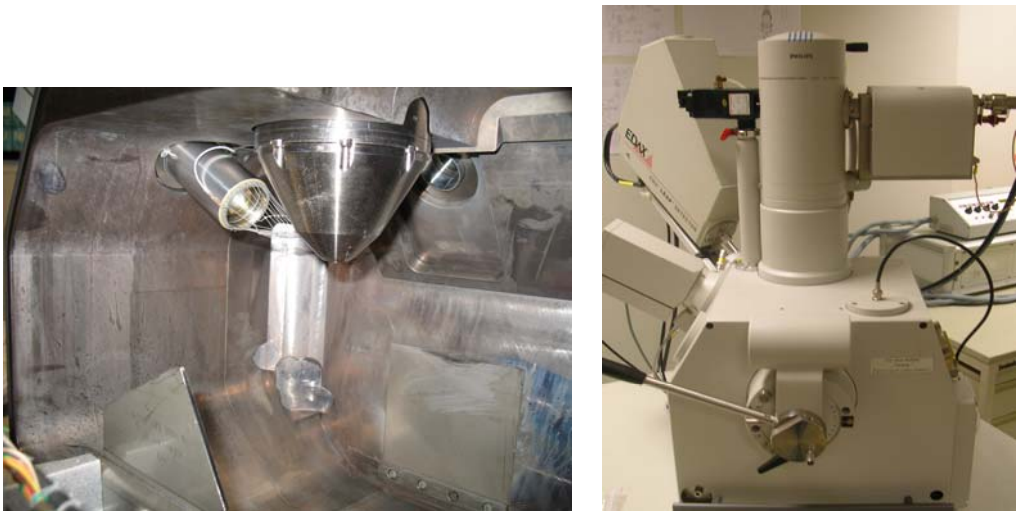

Figure 1.3-1: SEM Philips XL40; inside and outside the chamber

Figure 1.3-2: SEM Philips XL40; in laboratory

- The optical microscope is Olympus, SZ-STU2 (correspond to new SZ11); working distance is 73mm. Zoom magnification 1.8x-11x (total magnification 18x-110x). Fields of view are 12.2; 5.5; 2.8; 2 mm respectively.

- Micro manipulation stage
  The system used for micro assembly at the Institute of Sensors and Actuator Systems consists of a module with two micro grippers that are exchangeable, see Figure 1.3-3

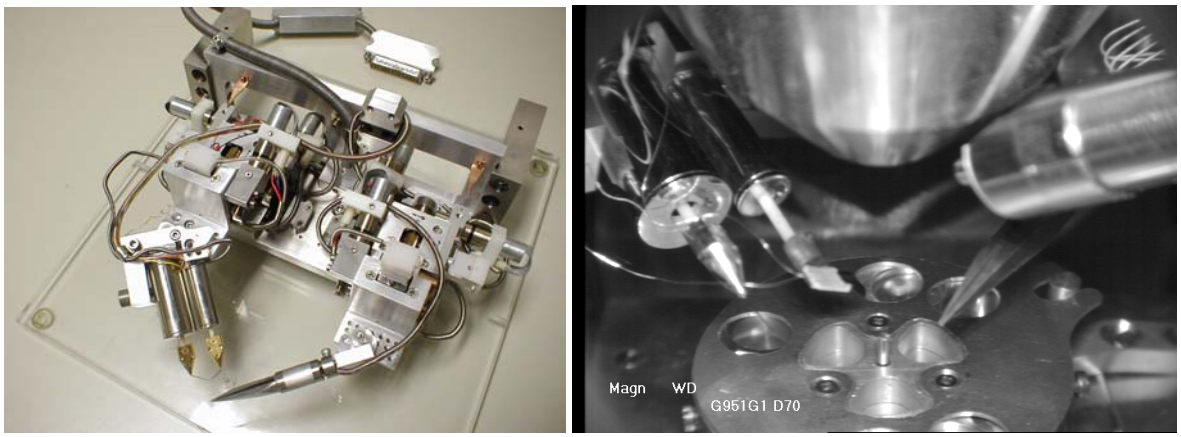

Figure 1.3-3: Micro assembly station: different micro grippers

		Range	Step size	Velocity
Servomotors	X	± 6,5 mm	0,8 µm	~ 0,48 mm/sec
	Y	± 6,5 mm	0,8 µm	~ 0,48 mm/sec
	Z	± 5,5 mm	-	~ 0,48 mm/sec
Piezo-elements	X	± 5 µm	10 nm	~ 3,1 µm/sec
	Y	± 5 µm	10 nm	~ 3,1 µm/sec

Figure 1.3-4: Characteristics of the micro assembly station

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Chapter 2. Micro manipulation Process

2.1 General Phenomenon of Micro Handling and Assembly

Micro handling is a process of manipulating micro components, under micro scale tolerances, translating, placing, orienting, aligning or rotating them; micro assembly is fixing (bonding, joining, soldering, cutting, gluing) them at a defined position. Micro manipulation process includes handling and/or assembly of the micro components.

Micro assembly is an extremely difficult and complex process that is realized in order to:

- assembly micro component at a system level- realisation of miniature systems e.g. miniature gears, pumps, sensors
- integration of the micro system to a macro system- embedded systems, insertion MEMS into macro devices

There are two major trends in micro-assembly:

- development of technologies for zero-assembly solutions,

This concept limits the number of realisable micro systems due to using only one material and incompatibility with other technologies. Complete monolithic integration is economical only in serial production. Many micro systems, e.g. in medicine, are required in the small or middle volume production. The introduction of the hybrid MEMS is a consequential step.

- development of high precision assembly enabling technologies
  - parallel
  - serial

Figure 2.1-1 shows micro handing and assembly classification.

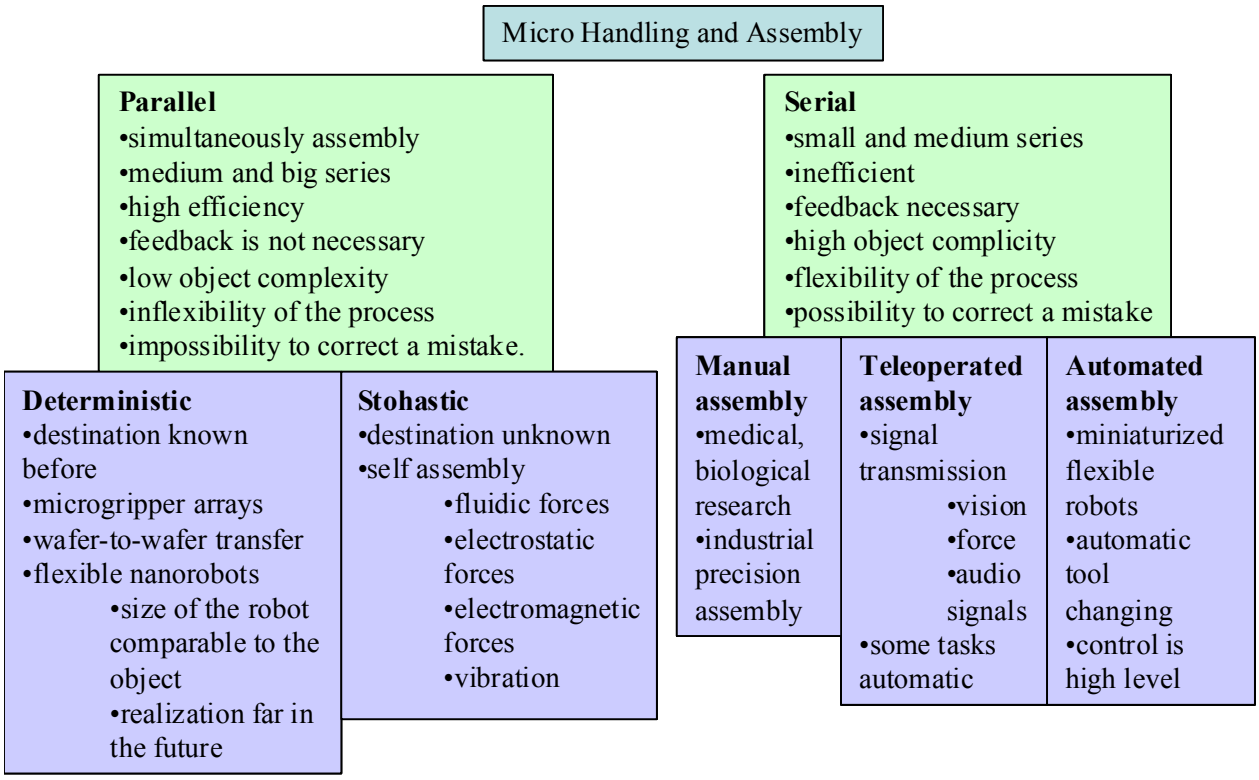

Figure 2.1-1: Micro handling and assembly classification

2.1.1 Parallel micro assembly

Parallel micro assembly is operation of simultaneously self-assembling of multiple micro components (of identical or different design), under the influence of an external force (electrostatic force, magnetic field). Parallel micro assembly techniques enable fast integrating and packaging of micro devices, increasing the operational capacity of micro assembly process.

Parallel assembling implies the designed character of grouping components. Microsystems are assembled by mounting the substrates one on the other, making a sandwich structure. Substrates are aligned relatively to each other using adjustment markers. The tolerance of micro component distribution on every substrate inside the sandwich must be compatible in order to achieve a reasonable tolerance of the assembled micro system. Different techniques of bonding may be used for connecting the substrates, for example anodic or adhesive bonding or laser welding. Finally, the assembled systems are split up and it results in separate micro systems. High efficiency could be achieved with parallel assembling in terms of the number of systems assembled in one step.

Parallel assembling in liquid is also demonstrated by techniques known as template-based assembly. [2-1]

There are two main categories in parallel micro assembly:

- Deterministic, when the relationship between micro component and its destination is known in advance.

- Stochastic, when relationship between the micro component and its destination is unknown or random; the micro components are moved by different motive forces

This technique has its advantages, as: high efficiency and economically, feedback is not necessary.

The disadvantages are: no possibility to assemble of the complicated structures, inflexibility of the process and impossibility to correct a mistake.

In [2-2] is a novel parallel micro assembly process based on both shape recognition and capillary-driven self-assembly in an air environment demonstrated. This process assembled micro components to 1000 densely packed receptor sites in about 2 min with a defect rate of ~1%.

2.1.2 Serial micro assembly

In serial micro assembly are the micro components in a traditional way one-to-one picked and placed together in the system. The handling and assembly tasks are performed sequential, one micro componentat the time and then the other. It has lower assembly rate than parallel micro assembly, but the assembled microstructures are more complex. Serial micro assembly technique requires microscope, visual control, high precision positioning of the handling tools. Serial micro assembly implies that every micro component has to be contained in some kind of storage space, in defined position and orientation. Initially, the process of serial assembling is similar to the SMD insertion of micro componentss in the industry of electronics, where SMD insertion machines achieve impressive performance due to standardized micro components they position and the limited number of connecting techniques.

Serial assembling is different in regard to the required accuracy which is much greater (200 nm – 10 μm); surface forces affect much more the assembling process since the micro components are much smaller; there is a lack of standardized shapes, materials and tools (micro grippers), and therefore storage space for micro components and carriers of group

components; the micro components are much more sensitive to impurities or mechanical damage; there are several available connecting techniques; the macro and micro interfaces are more diverse (mechanical, optical, liquid…). According to the analysis there are very few similarities between assembling in microelectronics and micro system techniques.
Compared to parallel assembly, this method is characterised by possibility of assembly of the complicated structures, sufficient control of the force in order to avoid the object destroying, high process flexibility, possibility to correct a mistake. The arguments against are required feedback, low efficiency and high costs.
Micro handling and assembly process can be arranged on the three levels, depending on the automation degree, see Figure 2.1-2.

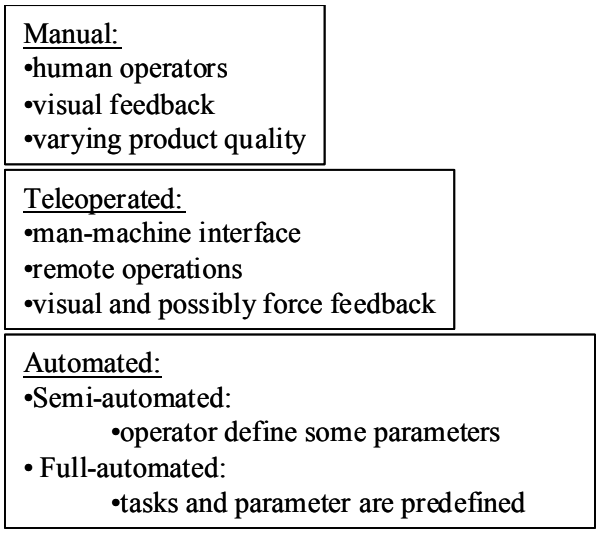

Figure 2.1-2: Micro assembly automation levels

2.2 Sub processes

In this dissertation, focus is on serial micro assembly which comprises manipulation and handling of the micro components; from preparation and transportation, to the joining and fixing, see Figure 2.2-1. The problems arise during micro manipulation are numerous; they come both from the nature of the micro components (scaling effect, phenomena in micro world) and from the imperfection and absence of the manipulation tools.

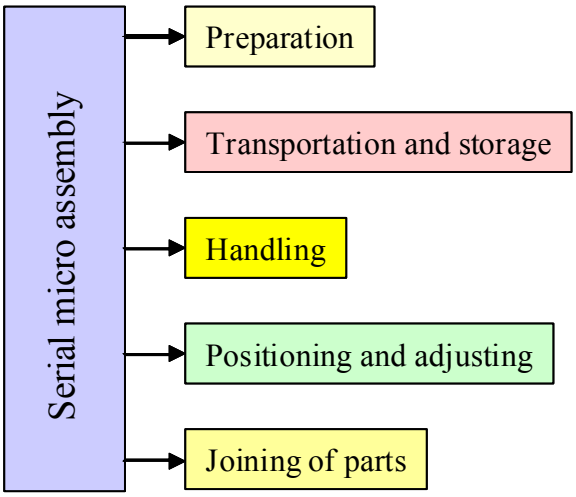

Figure 2.2-1: Micro assembly operations

2.2.1 Preparation

Preparation of micro components comprises micro components conveyance and their preparation for further manipulation. Manipulation under optical microscope requires their cleaning, but manipulation in SEM chamber needs thorough cleaning, spattering non/conductive micro components, drying i.e. freezing biological samples and possible spraying against electrostatic charge.

2.2.2 Transportation and micro components storage

As long as the micro components are similar to chips, i.e. flat, square and mechanically stable, they are available for exploring feeding and storage systems in electronic manufacturing. However, due to the huge diversity of geometry and materials in MST they cover only a small part of the micro components spectrum. Therefore, special devices have been developed in many occasions. These special solutions, however, are inappropriate for flexible accommodation of the system for other assembling tasks. Thus, there is a considerable need for standardization that is already present in all segments of micro techniques. Chapter 5 make a contribution to this part of micro assembly process.

Micro components positioning on the carrier is performed through a defined surface and by means of mechanical connection. The carrier has mechanical structure that extends into appropriate opposite parts of micro components, ensuring their positioning on outer edges of the carrier. If the micro componenets are made of, for example, polymer resist by lithographic process on Si substrate, they are cut and jointly placed on the carrier. Thus, it is possible to place up to several hundred micro components on a single carrier.

If the micro componenets are manufactured by the so-called bulk fabrication process, then they are separately placed into pockets of a typical "Waffle-Pack". They are commercially available, for example Figure 2.2-2 [2-3]

Figure 2.2-2: WafflePack-tray: 4x4, cavity size: 0.098"x0.098" [2-3]

2.2.2.1 Feeding systems

Feeders could be divided into two groups:

- Bulk micro components feeding that could be used for inexpensive micro components placed into open boxes without arranging them
- Precision micro components feeding for sensitive and expensive micro components. They are placed into trays, oriented and located. Trays are arranged into stacks, representing columns of storage space that make the feeder.

Many assembling machines are equipped with appropriate feeding systems in form of customized micro components carriers, conveyor belts or storage space. This is due to the enormous diversity of micro components and materials in micro techniques. Contrary to

microelectronics, there is a lack of standardisation in shape (configuration) and geometry, except for special cases. One of the exceptions is ‘‘easyKit’’, proposed by the VDMA working group, who develop and manufacture modular micro mechatronic systems. Therefore, every modification of machine or concept involves heavy consumption of work and assets.

In order to avoid it, a standard for micro components carrier has been made as DIN NAFuO AA F3 "Fertigungsmittel fur Mikrosystemtechnik", which defines the external measures and the rotating edge, while the internal surface is left to be specially defined with pockets, clamping devices etc. The format is specified in sizes from 1" to 12", oriented towards the glass masks and chip carriers from the industry of semiconductors, and therefore, it is compatible with the existing infrastructure, such as the transporting container for the clean room and handling devices. Definition of the edge provides a unique interface on clamping devices, the griping and transporting systems and has been designed with a cut for aligning and a labeling surface. This solution has already been used for different assembling applications, for example in assembling micro fluid systems for analyzing or assembling micro optical duplexes. [2-4]

There are feeding systems with or without contact. Examples of traditional contact feeding systems are conveyor belts and linear vibrators. For delicate micro components they are not applicable, since they cannot withstand the resulting mechanical impact and abrasion.

Feeding systems without contact use the electrostatic field. Forces acting on the micro componenet may be the result of:

- Dielectrophoresis, used for cells or viruses suspended in liquids, emerging from polarization of material and body, both in AC and DC field
- Electrophoresis, emerging from electric charging on the body and works only in the DC field, lifted off and propelled with electrostatic forces, limited to small particles.
- Combination of both

Electrostatic feeder for contact free transportation of micro components is proposed in [2-42] as a conveyor that provides transport on decomposition of motion on vertical (levitation) and horizontal (feeding motion) components.

Moll et al. [2-5] is proposed a solution for the problem of orienting micro-scale components without sensing using limited degree-of-freedom manipulators and gave a review of research efforts in the area of micro manipulation and micro component feeding.

2.2.3 Handling

Gripping of the micro mechanical components has the central position in the assembly process. This operation is necessary as during the transport of the single components so by joining and connecting. It is an established macro technical procedure. However, due to the different phenomena that dominate micro techniques, and the fact that they depend on micro dimensions, these experiences from the world of macro techniques can't be simply applied here (e.g. reducing conventional grippers).

When considering the principles that are used for gripping micro components, a variety of physical principles have been investigated and used. Some of them can be considered as miniaturized solutions from the macro-domain to the micro-domain, e.g. friction based gripping or form closure gripping. Most of the other is rather based on the special characteristics of downscaled objects and their interaction, e.g. capillary gripping or optical pressure based gripping. Many different methods to perform micro-gripping can be distinguished on the basis of their physical principles.

The problem of standardization caught great interest in the field of micro grippers as well, because the simple interchangeability of gripping and assembling tools, besides the

gripping system defines the flexibility of an assembling system. The DIN 32565 norm design specifies the interface on four levels:

- geometry of mechanical conjugation
- position, size and shape of the design
- standard definition of the design with electrical and fluid coupling
- technical specification of elements for coupling

2.2.3.1 Micro grippers

The most common division of micro grippers is based on principles of actuation. The constructions and principle of actuation are interdependent, e.g., vacuum micro grippers have only one pipe, while for the mechanical micro grippers it is necessary to have two hands. Micro grippers may also be divided according to their working environment, as well as on the size of micro components being handled. The division of micro grippers according to the principle of actuation, considering the construction and actuation principle as well, see Figure 2.2-3.

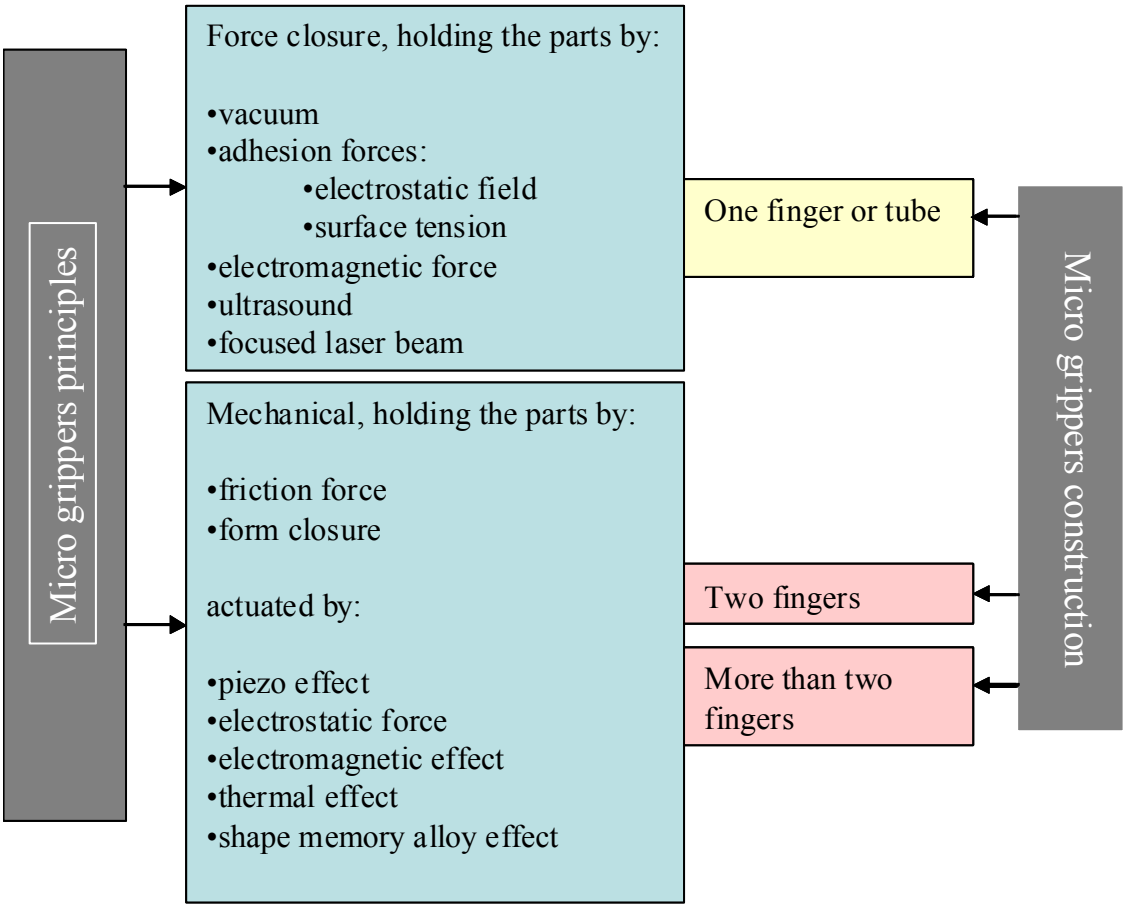

Figure 2.2-3: Micro gripper classification

Each type of micro grippers has its advantages and limitations when handling specific micro component.

For example, gripping based on optical or ultrasound principle may result in very weak gripping forces in comparison with mechanical or vacuum principles. [2-6]

Vacuum micro grippers are characterized by the simple construction, high efficiency and adaptability in wide dimensions range.

The vacuum micro gripper may be applied to a variety of fields such as the bio-field, without special energy sources such as a voltage because it uses the pneumatic. Further, the vacuum micro gripper may grip an object appropriately since it can be manufactured in the shape of a finger joint. However, as the pneumatic micro gripper has a weak gripping force in case of gripping an object, it is difficult to perform pneumatic control and process, and it is necessary for separate package processes for allowing the air to enter, thereby increasing entire manufacturing cost.

In micro and nano-scale manipulation and assembly issue is interesting the investigation of non-contact manipulation and assembly techniques, such as by levitating components (i.e. through the use of electromagnetic and optical tweezers, for example).

At present, the major limitation or challenge with respect to these electromagnetic and optical tweezers is the size of the devices themselves.

Electromagnetic and optical tweezers are often relatively large and, as a result, their applicability is limited to relatively large unobstructed areas.

Although electrothermal microactuation provides much larger output forces, hysteresis and thermal drift make the positioning accuracy relative low (tens to hundreds of nanometers) in open-loop operations. Furthermore, the difficulty of well controlled temperatures at the probe tip prevents its use in temperature sensitive applications.

To select an appropriate miro gripper, it is necessary to analyze one particular problem with all influencing factors, limitations and characteristics, e.g., the working medium (with regard to humidity, temperature, purity, electric charge, pressure), materials of which the micro components consist of, the size and shape of the micro components and surface quality.

The micro gripper's hands have matched to the geometry of the micro components, and the other properties of micro components have to be considered as well, e.g., some sensitive optical surfaces, etc.

The additional important factor is positioning system which holds the micro gripper, its properties, its precise dimension, and way of connection.

The way of connecting and joining micro components in micro assembly also affects the choice of micro gripper in terms that a precisely defined force has been needed to insert a micro component into a desired position.

The choice of optimal micro gripper for the given assembling process is based on estimation of a series of factors.

The following algorithm (Figure 2.2-4) shows in a simplified manner the way of finding an optimal micro gripper.

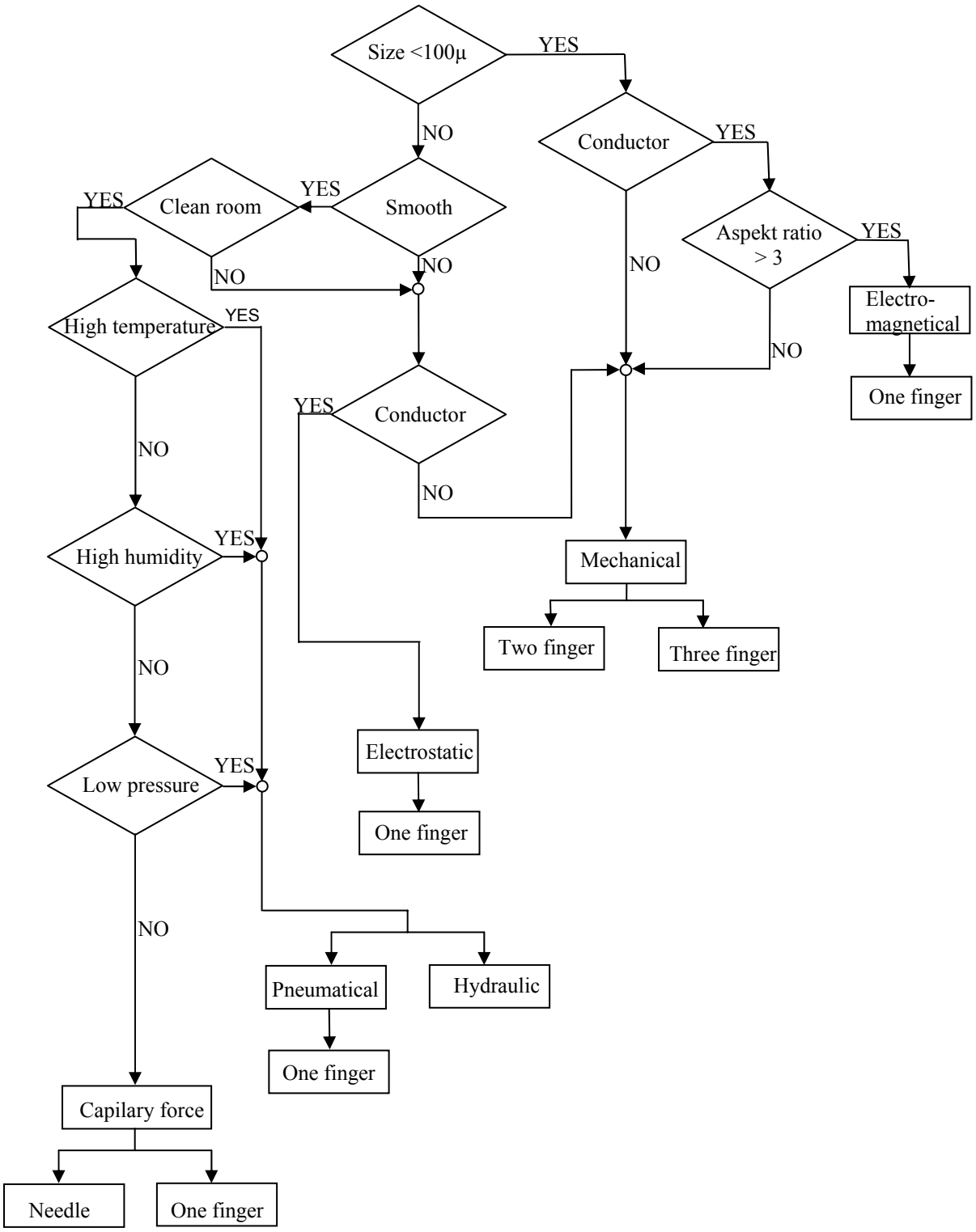

Figure 2.2-4: An example of algorithm for optimal micro gripper selection

During the gripping process, there are many influences acting on the gripping process. The Figure 2.2-5 presents the main factors that influence the micro handling process: micro tool (micro gripper and positioning system), surface conditions (material and finishing), environmental (humidity, temperature, cleanness, electrical charging, air pressure).

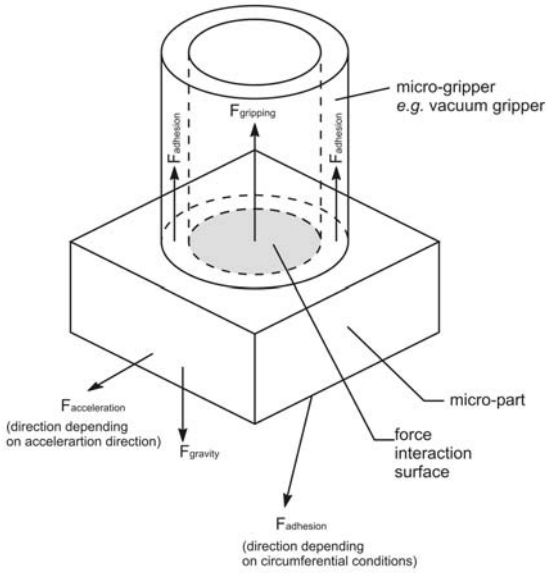

Figure 2.2-5: Forces that influence the micro handling process [2-7]

Besides miniaturization and electrical control, micro grippers must be capable of providing multi-axis force feedback to satisfy the following requirements:

- to protect the micro gripper and detect the contact between the micro gripper and the object to be manipulated; and
- to provide gripping force feedback during grasping to obtain secured grasping while protecting the object to be grasped

The vast majority of existing micro grippers lack force feedback due to the difficulty of integrating force sensors with micro grippers. The lack of force feedback does not permit force-controlled manipulation and easily causes breakage of micro grippers and damage to the object to be manipulated.

2.2.3.2 The gripping principle in the chamber of a SEM

The most important requierements that micro gripper must provide in order to be used in the chamber of a SEM are:

- vacuum compatibility
- electron beam compatibility
- sufficient gripping range
- minor sight obstruction
- short response time
- high path resolution
- small weight
- sensor integration possibility
- high reliability and repeatability
- maintenancefrei
- suitability for (automated) joining processes
- holding force in case of power failure
- easy replacement of broken parts

The external electromagnetic fields may modulate or deflect the electron beam; ultrasound does not propagate in vacuum. Vacuum micro grippers cannot function in the chamber of a scanning electron microscope.
In vacuum and under the electron beam can be used the grippers when its materials and the working principle is vacuum electron beam compatible. This means that outgasing, conductive or sputtered surfaces as well as strong electrical and magnetic fields are desired.

Vacuum gripers and the surface tension are not suitable for use in SEM, as well as ultrasound, because mechanical (sound wave) waves can not exist in vacuum.
The gripers that produce strong electromagnetical field are not electron beam compatibel und in SEM unapplicable.

The gripping principles that could be used in the chamber of a SEM and under the electron beam are:

- mechanical, actuated by:
  - piezoelectric effect
  - electrostatic force
  - thermal effect
  - shape memory alloy
- force closure
  - optical

The most common, and in SEM chamber most used are piezoelectric effect, electrostatic force acttuation, thermal effect and shape memory alloy, see Figure 2.2-6

piezoelectric actuation					
bimorph actuators				picomotors	
parallel		serial		large adjustment travel	slow actuation
simple construction	strong hysteresis and drift	robust	expensive	high travel resolution	comparatively large size
small package size	low stiffness	relative high siffness	hysteresis and drift appearance	no hysteresis und drift appearance	wearing
quick actuation	low stiffness	quick actuation	large size	robust	
	difficult to fasten	long lifetime		long lifetime	

thermal actuation		SMA actuation		electrostatical actuation	
large driving distance-adjustable travel	very time consuming setting-up	small package size	complex setting-up (especially in vacuum)	resolution and positioning capability	problematic release-stiction
small package size	strong hysteresis	high travel resolution	overheating danger	compatible with IC common technology	weak gripping force
robust	poorly regulated	versatile movement pattern	finite cycle number		small displacement
long lifetime	non-linear actuation		control problematic		high driving voltage
large driving force	high driving voltage				
high resolution (30 nm)	high energy consumption and heat dissipation				
high linear range	difficulty in application to a bio field				

Figure 2.2-6: Micro gripper actuation principle comparison, see also [2-8]

Characteristic for the thermal micro grippers (SMA, electrothermal) is the fact that heating phase is shorter than in the air, and the cooling phase takes more time, because in a

vacuum conduction and convection do not occur to any appreciable extent and radiative transfer is the dominant mechanism.

Also, in a vacuum is hysteresis more observable, while drift is lower, but the creeping apears. [2-8]

From Figure 2.2-6 can be concluded those piezoelectic micro grippers are most suitable for using in the SEM, particularly bimorph serial and picomotors.

Investigations in this field are numerous, since the SEM microscope is powerful in comparison with the optical microscope and there are considerable efforts to optimize the handling and assembly process in the chamber of SEM, as well as the handling and assembly equipment.

2.2.4 Positioning and adjusting

The precise positioning of components is increasingly important. For instance, optical communications systems require that the ends of optical fibers be precisely aligned with mating components or fibers to ensure minimal transmission losses. The precision alignment of components is also important in connection with the manufacture of semiconductor devices, and with devices having miniaturized components and/or fine tolerance requirements. As yet another example, precision surgery applications, including remote surgery, requires the ability to precisely control the position and movement of instruments. However, previous attempts at providing for the precise positioning of a micro componentor instrument have been incapable of providing high resolution positioning. In particular, previous attempts at providing devices capable of precisely positioning components and instruments have been incapable of providing a desired number of degrees of freedom in combination with a desired positioning tolerance.A review of research works in the emerging area of micro assembly is in
Figure 2.2-7 given. [2-9]

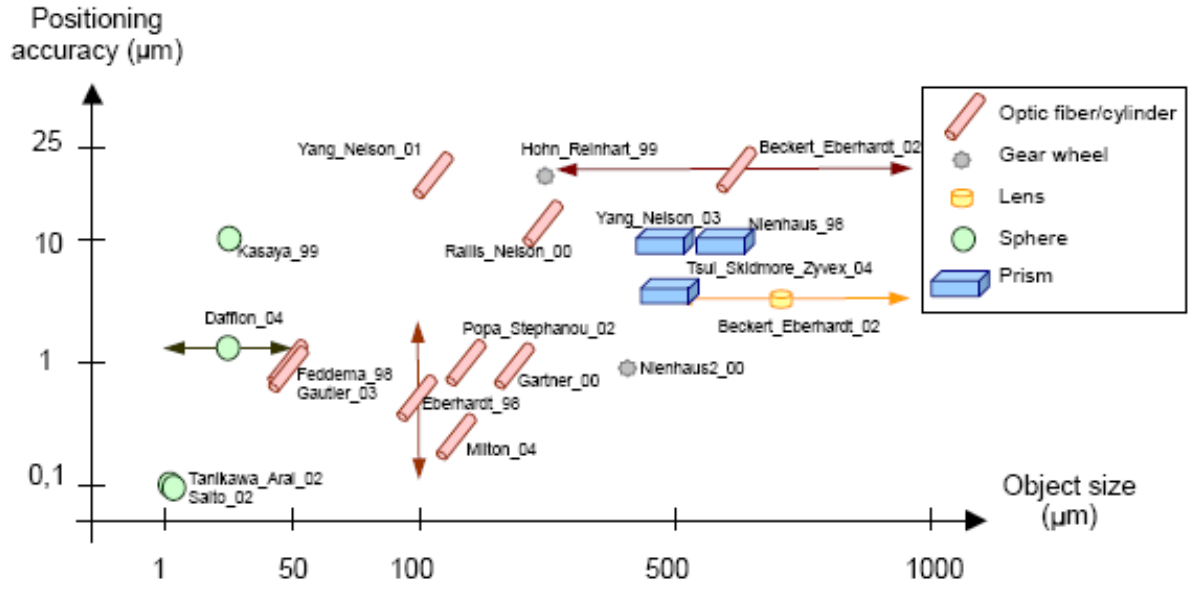

Figure 2.2-7: Size of manipulated objects and precision of the manipulation task (necessary or really performed) [2-9]

Assembling of hybrid micro systems imposes serious requirements with regard to accuracy of positioning. In most cases of micro assembling, it is sufficient to have 4 DOFs: three axes of translation and one axe of rotation. Tolerances for accuracy of positioning are at least +/− 10 µm, although in the case of assembling complex optical systems with tolerances of some

components in the range of accuracy of assembling, the accuracy requirements are few μm, so it is necessary to use the procedure of digital image processing. Positioning and alignment of micro components is performed by precise devices. There are numerous existing systems available on the market. Some of them are listed in Figure 2.2-8. Accuracy is an important factor as well as precision (resolution), rank of movement along the axis, the degree of freedom, velocity and repeatability.
The existing solutions have the common feature of being expensive, bulky and inflexible. Due to their dimensions, they are sensitive to environmental perturbations such as vibrations or temperature drifts.

Application field / Micro Assembly System	Resolution	Feeding	Tool turret	Monitoring system	Sensors integrated	Small sized	Joining Module	Modular construction	Environment (clean room)
Kleindiek Nanowork-station	++	-	-	-	-	++	-	++	-
Sysmelec	+	++	-	-	-	-	++	++	-
Klocke Nanotechnik	++	-	+	+	++	++	-	++	++
microLINE IEF-Werner	+	-	++	++	++	+	-	-	-
David Kopf Instruments	+	-	-	-	-	-	-	-	-
CSEM Pocketdelta Robot	+	-	-	+	-	-	+	-	++
Mitsubishi	+	-	-	++	+	-	-	-	-
Deprag	+	++	+	+	+	-	++	+	++

Figure 2.2-8: Some commercial micro manipulation system

2.2.5 Joining

Microassembly process involves all tasks related to positioning and alignment of the components with the required tolerances, fixing or joining them by different means and packaging the whole device. After the micro components are positioned in the micro system, it is necessary to fix them. Some of the main assembly processes for joining operations:

- Mechanical fasteners and press fit
- Micro adhesive bonding (gluing)
- Welding
- Soldering
- Silicon bonding

2.3 Automation of the micro handling and assembly

Micro assembly practices require the human operator to grip and position the micro components, using high-scale magnification and high resolution microscopes, and different micro grippers. This method is tiresome, lengthy, slow, unreliable and expensive. In order to increase efficiency, reliability and to decrease costs, it is necessary to develop new, computer based methods of automatic assembling.
Chapter 7 presents a contribution in this segment of the micro manipulation process.
Hybrid microproducts have a high level of innovation, but often do not reach the market because of the difficulties of their automatic assembly. While the single micro components comprising hybrid micro system may be produced cost-effectively in large batches using the LIGA procedure or silicon technology, the procedures and devices for automatic assembly of these micro components into a micro system exist only in exceptional cases. In order to produce hybrid micro systems in a cost effective manner and in large batches, it is necessary to develop cost effective and economical assembling techniques. The uniformity of automated assembling process performed by an assembling machine leads to high reproducibility and high quality necessary to achieve a break similar to the one achieved in microelectronic elements. There are barely existing standardized means of production in this sector due to a small number of products, different materials in use and diversity of forms and sizes of assembled micro components.

It seems to be useful for all the elements entering the system of automated assembling to be designed modularly for the purpose of introducing automation into the process of micro assembly, so arbitrary number of micro components may be assembled, different equipment may be used and combined, and different operations may be performed with minimum consumption of time and assets for adaptation.

According to the previous development of MEMS, it is expected that in the future the majority of devices will be assembled from individual micro components, which enables larger freedom of the choice of materials and adjusting both to the need of optimal function performances within the assembly and the customer's requirements. Since the components are becoming smaller in size, and large assemblies require more subassemblies, there is a growing need for automated precise assembling procedure. Further reasons for introducing automation are the lack of human operators in terms of possible contamination of micro components and sheer impossibility of carrying out persistent intensive work due to the exhaustion, as well as the factor of cost efficiency in terms of fast production and market boom. There are two important aspects when considering the automation of the assembling process:

- accurate alignment (positioning) of micro components
- pick up and place operations

Assembling can be performed by microrobots, automatic assembly machines and a future perspective is in the microfactory.
The main purpose of control of precise positioning in the field of microrobotics is the high-dynamic range procession, i.e. the combination of nanometric resolution and large operating area (few cubic centimeters). There are designs that allow coarse and fine modes of operation with the same actuator, e.g. stick-slip actuator. [2-10]

To assemble complex microsystems, consisting of several individual components, it is necessary to develop flexible, highly accurate and fast assembling systems. Such flexible micro-robot, which can be used both under LM and in SEM, is developed in Karlsruhe, where different piezoelectric micro-robots are developed, and which are able to perform highly accurate manipulation with precision up to 10-20 nm and to transport the gripped objects at maximum speed of 2-3 cm/s. [2-11]

Since the abilities of human hands are rather limited, a highly accurate system for micro-handling is of great interest for medicine and industry, especially for the mass production of hybrid microsystems consisting of different micro-components. In order to advance from a few manually assembled hybrid microsystems to high quality mass production, it is necessary to utilize automatic systems for assembling micro-components. Such a system is also indispensable to manipulate individual cells in medicine, as well as to test IC. In order to manipulate objects of micrometer and nanometer range, highly accurate robots are necessary, with accuracy from few μ to few dozens of nm. In the same time, motion in the macroscopic range is vital, which should be reasonably fast.

Recently researchers strive to solve the problem of gripping and releasing the micro components, where the greatest obstacles are the surface forces dominating the volumetric ones. In addition, the tolerances are much lower as the dimensions of the micro components are much smaller. To introduce automation, the following assumptions are necessary:

- Reproducibility of positioners: better than 1 μm
- Adjustment of the micro components orientation: better than 20 nm
- Many degrees of freedom in smallest volume
- Compatible system of modules
- Protection of sensitive micro components and micro grippers (force limitations)
- Transport "without" gravity
- Integrated sensors
- Quality control with suitable resolution
- Micro adhesive bonding technology

Besides the above mentioned tasks which should be performed by an automated system, the following steps are necessary:

- feedback, visual and force (Nelson et al.[2-32]have presented a technique that provides force feedback and position feedback of n level)
- adjusting the design of micro components to the requirements of assembling and connecting by relatively simple rules of construction, even when some components need to be completely redesigned. In microelectronics, this procedure provided an increased level of automation from 15% to 100%.
- standardization; in this framework, the following should be standardized
  - micro systems
  - micro components
  - interfaces with the environment that may be:
    - electrical
    - optical
    - fluid
    - mechanical contacts
  - materials for micro systems
  - connecting processes
  - equipment for assembling micro systems:
    - micro grippers
    - carriers
    - storage space
    - test equipment
  - institutions and industrial organizations
    - SEMI

- DIN
- ISO

Present micro assembling systems, which are very expensive and require frequent maintenance due to mechanical wearing, are usually intended for specific tasks and depend on the operators' proficiency, or consist of conventionally driven micro assembling robots. However, as the assembling room decreases more and more, it is even more difficult to use conventional robots for manipulation, due to the significant role of disruptive factors in the micro world, such as the errors in manufacturing procedure, friction, thermal growth and computer errors, which are negligible in the macro world.

Murthy et al. [2-12] presented multiscale robotic platforms. Automatic assembling systems in the semiconductor industry have been in use since the 1970s, but they exclude direct handling of micro components. Two multiscale assembly and packing systems are developed by the Automation & Robotics Research Institute at the University of Texas Arlington. The system could be adjusted to different needs, so we can use it for different applications, such as the assembly of heterogeneous MOEMS devices.
Dechev et al. [2-13] described the design and development of a robotic manipulator of 6 degrees of freedom, which is used to assemble three-dimensional MEMS structure. The new system is able to simultaneously rotate and translate micro components with regard to the MEMS chip. It is intended for using under the LM.
Hollis et al. [2-14] proposed a virtual mini factory for assembling small mechatronic products (electret microphones), as the modular tabletop precision assembly system.
Gengenbach [2-15] describes a modular micro assembly system MIMOSE, designed at IFK for automated assembly of micro systems in small and middle sized batches.
In the U.S., work has progressed at Sandia National Laboratories to produce automated microassembly systems
Zyvex has produced small semi-automated robotic systems for microscopic and nanoscopic assembly.

Sysmelec, in Switzerland, produces several robotic assembly workstations for MEMS and microoptoelectromechanical systems

Assemblies of four layers of microlenses and eight micromachined chips have been produced automatically at CSEM SA.

2.3.1 Standardization

Semiconductor fabrication and automatic assembly in electronics have reached a high degree of maturity due to standardisation of materials, equipment interfaces, chip and package shapes and interconnection techniques. The availability of these standards made cost effective production and thus affordable products such as consumer electronics and PCs feasible. This standardisation process was mainly driven by industrial organisations such as SEMI.
In micro system technique such standardisation has not yet taken place. The main reason for this situation is the large variety of micro component shapes sizes, materials, as well as manufacturing and assembly processes. Hybrid micro systems are made up of micro components of different shapes and material, and electronic system consist of micro components that are chip-like. In order to improve the situation the German standardisation committee DIN NA FuO AA F3 “Production equipment for micro systems” supported by a joint research project Microfeed2 has set out to develop standards for micro system production equipment.

DIN standardisation projects in micro fabrication:

Standardised micro tray has been published as German standard DIN 32561 in early 2000.
The endeffector interface that consists of two micro components, only one is standardised. The standard is published as DIN 32565 and is being implemented in products by Schunk Spann- und Greifsysteme and Milasys GmbH.

Activities with regard to standardization on international level:

In 1997, on the initiative of prof. Howard Dorey of Imperial College London in IEC TC 47 "Semiconductor Devices", a workgroup was established, and set up the project of standardization "Measurement and Measurement Devices for Micromechanical Devices"; but the work was cancelled.

In the Japanese Micromachine Centre, the work on standardization is in progress and it is focused on tree fields:

- standardization of micro machine technology
- technical terminology
- methods of measuring and assessing

Semiconductor equipment and materials international (SEMI):

SEMI is an association of manufacturers of semiconductor devices, flat monitors and semiconductor materials. Based on their experience in standardization of semiconductor techniques, SEMI took the first serious steps in creation of a "Micro System Technology Roadmap".
Relations to other standardisation bodies' ant to European projects:

The Network of Excellence on Micro optics (NEMO) has a standardisation working group with the task to assess the situation respecting standards relevant for development and fabrication of micro-optical systems.
A similar approach but on the equipment side is being pursued in the integrated project EUPASS (Evolvable Ultra Precision Assembly Systems).The goal is to develop an architecture for modular and evolvable assembly system, that are rapidly deployable and easy reconfigurable.
Both projects started 2005.

- Standardization by SEMI:

It is mainly the standardization of semiconductor technology. It has been divided into standardization of gases, materials, automation equipment and software, MEMS, packaging, safety, etc. SEMI MS6-0308 - Guide for Design and Materials for Interfacing Microfluidic Systems

- Standardization by DIN:

DIN study group "Tooling for microsystems", general management lies at Research Centre Karlsruhe and fabric Schunk.

DIN 32563

Tooling for microsystems – Classification system for micro components

DIN 32564-1

Tooling for microsystems - Terms – Part 1: General terms in the microsystemtechnic

DIN 32564-2

Tooling for microsystems - Terms - Part 2: Basis technology and fabrication

DIN 32564-3

Tooling for microsystems - Terms - Part 3: Handling, Storage und Transport

DIN 32565

Tooling for microsystems – Interface between endeffector und manipulation device

- VDI guidelines

Department 4 - Microsystemtechnic und Nanotechnology is divided into the technical comittees:

4.1 – Fundamental questions of the microsystemtechnic und nanotechnology
4.2 - Microoptic
4.3 - Sensoric
4.4 – Micro actuatoric
4.5 – Masc technology
4.6 - Functional buondary surfaces
4.7 - Micro-Nano-Integration
4.8 - Materials and manufacturing methods
[2-41]

- Standardization by ISO:

Geometrical Product Specification, project driven by the ISO/TC213. The goal is standardization in the field of surface properties, macro/micro geometry specifications, dimensional and geometrical tolerance, verification principles, measured equipment, calibration requirements.

ISO/TC/39/WG16 Tooling for Microsystems
ISO/NP29261 Production equipment for Microsystems-Tray-Dimensions and tolerance
ISO/NP29262 Production equipment for Microsystems-Interface between micro grippers and handling system

2.4 Recent research

Major Labs and Investigators:

- in the US
  - RPI Center for Automation Technologies-Akella, Bellouard, Huang, Lee, Popa, Sandeson, Sin, Stephanou:micro grippers, arrayed micromanipulation, prcision placement
  - UC Berkeley-Fearing, Goldberg, Howe, Pister:flying and crawling micro-robots, dextrous manipulation, microassembly, fluidic selfassembly
  - Michigan State University-Xi: force controlled microassembly

- Sandia National Labs-Feddema: precision visually guided microassembly
- Zyvex: in-SEM manipulation
- Univ. of Minnesota-Nelson, now moved to ETHZ
- Univ. of Washington-Böhringer:array micromanipulation, selfassembly

- outside the US
  - Univ. of Toronto-Mills:microrobot microassembly system
  - ETHZ-Nelson:wafer level microassembly, visually guided microassembly, biological micromanipulations
  - EPFL-Siegwart: mobile microrobots
  - Univ. of Tokyo-Sato:micro and nanomanipulation
  - Nagoya University-Fukuda and Arai: mobile microrobots, biological micromanipulation, micro components handling
  - University Oldenburg-Fatikow: microrobots for SEM, micromanipulation
  - Scuola Superiore Sant'Anna-Dario Paolo: medical microrobots

[2-16]

2.4.1 State of the art in micro manipulation under the SEM

The large depth of focus, the high magnification and the clean environment of a SEM provide very good conditions to micromechanical studies or to microassembly. These researches were financed by different national or EU projects and led toward the development of very compact and SEM compatible devices.
EUPASS, European project, with the fundamental vision to enable the rapid configuration and deployment of ultra-precision assembly system solutions.
The idea behind EUPASS is that future production systems for micro-assembly should be based on a recognisable, open and well-chosen architecture. This architecture will enable standardisation amongst different suppliers and enables the realisation of a production system significantly faster and more reliable than in the past.

- Challenge

Develop affordable, cost effective and sustainable ultra-precision manufacturing solutions by offering rapidly deployable ultra-precision assembly services on demand.

- Result

Assembly systems based on:

- Reconfigurability and modularity
- Standardized open architecture
- Ultra-precision solutions

ROBOSEM is developing nanorobotic tools to handle minute quantities of materials and individual biological cells with nano-scale accuracy for integration into easy-to-use scanning electron microscope workstations.

- Within the ROBOSEM project, a nanohandling robot system for a desktop SEM station was developed, with a powerful sensory support and very high flexibility, see Figure 2.4-1. To enable powerful sensor feedback, a robot sensor system consisting of video cameras and tactile-/force microsensors integrated into the manipulators has been developed. [2-17]

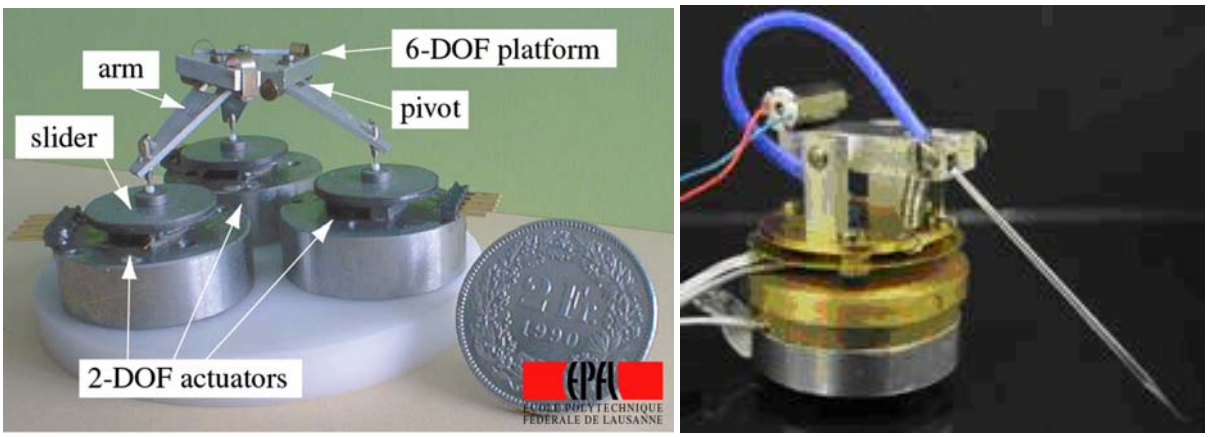

Figure 2.4-1: ROBOSEM robot prototype [2-17]

Fahlbusch et al. [2-18] developed a concept Lab-in.SEM. For gripping and pick-and-place operations at the microscale, a piezoelectrically driven micro gripper has been developed, see Figure 2.4-2.

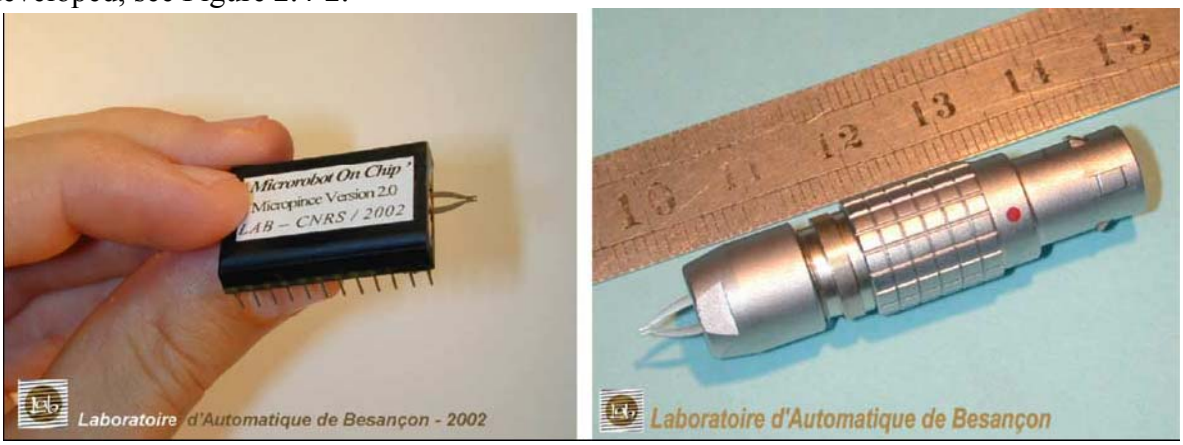

Figure 2.4-2: Micro gripper integrated in an electronic DIL packaging (left) and in a Lemo® connector packaging (right) [2-18]

Powder particles Ni-Co, diameter ranges from 150-200 µm, for thermal spraying or sintering of ceramics in industrial applications were picked up and placed, see Figure 2.4-3. It was observed difficulties in approaching in the vertical direction and at the end of the pick-and place trajectory the release of the particle is not still totally ensured, notably because of the electrostatic conditions.

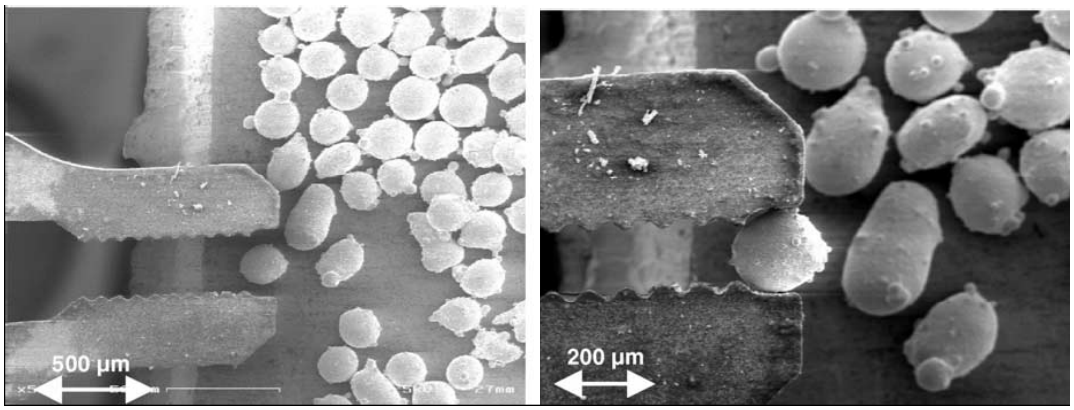

Figure 2.4-3: Gripping of a micro-sized powder particle [2-18]

MINIMAN is financed by the European Union (ESPRIT Project "MINIMAN"). Within this project a micro robot MINIMAN were developed, see Figure 2.4-4. The prototype MINIMAN III, is equipped with a piezoelectrically driven micro gripper having three rotational DOF. A steel ball as interface permits easy tool exchange. [2-19]

Figure 2.4-4: Piezoelectric MINIMAN III and MINIMAN IV robot prototype [2-19]

Fatikow et al, since several years, have developed a semi-automated microrobot based nanohandling station for an SEM. A combination of mobile platforms and nanopositioning tables mounted inside the vacuum chamber of an SEM is used for the manipulation of micro objects. [2-11] [2-20]
ROBOTMAN is financed by BMBF (Germany); its concept is based on the use of piezoelectric actuated robots. Particularly is emphasized the ability to execute the finest manipulations with various objects as well as quickly getting over the long distances.
Prototype RobotMan (Figure 2.4-5) uses a two-fingered micro gripper with two translatory degrees of freedom. [2-20]

Figure 2.4-5: Microrobot ROBOTMANwith integrated CCD camera [2-20]

Saito et al. [2-21] noticed that adhesional force increases according to the EB-irradiation time after the contact interface is formed; the increment rate of adhesional force depends on the EB current and adhesional force initiated by the EB irradietion increases irrevirsibly even after the irradiation is suspended. The adhesional force of a polystyrene sphere of 2.0-mm diameter has been measured, see Figure 2.4-6.

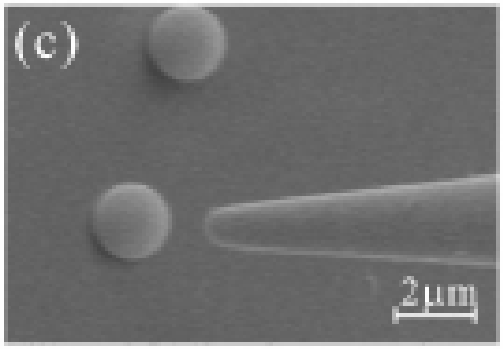

Figure 2.4-6: Micromanipulation under a scanning electron microscope. The micro-objects are polymer spheres of 2µm diameter in this example. The tool is a glass needle coated with Au. The substrate is a glass plate coated with Au. [2-21]

Miyazaki et al. constructed an ultra micro manipulation system, named Nanorobot [2-28], based on visual control, which with SEM (equipped with a realtime image processor) and a sysatem integrating processor make a "Nano-Hand_Eye System". This Nanorobot consists of the left hand robot with a stage to hold the object, and the right hand with an end effector, that make fine motion of 10 nm accuracy. Iron particles of 5 µm were picked up and placed with a tungsten needle, releasing was performed by rubbing the particles against the substrate, oft used method. Particles tended to stick together and took almost 30 minutes to arrange nine particles and the needle was curled because the vertical distance could not be observed. The visual feedback was proved through the scratching task of a thin line with uniform width in desired direction.
The manipulating equipment developed at the Department for Technology at Upsala University has been adopted for use in situ in commercial SEM [2-22] the working distance can be varied between 10 and 50 mm, see Figure 2.4-7.

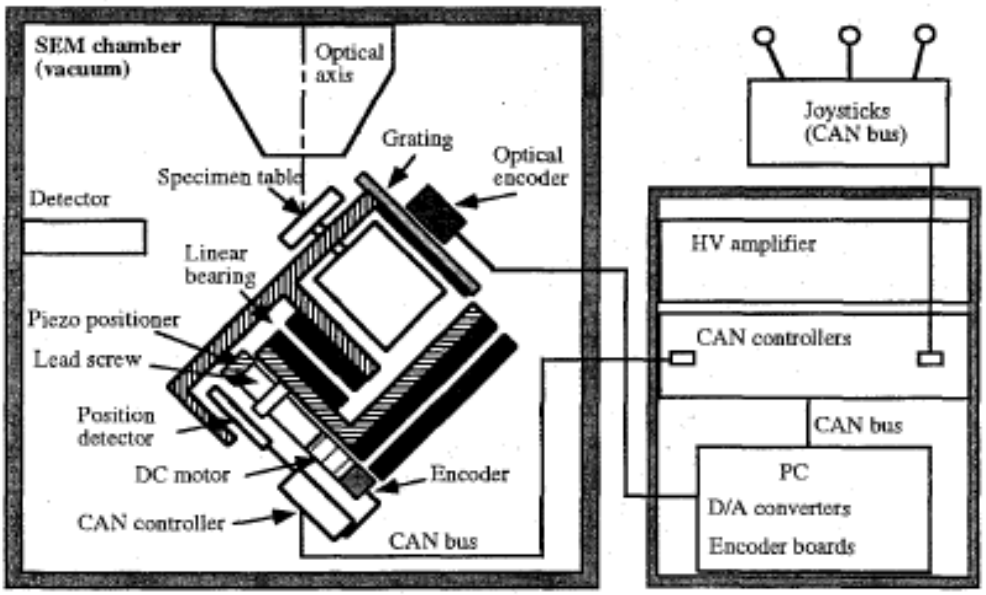

Figure 2.4-7: Schematic drawing of the micromanipulator system for use m situ in a SEM [2-22]

Micro-manipulation system for a SEM, called the Micro Handling System II, developed by Koyano et al. [2-23], is composed of a specimen stage with three translational freedoms and a probe for manipulation with three translations and two rotational freedoms see Figure 2.4-8.

Translations of the probe are generated by piezoelectric actuators with a resolution of 10 nm and a maximum range of 15 μm.

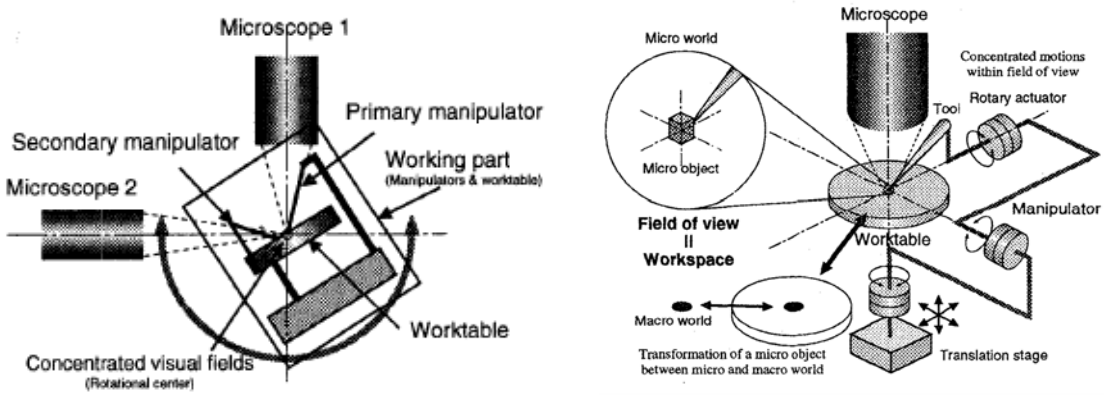

Figure 2.4-8: Conceptual diagram of Concentrated Visual Field and manipulator configuration [2-23]

Clevy et al. [2-24] have been tested the assembly of ball bearing in the chamber of a SEM (High vacuum SEM, Carl Zeiss DSM 962) with the micro griper with changing tools. The external diameter of this bearing measures 1.6 mm and the diameter of the balls of this bearing is 200 μm (Figure 2.4-9). Several kinds of pairs of tools were necessary requiring the use of the tool changer.

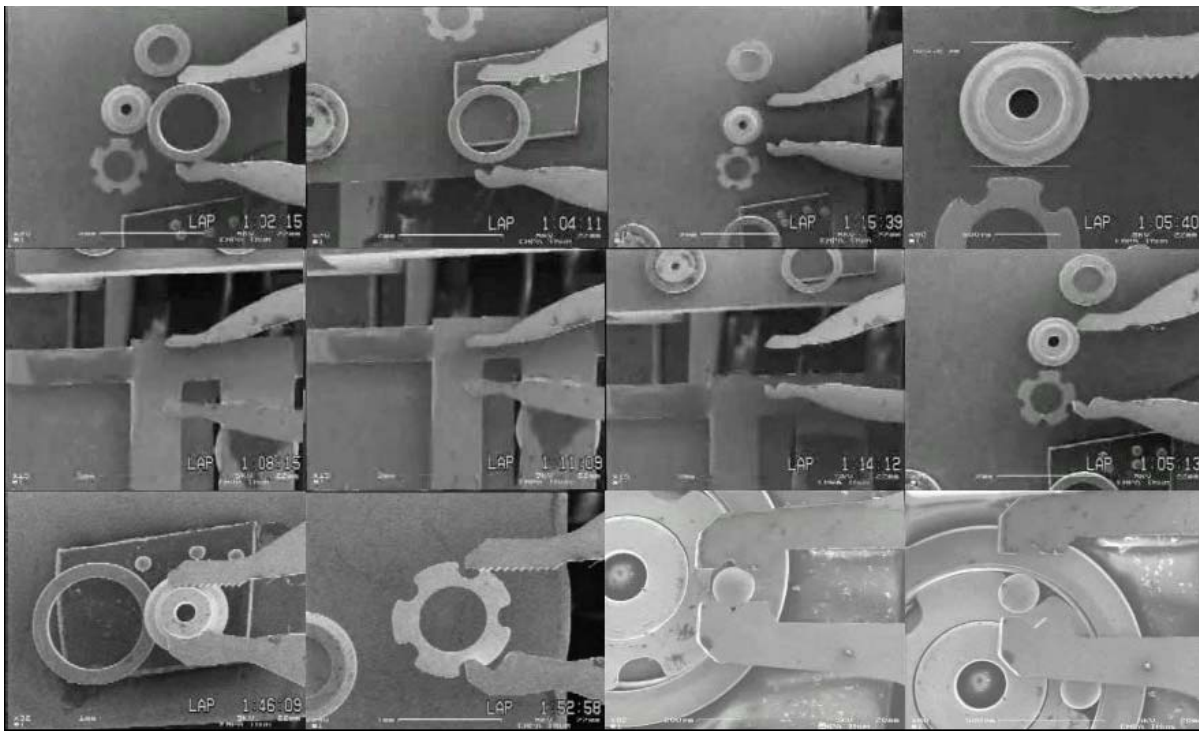

Figure 2.4-9: Assembly of a ball bearing in the SEM [2-24]

Kasaya et al [2-25] demonstrated a completely automatic arrangement of several micro-objects of 30 μm in diameter under SEM monitoring. The accuracy of arrangement is within 10 μm.

Saito et al. [2-21] analyzed the kinematics of mechanical and adhesional micromanipulation using a needle-shaped tool under a SEM and introduced adhesional and rolling- resistance factors into the kinematic system and considered the time dependence of these factors due to the electron beam (EB) irradiation.

Morishita et al. [2-26] made an experiment by cutting the Al wiring on the surface of LSI chip, using own developed Nanorobot System II. The width of the Al wiring was about 5 μm, tools, a tungsten needle, radius at the top about 1 μm and diamond with 5 μm was made by mechanical grinding. The adhesion of the chip to the needle was significant; it is supposed to be effect of electrical charge from the electron beam.
Saito et al. [2-27] have demonstrated the manipulation of microspheres, 2μm diameter, inside a scanning electron microscope using a pick and place operation based on a model of the adhesion between the probe and the microspheres.

2.4.2 State of the art in micro manipulation under the LM

One of the leaders in this field is Precision Micro Assembly Laboratory of Sandia Laboratories. Microscopic machines are the focus of the Precision Micro Assembly Laboratory. Created to investigate the automated assembly of microelectromechanical systems (MEMS) components, the laboratory is developing technologies for a robotic workcell that can assemble MEMS parts 10 to 100 microns in size into tiny machines for use in weapons components, surveillance devices, and microsurgery.
Gorman and Dagalekis, [2-29] presented manipulation system which consists of two microscope perpendicular to the other with digital cameras for visual feedback. PMMA microspheres, 65 μm are moved 140 μm by pushing, see Figure 2.4-10. The force sensor, uses to determine the approximate contact forces while rolling a microsphere, is silicon cantilever which has two doped piezoresistive strain gauges, one on each side of the beam. The force resolution is on the order of 10 μm.

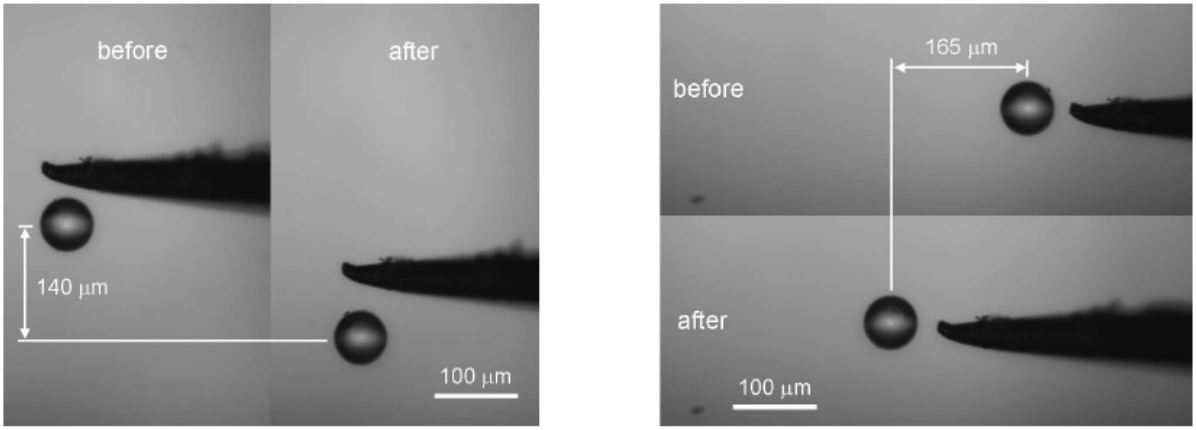

Figure 2.4-10: Pushing using the side of probe, and using the tip of probe (before and after) [2-29]

Sulzmann et al, [2-30] are developed and tested a micro robot capable of manipulating micro systems and microstructures with a resolution higher than 10 nm and a vision feedback allowing a sub micron absolute, and nanometric relative positioning. A LIGA micromotor has been sucesfully assembled. A microtelemanipulation has been shown and a rotor (250 microns in diameter) has been mounted on an axis having 2-3 microns play between the components

Hesselbach et al. [2-31] presented the current results of the development of assembly equipment with integrated measuring system that will permit high position accuracy. The micro gripper is designed for the cleanroom.
Saini et al. [2-32] presented the latest results of their manufacturable miniature scanning electron microscope (miniSEM) development effort that incorporates a micro-electro-mechanical-systems (MEMS) electrostatic microcolumn and a carbon nanotube (CNT)

emitter. The microcolumn is designed for a beam diameter of 10-20 nm at the sample with beam energy of 1 keV at currents of up to 1 nA and a 100 μm field of view (FOV). The microcolumn components are fabricated on single 50 μm thick silicon on insulator (SOI) wafer and are assembled to the pre-fabricated, self-aligning sockets to realize an inexpensive and compact microcolumn.
Nelson et al. [2-32] described Feinerman's miniature scanning electron microscope. This sugar cube sized device is able to provide high resolution scanning electron micrographs using low voltage, making it useful for the inspection of biological specimens and semiconductors while minimizing damage to the observed specimens. It is important to note that one of the major design considerations for this particular device is assemblability. Several silicon die must be stacked and separated by optical fibers in order to create a miniature electron column. Submicron alignment accuracy of the stages of the stacked silicon die is required for a fully operational device.
In Shimada et al. [2-34] is described a set of dextrous micromanipulation primitives for reorienting and regrasping rectangular parts. The parts can be combined to build 3 dimensional microstructures, see Figure 2.4-11

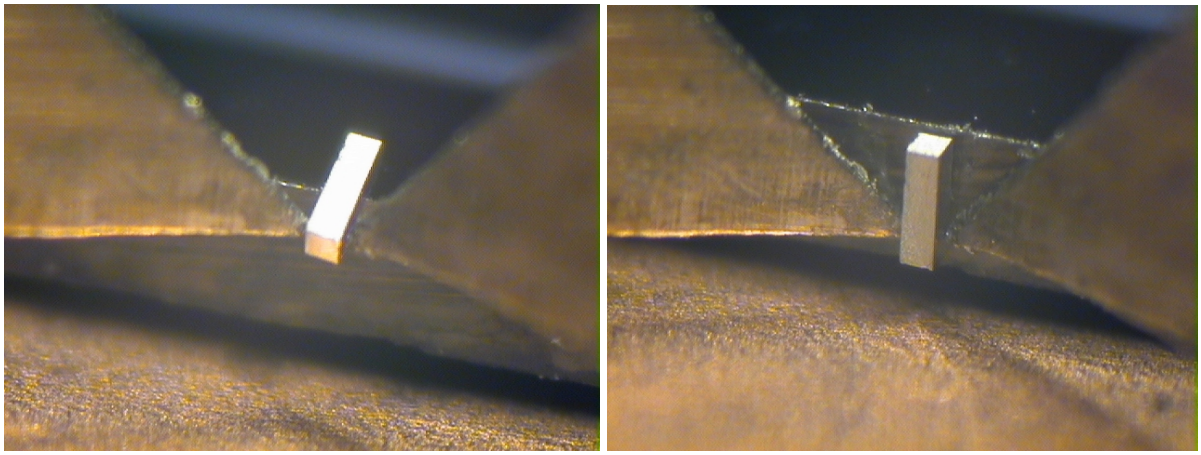

Figure 2.4-11: Pivot'' grasp using fixture to generate moment on 75 by 100 by 400 micron part, rotating part [2-34]

At University of California, Berkeley a microrobot has been developed, such a micromechanical flying insect (MFI), made by combination of folded structures with micro-assembled electronics, actuators, and sensors.[2-35] The goal of the micromechanical flying insect (MFI) project is to develop a 25 mm (wingtip-to-wingtip) device capable of sustained autonomous flight. The high performance of true flies is based on large forces generated by non-steady state aerodynamics, a high power-to-weight ratio motor system, and a high-speed control system with tightly integrated visual and inertial sensors (Figure 2.4-12).

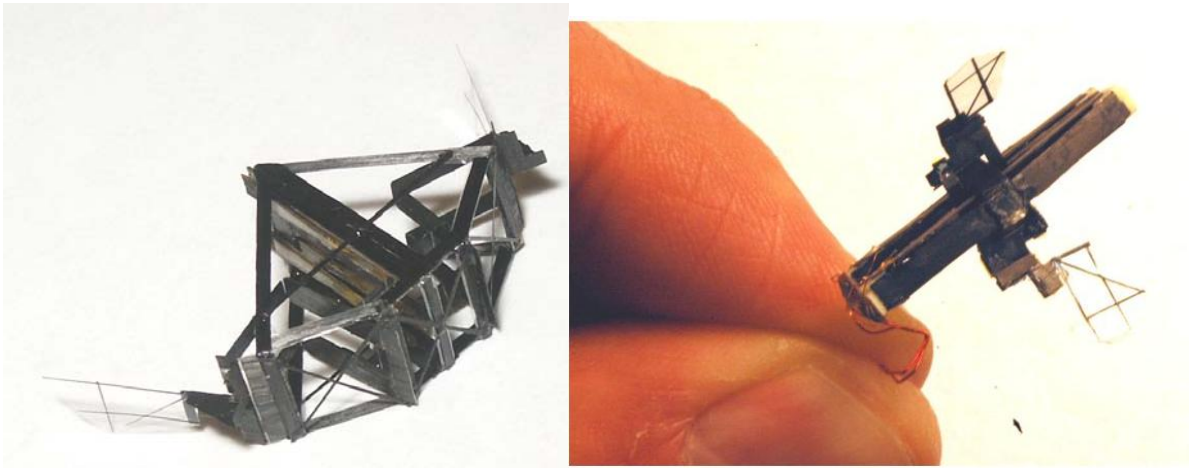

Figure 2.4-12: Two wing carbon fiber air frame and thorax with actuators (Dec. 2003), and single actuator piezo amplifying thorax. E. Steltz. (2007) [2-35]

Institute of Micro technology Mainz: the assembly of three micro electron lenses in clean-room conditions, using a suction micro gripper and optical fibre ribbons,
Figure 2.4-13. [2-36]

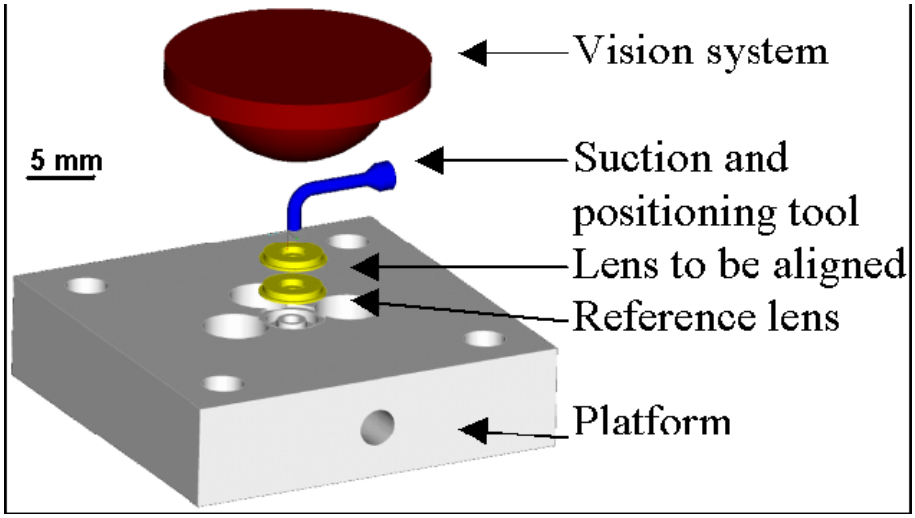

Figure 2.4-13: Assembly platform for micro electron lenses [2-36]

Components on the order of 500µm have been aligned using a force controlled pushing method developed by Zesch. [2-37]
Cecil et al. [2-38] described the development of a physical and virtual cell to support the assembly of micron- sized parts; micro assembly activities included the insertion of micron-sized pins in holes.
In Figure 2.4-14 a silicon nanowire is picked up by the threebeam micro gripper under an optical microscope, using a Burleigh piezo actuated xyz-stage to move the micro gripper. [2-39]

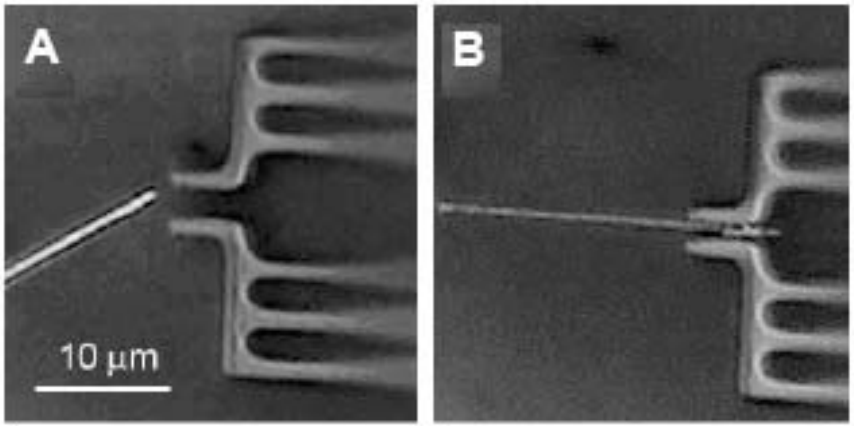

Figure 2.4-14: A micro gripper is used to pick up a silicon nanowire under an optical microscope. [2-39]

Dechev et al. [2-40] describes a novel microassembly system with a compliant, passive micro gripper. Figure 2.4-15 shows a scanning electron microscope (SEM) image of several "proof of concept" micro parts, a few of which have been joined perpendicularly to other micro parts (base structure) on the substrate, and SEM of a microcoil constructed from four micro parts. The microcoil is 200 µm tall and 140 µm wide.
Stiction does not present a problem during the releasing of micro parts, since each micro part used in this work is always snap-lock joined to another object before it is released. In order to grasp a micro part, the micro gripper tips are pushed against the interface feature of the micro part. Since the micro part is tethered to the substrate, a reaction force is developed on the tips that cause them to open up.

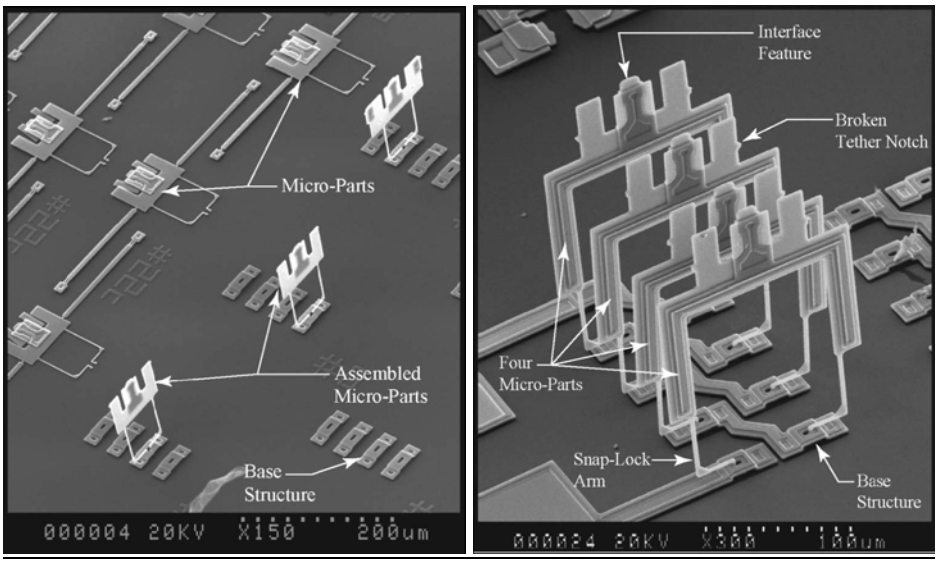

Figure 2.4-15: Micro parts tethered and joined to substrate and microcoil constructed using snap-lock microassembly [2-40]

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Chapter 3. Phenomena in micro world

In order to manipulate the components in the micro domain, the special conditions that govern in the micro world must be considered:

- Surface tension is dominant in comparison to the inertial forces. Especially the gravitational force, which is the most common in the macro world, becomes less important. Instead the adhesions forces, which are unpredictable, become dominate.
- Due to the negligible size and weight of the components, a feedback cannot be received and it is difficult to aquire information about the operation flow by the common way.
- Due to disproportion in size between the micro component and the macro equipment used for manipulation, the transfer from the meter range to the μmeter range has to take place on a very small distance.
- The very high accuracy (μm range) over a large range of motion.
- The lack of the commercially attainable manipulations tools (micro grippers, assembly systems...) and their high price.
- The absence of the standards in this field leads to the complicated situation where for different manipulation tasks new tools must always be produced, because the existing can not be adapted.
- The minimal workspace, fragility of the micro components (risk of damage during manipulation or losing)
- The visualisation problem-need for microscope
- The special work conditions (clean room, vacuum, laboratory)
- The necessity for skilled staff

3.1 Forces and scaling law

3.1.1 Introduction

The scaling effect is an appearance that makes the mechanics of object interactions in micro assembly domain remarkably differs from conventional assembly. As dimension of a micro component decrease (when it is less than 100 μm), the component's volume, mass and weight decrease with (length) ^{3}, while the component's surface area decreases with (length) ^{2}. [3-1]
It means that the adhesion forces, such as van der Waals forces, electrostatic forces and surface tension, deriving from the physics and chemistry of the surfaces (mass density, surface roughness, micro component geometry) and the ambient conditions (temperature, relative humidity, mechanical vibration, air cleanness, air pressure, airflow velocity, electrical grounding, etc), become more dominant than inertia and gravity. Many researchers have attempted to isolate these components and evaluate their influence. [3-2]
In [3-31] researched the environmental influences on micro assembly, in environment controlled micro assembly station. Temperature (in the range of -10-40 °C) and relative humidity (in the range of 5-80 % RH) can be controlled in a closed chamber where a micro assembly is carried out, mechanical vibrations are reduced and air flow controlled at a certain level. Results from the experiments showed significant effects of environmental parameters to not only the precision of micro assembly process but also the performance of the instruments used in micro assembly.

In [3-3] is reported the study of adhesion in different environments: ambient air, nitrogen atmosphere, and vacuum. Gold spheres, of 13 μm and 12 μm radius, were glued onto an AFM cantilever and a piece of optical fiber, respectively, and used as probes. Atomically smooth gold film on mica was used as the substrate. The spring constants of the AFM cantilever and optical fiber were measured using a TriboIndenter. The experiment has shown that the meniscus force dominates the pull-off force in ambient air and is not eliminated even after a few days of continuous nitrogen purge. A much smaller pull-off force is measured in a vacuum where the meniscus is absent. In contrast, the snap-on forces measured in ambient air, nitrogen atmosphere, and a vacuum are essentially the same. Therefore, in micro assembly, it is very simple to pick up the micro component but the releasing is very difficult.

Interaction between a micro gripper and a micro component are mostly caused by electrostatic and Van der Waals forces or by a water meniscus between micro gripper and a component, that is caused by capillary condensation. Which of these forces are dominant, depend on the environment condition as air humidity, temperature, materials and the surface condition, as on the micro component dimensions. Electrostatic forces can be both attractive and repulsive and arise by charging on the surfaces. They can be reduced by increasing the conductivity of the surfaces or working environment. Van der Waals forces act most intensive between two smooth planes and can be minimised by adequate structuring of the micro gripper's surface. Surface roughness is much less important for electrostatic forces than for van der Waals. These forces are only significant for gaps less than about 100 nm. [3-4], [3-5]

3.2 Overview

There are three aspects that are of particular importance for any interaction:

- Its strength,
- The distance over which it acts, and
- The environment through which it acts.

The integral form of interaction forces between surfaces of macroscopic bodies through a third medium (e.g., vacuum and vapor) is named surfaces forces. One differentiates between short range (e.g., Van der Waals interaction) and long range surface forces (e.g., electromagnetic interactions).
Figure 3.2-1 shows comparison of the forces that act on the object. Interaction between a micro gripper and a micro component in range 10 μm diameter are mostly caused by electrostatic and Van der Waals forces or by a water meniscus between micro gripper and a component, that is caused by capillary condensation. Gravitational force is less important than van der Waals already for the micro components radius of 10 μm, and than electrostatic for the micro components less than 1 mm. Electrostatic forces is crucial for micro components diameter in range 10 μm to 1 mm. In range 100 nm and less, van der Waals force is most influential; if the surfaces are smooth, it is significant already for micro components 100 μm in size.

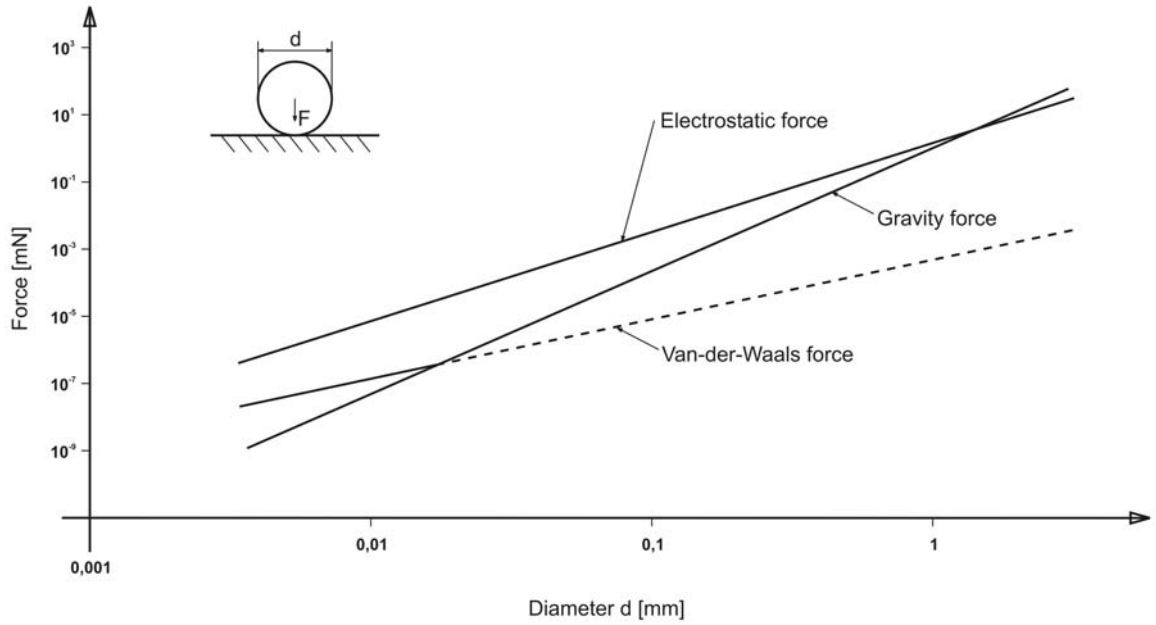

Figure 3.2-1: Forces acting on object depending on object diameter [3-6]

Which of these forces are dominant, depend on the environment condition as air humidity, temperature, materials and the surface condition, as on the micro component dimensions. Electrostatic forces can be both attractive and repulsive and arise by charging on the surfaces, it is the most significant force for handling and manipulation of 10µm to 1 mm. They can be reduced by increasing the conductivity of the surfaces or working environment. Surface roughness is more important for van der Waals force than for electrostatic force. Van der Waals forces act most intensive between two smooth planes and can be minimised by adequate structuring of the micro gripper's surface. These forces are only significant for gaps less than about 100 nm. [3-4], [3-5]

The water meniscus caused by capillary condensation can be avoided by hydrophobic coating of the micro gripper's surface. The reducing of the air humidity would have the similar effect but in that case could be charging and electrostatic forces intensified. Furthermore, the appropriate movement of the tools can affect the disturbance caused by adhesive forces. The smart combination of the mentioned methods and operations lead to the best possible solution. [3-1]

- Electrostatic force

The electrostatic forces arise from charge generation (tribo electrification) or charge transfer during contact. Electrostatic perturbations observed in micromanipulation are caused by triboelectrification. During a micro assembly task, friction between manipulated objects induces electric charges on the objects surface. The charge density depends on the triboelectrification and conductivity of the medium. Effectively, a higher electric conductivity medium is able to discharge objects' surfaces.

In principle, using conductive micro grippers can reduce static charging effects. However, the objects to be handled, such as silicon micro components, may be covered with insulators, such as native oxides.

The force applied by an electrostatic surface on an electric charged particle is given by:

$$F_e = \frac{Q^2}{4\pi\varepsilon\varepsilon_0 l^2}$$, where Q is the charge on the particle,

ε is the permittivity of the immersion medium between the particle and the surface, ε_o is the permittivity of vacuum, $\varepsilon_o = 8.854 \times 10^{-12}$ C^2/Nm^2), and
1 is the separation distance between the charge centres (approximately equal to 2r when the charge is uniformly distributed on the particle surface).

Air has better electric conductivity (relative permittivity of the dry air is 1 Fm^{-1}) than vacuum. Consequently, charge density in vacuum is increased and the electrostatic force directly proportional to the charge density. In the SEM chamber, under electron beam, the influence of the electrostatic charging even more intensive.

- Van der Waals force

This is an attractive force that arises due to instantaneous fluctuations of atoms and molecules when they are set close. Van der Waals forces decreases very rapidly with distance. It is a much weaker bond than ion and covalent bonds. Metallic bonding and van der Waals forces differ one from another. Metallic bonding involves the sharing of electrons, whether that sharing is binding atoms together or binding particles together. The smaller the nano particle, the easier it is for one atom in a particle to bind with and share electrons with atoms in another particle.

Van der Waals forces have to do with the shape and polarity of molecules and are electro dynamic in nature. There is no sharing of electrons. The positive end of one molecule is attracted to the negative end of another molecule and they are bound together like tiny magnets. The only atoms which can be bound together by van der Waals forces are the atoms of noble gases (Helium, Neon, Argon, Krypton, Xenon and Radon, which cannot share electrons.) Except for noble gases, van der Waals forces bind two or more molecules together. That is also very different from covalent bonding and ionic bonding which are the forces which hold two or more different atoms together to form a molecule.

Many molecules that are too stable to become an integral part interact with each other through the van der Waals force.

At the right side of the curve the atoms are separated by a large distance, see Figure 3.2-2. As the atoms are gradually brought together, they first weakly attract each other. This attraction increases until the atoms are so close together that their electron clouds begin to repel each other electrostatically. This electrostatic repulsion progressively weakens the attractive force as the interatomic separation continues to decrease. The force goes to zero when the distance between the atoms reaches a couple of angstroms, about the length of a chemical bond. When the total van der Waals force becomes positive (repulsive), the atoms are in contact.

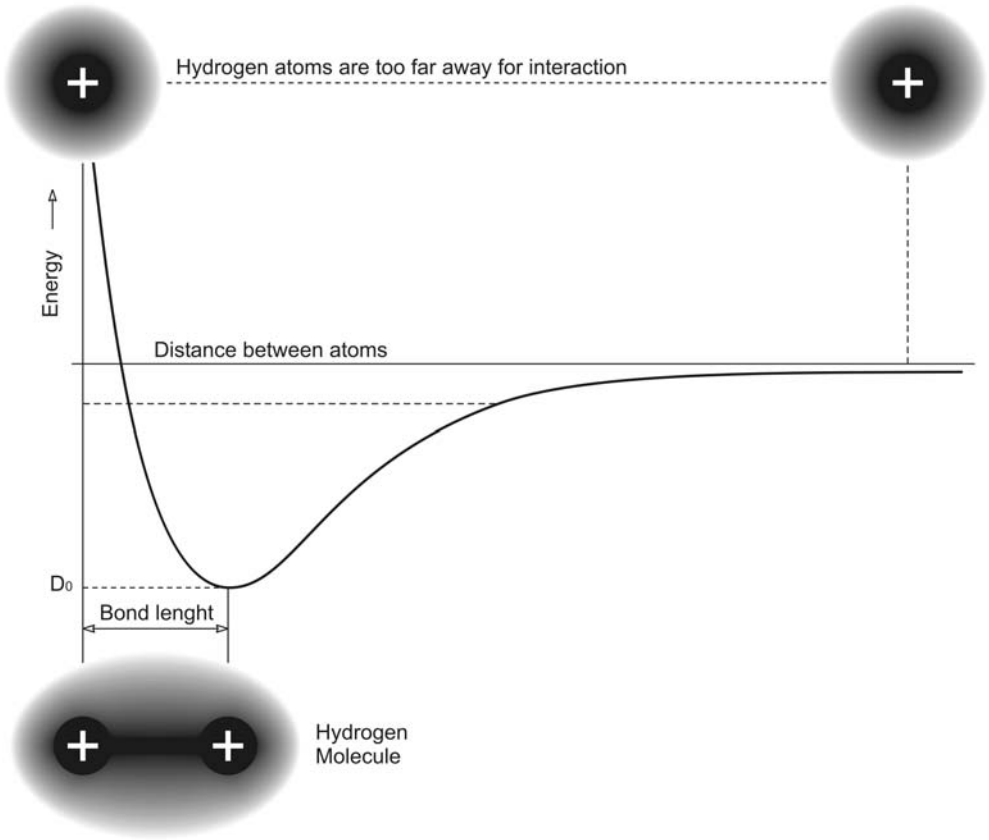

Figure 3.2-2: Van der Waals force between two hydrogen atoms [3-8]

The van der Waals interactions are one of the most important for the stability of the biological macromolecules. It exist between any molecules (neutral but polar), effective is only at distance about 0, 1 nm.

In [3-9] has been described the van der Waals force when the parts (sphere and block) move away. The force of interaction decreases when the block rotate to 45 degrees and fasterin the case when the block radial or tangential is moved away. This position of minimum in-force may be used to plan the path of the releasing.

- Capillary forces

Sticking effects originate substantially from capillary forces. In ambient conditions, the dominant force appears to be the meniscus force associated with the formation of a small liquid capillary between the two surfaces. When an object is exposed to the environment, a thin film of water is formed on its surface by adsorption of moisture. When two objects are brought together very closely, the films touch first and melt together. Due to the surface tension, the objects are pulled together. High humidity, large radii of curvature, long contact times and hydrophilic surfaces increase the adhesion force. The solution consists of removing the water by drying techniques such as critical point drying and freeze-drying. Also dimples and sharp corners on the contact surfaces can be used to reduce sticking. But this can only remove moisture due to fabrication methods, for instance after rinsing in sacrificial layer removal techniques.

When the microstructure is not enclosed in a sealed container, water vapour can also condense on it during use as the native oxide layers of silicon and other non-precious metals are hydrophilic. An effective way to avoid in-use sticking is the application of hydrophobic

coatings. A common way to study meniscus effects is to measure pull-off forces at different relative humidity levels.

The capillary phenomenon between an object and a substrate in air can be described by a liquid bridge presented in Figure 3.2-3 characterized by a volume V, a liquid surface tension γ and wettability properties defined by the contact angles θ_1 and θ_2. With the assumptions that the equality of the contact angles $\theta_1 = \theta_2 = \theta$, a constant volume and a small immersion height (D), capillary force between a plan and sphere (radius R) is equal to:

$$F_C = \frac{4\pi R\gamma\cos\theta}{1+\frac{D}{d}}$$

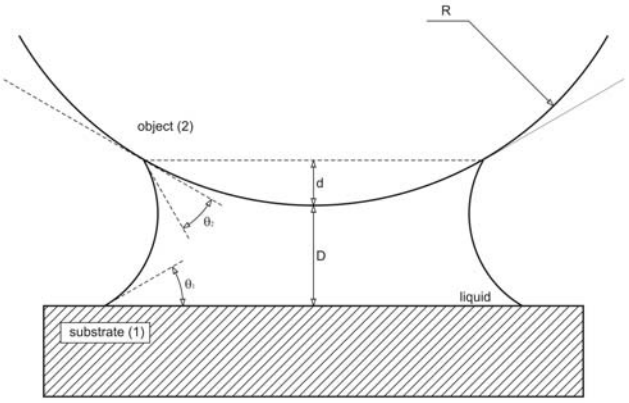

Figure 3.2-3: Liquid meniscus formation between a spherical object and a substrate [3-10]

This capillary force is induced by the surface between the liquid and the air near to the object. In a liquid this surface disappears, so this force is cancelled in a liquid medium. In the vacuum this force is cancelled, too.
A number of researchers are developed mathematical models for intermolecular and surface forces emerging during micro manipulation. [3-11] [3-12]
However, because of the great diversity, both in system parameters (material, humidity, temperature) and objects (geometry, charging on the surface) the problem is not solved yet.

3.1.2 Adhesion in a SEM chamber

Figure 3.2-4 shows Cu sphere, 40-60 μm that adhere to the top of the micro gripper. Figure 3.2-5 illustrates the adhesion between micro gear and micro disc (diameter 359 mm) in the SEM chamber.

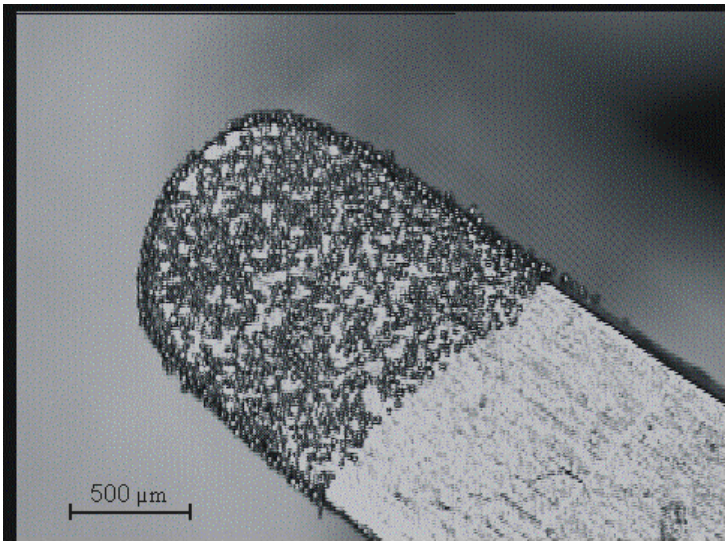

Figure 3.2-4: Cu spheres, 40-60 mm adhere to the tweezers tip

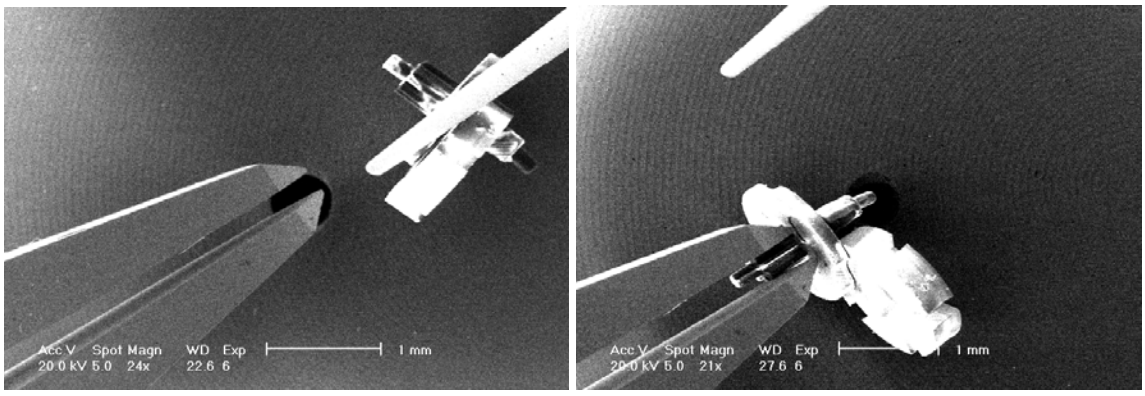

Figure 3.2-5: Adhesion between micro gear and micro disc (diameter 350 µm)

In the SEM chamber, see Figure 3.2-6, adhesion arises predominantly from electrostatic charging. In order to establish an efficient manipulation technique with an individual micro object in the SEM chamber it is necessary to properly understand the adhesion forces between micro objects and other objects, i. e. substrate (specimen holder) in the vacuum under the electron beam. Those are the conditions which differ significantly from the normal room conditions.

Theories about different kinds of adhesion forces that act on a micro object can be found in literature**.** [3-12][3-13]The conditions in the chamber, electron beam, electric charging of the micro objects and the trajectories of the objects, as well as substrate and object material are the factors that determine the adhesion forces in the chamber.

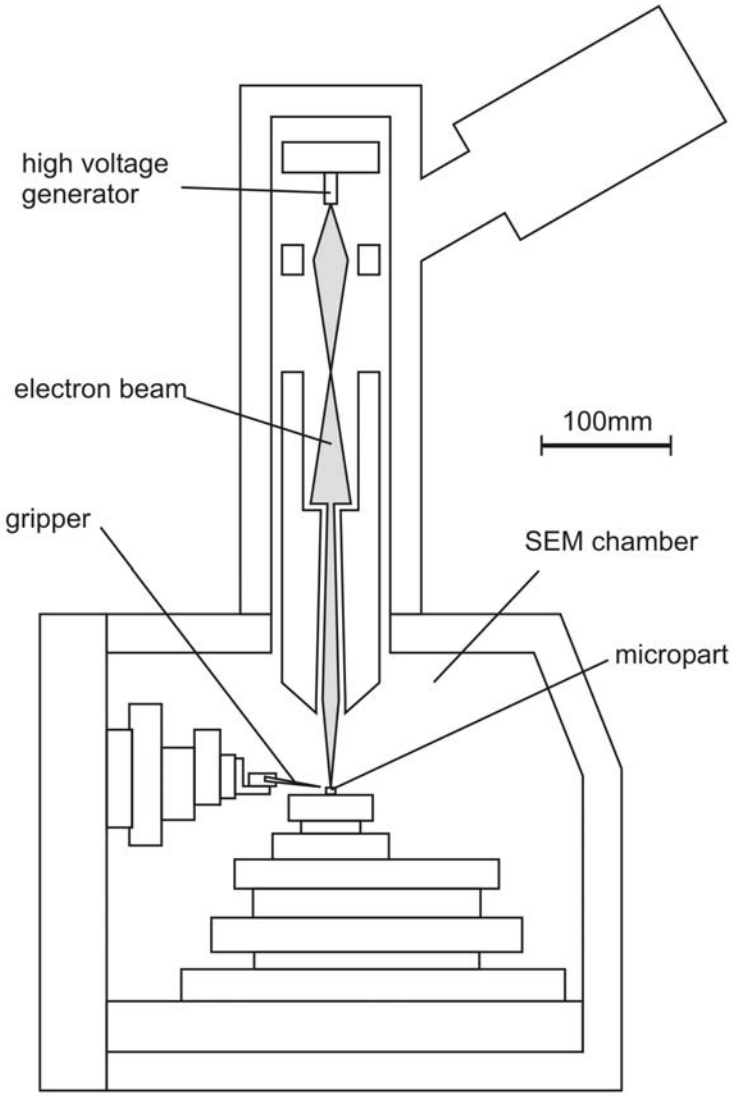

Figure 3.2-6: Schematic presentation of the SEM chamber

The factors as surface roughness, viscoelasticity and chemical reactions caused by electron beam play an important role, and the values of the parameters used in the conventional theories could be a source of error. An example of distribution of the electrostatic field in the SEM chamber, with the electron beam voltage of 20 kV is shown in Figure 3.2-7.
Particularly, the theories for correctly defining the charging of the micro object under the electron beam are not very known, thus the calculated values of electrostatic forces include large deviations and uncertainty. Therefore it is necessary to base the explanation of the adhesion mechanisms on methodical experiments.

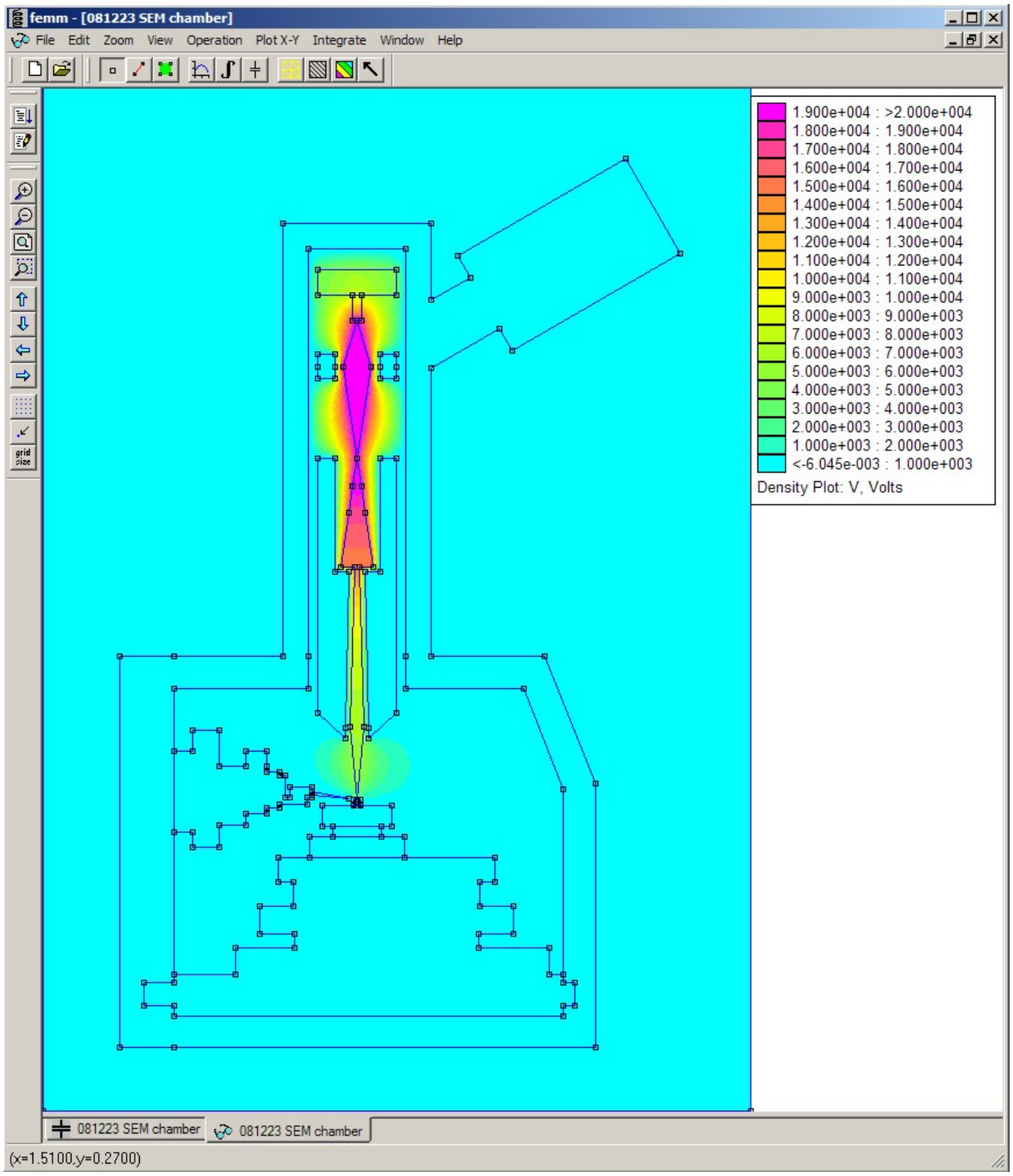

Figure 3.2-7: Schematic presentation of electron beam column

In [14] is noticed that adhesion force increases according to the EB-irradiation time after the contact interface is formed; the increment rate of adhesion force depends on the EB current, ands adhesion force initiated by the EB irradiation increases irreversibly even after the irradiation is suspended. These properties make it extremely difficult to operate a micro-object with high repeatability.

3.3 Methods for overcoming the difficulties caused by small dimensions

In order to reduce the adhesion most important effect has a proper choice of the micro gripper materials and geometry. Some rules are given:

- Using materials with a small contact potential difference between micro gripper and object.
- Using conductive materials which do not easily form highly insulating native oxides.
- Keeping the contact area small. Therefore, spherical fingertips are preferred above planar ones. The contact area can also be reduced by increasing the roughness of the micro gripper. This will considerably reduce the van der Waals forces.
- High contact pressures, caused by the adhesion forces, can cause local deformations at the contact site (Hertzian deformations). This deformation will increase the contact area and hence the net adhesive force. Therefore, hard materials are preferable.
- The surface tension effect can be reduced with a dry atmosphere and hydrophobic coatings. An attractive alternative is assembly while immersed in a fluid, which eliminates electrostatic and surface tension effects. The surface tension effect can also be used to help micro components adhere better to the target location than the micro gripper.
- Free charges such as in ionised air can combine with and neutralise exposed surface charges.

3.2.1 Releasing

Releasing an object from micro gripper, when dominant force is not gravitational force, can be very complicated operation. The methods that can help are:

- Gluing (as joining method) the micro component to the substrate on the right place
- Releasing the micro component by positive mechanical engagement
- Injection of gas: a small puff of gas pushes the object while removing the micro grippers. This technique is especially suited for vacuum micro grippers.
- Mechanical release mechanism with needle: the needles push the object and since the contact surface between the object and the needles is very small, the gravity becomes dominant again and the object will stay in place when removing the needles.
- Destruction of the gripping mechanism. For instance, with a micro gripper using the surface tension force to pick an object, the object can be released by heating the micro gripper and evaporating the adhesive liquid.
- Vibration of the micro gripper
- Mechanical release by stripping off against a sharp edge
- Using the adhesion effects described above: the adhesion between the substrate and the micro component must be greater than that between the micro component and the micro gripper
- To remove the object from the micro gripper, the micro gripper can make a rolling motion [3-27]

In [3-15] is reported covering the micro gripper surface with small pyramids. The pyramids are made by anisotropic etching of Si and are placed at intervals of 10 μm and are a few micro metres wide and high. A second advantage of the pyramids is the self-discharge possibility due to the high electric field strength at the tips. Sharp tips enhance discharge and reduce contact area but may damage the surface. Small particles scraped off by the micro pyramids

can contaminate the environment. The micro pyramids are coated with a thin metal layer to enhance the effect.

In [3-16] has reported about ultrasonic excitation that can reduce the adhesion.

In [3-17] is developed an in situ measurement system for the adhesion forces acting on micrometer-sized objects (objects with a radius 1-10 μm) in a SEM. It was found that the adhesion force between a 25- μm solder sphere and a metal probe tip under SEM observation were on the order of 100 nN. Interesting is the fact that the values for each measurement (the results of 20 measurements) significantly differ. Such a large deviation in the measured force id generally observed for the adhesion of micro-objects in a SEM. Similar deviation in the adhesion forces can also be found in reports. [3-18] [3-19] This fact means that slight differences in microscopic contact of the surfaces significantly affect the adhesion forces.

Adhesion forces between surfaces have been investigated using the surface force apparatuses (SFAs) developed by Israelachvili et al. since 1970s. A SFA is used for measuring the adhesion between mm-sized object under controlled conditions, for examining the forces between mm-sized objects is not suitable. [3-17]

3.4 Visual and force feedback

In order to handle very small objects freely, it is necessary to transfer to the operator information received from events in the micro- and nanometric world, as it is necessary to transfer the operations from the macro-scale into the micro- and nanometric domain. Shifts and actions performed by the operator have to be reduced and transferred into nanometric dimensions, and the feedback from nano-dimension, e.g., sound, vision and the force induced by the operation has to be magnified and transferred to the operator, so he may monitor the operation.

Visual feedback is obtained by visual sensors, mostly used are CCD camera and optical fiber.

In the ideal case, all the information on the world around us could be detected by sensors, transferred from the nano-world to the operator, scaled and represented appropriately, yet this is impossible. In order to establish this kind of data transmission, it is necessary to realize correctly and effectively the following functions between the nanometric world and the world of common dimensions:

- manipulation
- positioning
- detection, visualization and fixation (sensing) of information, displacement and force
- transformation and amplification of information
- reproduction of information

Analogue to the handling process in the macro world, a system which allows observation with two 'eyes' (stereo SEM, made in cooperation with SANYU ELECTRON Co. LTD.) is constructed and operates with two micro grippers, one on each side, controlled externally by two joy-sticks. The authors developed a Nanorobot System, with the following characteristics: the left hand robot can generate fine/coarse motion along the x, y, and z axes within the range of 20x20x20 mm, at resolution of 10 nm. The right hand robot has a 15 μm full range motion along the x, y and z axes with 10 nm resolution, as well as exchangeable end effectors (tungsten or diamond needle).

The sound generated from the high frequency component, as information on the force, is an essential information for the operator. The change in brightness of the SEM image is also a kind of feedback, since the operator can not see the contact point.

- The visual control is derived from measuring the components' position and orientation between two points: one where it is situated (reference point) and the specific destination position. There are two methods to realize visual feedback:

  - Teleoperated by the human operator performing the visual inspection on which he operates the robot. The advantage of this method is that the operator is able to perform a descriptive scene analysis and to respond to unexpected events as well. It has perfect cognitive abilities, effortlessly recognizes the objects and qualitatively interprets the entire scene. When defining the handling operation, it is able to consider all relevant components of the visual information, which is a rather poor source of information. On the other hand, the teleoperated control is qualitative, not quantitative and it is very sensitive to disruptive factors, such as the presence of noise and sensor deformation.

  - Automatic, by computational vision, where the supervisory information is obtained based on digital image. The advantage is in the resolution, accuracy and repetitiveness of the task. Additionally, it is possible to entirely automatize the visual feedback.

Image in the SEM chamber enables good visual control, thanks to large depth of field. Koyano et al, [3-20], Sato et al. [3-21], Miyazaki et al. [3-22], Schmoeckel et al. [3-23] used SEM as sensor in order to control teleoperated micro assembly.

Force feedback is achieved by integration of different sensor types into manipulating devices, as strain gauges, bonded on the micro grippers' hands, or optical techniques as the optical beam deflection, which advantage is in the fact that it is electromagnetically impervious with high resolution potentials. [3-1]

- Force sensing can prevent the damage of the fragile micro componets but also helps to characterize adhesion forces. The produktion and implementation of self-sensing tweezers with the ability to overcome attraction forces and incorporating force sensing would lead to new manufacturing and assembly process capabilities and, therefore, lower production costs.

Fatikow et al., [3-24] described possible technics for force micro sensor integration:

- Strain gauges are either made out of metal-foils or of semiconductor materials using the piezoresistive effect. One disadvantage is the geometrical constraint that has to be considered in the design of endeffectors for micromanipulators, as the fabrication of strain gauges has miniaturization limits. The resolution of force sensors based on strain gauges enable to measure with 10 μm to 400 μm resolution in the range of 10 to 350 mN.

- Piezoresistive materials. Piezoresistivity is one of the causes of the electrical resistance variation produced by mechanical stresses. Semiconductor materials have significant piezoresistivity, which leads to sensors with a high sensitivity. Nonlinearity and temperature sensitivity are the main drawbacks of sensors based on this material. The resolution of piezoresistive force sensors is also in the range of sub-mN.

- Piezoelectric materials-PVDF (piezoelectric polymer). Piezoelectric force sensors are based on the piezoelectric effect. This effect is observed in some materials which become electrically polarized when subjected to mechanical strain. The difficulties in

static measurements of the generated charges and the sensitivity of piezoelectric materials to temperature, especially to temperature gradients, limit the use of this type to dynamic measurements. The main advantages of piezoelectric sensors are that they do not require power supplies and can be designed in small dimensions and with a low weight. The resolution of force sensors based on piezoelectric materials is in the range of μN.

Kasaya et al. [25] used a cantilever as force sensor, made of carbide steel, on which four strain gauges are glued. It has linearity up to 20 mN and a force resolution of 14 nN.

3.5 Dynamic range

The main purpose of supervision of precise positioning in the field of micro-robotics is the high-dynamic range procession, i.e. the combination of nanometric resolution and large operating area (few square centimeters). To realize very high precision over large range of motion is especially difficult. Therefore, it is necessary to design tools and processes at multiple scales and to integrate them into a harmonious system. The possible respond to this challenge is to apply the coarse-to-fine strategy. Thereby, a conventional manipulator for coarse motion of lower accuracy but greater range of motion is used, and between the micro grippers, i.e., end-effectors, and the manipulator there is a device of high accuracy and very small range of motion.

The other possibility is to use a manipulator of high accuracy directly. On the market, there are commercially available robot systems with resolution and repeatability of few microns, e.g., made by the MRSI in Chelmsford, MA, or Sysmelec in Switzerland). More accurate prototypes are described by Quaid et al. [3-26]. In the papers [3-27] system prototypes of even higher accuracy are described, which also use stepping motors and inertial drives, to achieve submicrometer resolution of motion.

There are designs that allow coarse and fine modes of operation with the same actuator, e.g. stick-slip actuator, Bleuler et al [3-28].

The second example of an accurate system is the parallel RP-1 AH robot from Mitsubishi Electric. It is a miniature robot, designed specially for micro manipulation applications of high accuracy. [3-29]

3.6 Sensitivity and accuracy of the equipment

The most obvious difference between micro and macro assembly is in the accuracy of positioning the automatic assembling systems. In the macro domain, accuracy of few hundreds of microns enables the correct functioning of robotic manipulators with 4-6 axes. In the micro domain (objects dimensions range from μ to mm), submicron accuracy is necessary. Conventional open loop assembling devices, used in the industry, could not achieve this level of accuracy. [3-30]

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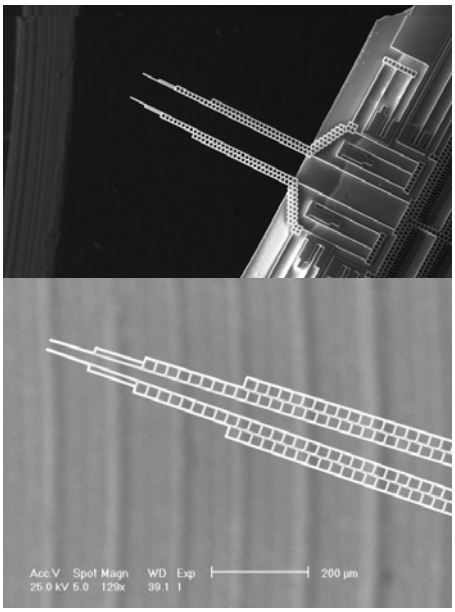
Chapter 4. An overview of relevant characteristics for the micro manipulation process under a scanning electron microscope and an optical microscope

Figure 4-1 illustrates difference between OM and SEM. The picture of electrostatic micro gripper, made by NASCATEC, is taken both in the OM and in the SEM.

Optical microscope

•optical lenses
•compact, practical
•applicable at atmospheric conditions
•light wavelength 200-700 nm
•resolution 200 nm
•max. reasonable magnification 1000 times
•working distance small
•on-line display possible

Scanning electron microscope



•magnetic lenses
•complex control
•vacuum chamber necessary
•electron wavelength 0.001-0.01 nm
•resolution 0.02 nm
•magnification to 1000000 times
•working distance large
•on-line display max to sampling frequency

Figure 4-1: Shortly characterisation of the OM and SEM

4.1 Scanning electron microscope imaging

The basic property of the SEM is in the manner it builds up the image. It is formed in the way that the electronic beam scans the sample and the rejected electrons are sent to the detector giving the image on the display. Depending on which rejected electrons (of which wavelength) are sensed, different data are being obtained about the sample (in depth and surface). There is a vacuum in the chamber where the electronic beam is created.

The first SEM image was obtained by Max Knoll, who in 1935 obtained an image of silicon steel showing electron channeling contrast. Further pioneering work on the physical principles

of the SEM and beam specimen interactions was performed by Manfred von Ardenne in 1937, who produced a British patent but never made a practical instrument. The SEM was further developed by Professor Sir Charles Oatley and his postgraduate student Gary Stewart and was first marketed in 1965 by the Cambridge Instrument Company as the "Stereoscan". The first instrument was delivered to DuPont. [4-2][4-3][4-4][4-5]

The environment within the column is an extremely important part of the electron microscope. Without sufficient vacuum in the SEM, the electron beam can be neither generated nor controlled. If oxygen or other molecules are present, the life of the filament will be shortened dramatically. A basic requirement for the general operation of the SEM is the control and operation of the vacuum system. When changing samples, the beam must be shut off and the filament isolated from atmospheric pressure by valves. A vacuum is obtained by removing as many gas molecules as possible from the column. The higher the vacuum the fewer molecules present. The higher the vacuum (the lower the pressure), the better the microscope will function. To pump from atmospheric pressure down to 10^{-6} Torr, two classes of pumps are used: a low vacuum pump (atmosphere down to 10^{-3}) and a high vacuum pump (10^{-3} down to 10^{-6} or greater depending on type of pump). There will be one or more of each class in a SEM. Normal atmospheric pressure is 101 325 Pa, it is 1.01325 bar, 1 atm or 760 tor.

Modern electron microscopes can view detail at the atomic level with sub-nanometer resolution (e.g., 0.1 nm resolution, which is 1000 times better than conventional light microscopes) at up to around two hundred thousand times magnification. In an SEM, the beam of electrons is focussed to a point and scanned over the surface of the specimen. Detectors collect the backscattered and secondary electrons coming from the surface and convert them into a signal that in turn is used to produce a realistic, three-dimensional image of the specimen.

SEMs can magnify up to around one hundred thousand times or more and are used extensively, particularly in such scientific areas as biology, medicine, physics, chemistry, and engineering to, for example, study the three-dimensional ("3-D") structure of surfaces from metals and ceramics to blood cells and insect bodies.

Outgassing and contamination potential must be considered because they can disturb the evacuation process and vacuum environment in the SEM chamber. Any substance subjected to high-vacuum has the potential to release trapped gasses. These gasses can cause oxidation or contamination of surfaces in the vacuum environment. Depending on the application, outgassing may cause significant damage to the process or equipment. High-vacuum probe materials and processes are designed to minimize or eliminate outgassing.

Choosing the materials to use in a vacuum system design is not just a case of finding the materials with the lowest gas loads, but to also consider the various physical or chemical properties that will fulfill the process's requirements. The primary materials in probe construction are the metal body, epoxy, PEEK, conductors, and cabling. Vacuum compatible probes are constructed of the 303 stainless steel. The epoxy in the probes has been specifically tested for vacuum applications requiring low outgassing. Probe cabling uses a PTFE jacket which is highly stable and produces very little outgassing. Conductors within the cable and probe are silver-plated, oxygen-free copper (OFC).
There are a number of materials that will probably be used in a vacuum system for very specific applications that are process dependent. This overall category includes ceramics and glasses that might be used as thermal or electrical insulators, components of internal arrays, or even plastic substrates. In each case, the same careful assessment is required to ensure that the gas loads are as small as possible. Some examples are given in Figure 4.1-1. For example, ceramics are considered to be good vacuum materials, but only if high-density sintered

materials are used. This differentiates between the insulator in a UHV-rated feedthrough and a piece of firebrick.

Porous materials contain massive amounts of gas. Even normally acceptable metals such as Al need to be looked at carefully. Household Al foil is often found in systems where it is used as a chamber liner. This material is coated with peanut oil used as a lubricant in its manufacture, and it is virtually impossible to remove with solvent cleaning. [4-6]

Approximate outgassing rates to use for choosing vacuum materials or calculating gas loads

(All rates are for 1 hour of pumping)

Vacuum Material	Outgassing Rate *(torr liter/sec/cm²)*
Stainless Steel	6×10^{-9}
Aluminum	7×10^{-9}
Mild Steel	5×10^{-6}
Brass	4×10^{-6}
High Density Ceramic	3×10^{-9}
Pyrex	8×10^{-9}

Vacuum Material	Outgassing Rate *(torr liter/sec/linear cm)*
Viton (Unbaked)	8×10^{-7}
Viton (Baked)	4×10^{-8}

Figure 4.1-1: Outgassing rates [4-6]

A further characteristic of the SEM working principle is the influence of electric and magnetic fields. The magnetic fields influence can be avoid by appropriate material selection, but the influence of electric fields cannot be avoided because the electron beam supports the electric field genaration. This field has negative influence on both image quality and release the micro components. Decreasing the electron beam voltage can decrease the electrostatic charging, but then the resolution is reduced. The second action against the electrostatic charging is grounding of the micro gripper. Since it is observed that some charging on the tips remains, it is recommended to coat the micro gripper tips with nonmagnetic material, f.e. titan.

Microscopes have traditionally been used for imaging (e.g., viewing specimens). However, to provide greater utility, a recent trend has been to include a manipulator mechanism that may be used in conjunction with the microscope for manipulating a specimen being imaged by the microscope. Manipulation in SEM chamber requires integration of manipulation and handling system into the chamber.

Since the micro handling sequences takes a few seconds, it is possible to make photos of the process stepswise and analyse the details.

- Characteristic conditions in the chamber of the SEM:
  - dust,
  - humidity,
  - vibrations

Dust is a general name for minute solid particles with diameters less than 500 micrometers. There is no dust in the SEM chamber. In the µm dimension the dust can make a problem, it

could disturb the defined tolerances during the assembly and work and so lead to the failure of the micro mechanical system, or during the joining, it could penetrate into the joint and make it weak or broken. For the robust application, dust does not represent a problem.
In order to observe and examine specimens in the chamber of a SEM, in consideration of its specific working principle, preparation of the samples, i.e. micro components is requiered. It involves:

- sputtering,
- drying (freezing),
- cleaning
- electrically grounding

Conventional SEM requires samples to be imaged under vacuum, which mean that samples that would produce a significant amount of vapour, e.g. biological samples, need to be either dried or cryogenically frozen. This means that process involving transition to or from liquid or gas, such as the drying of adhesives or melting of alloys, could not be observed.

- Sputtering

In order to obtain a good image of most non-conductive specimens in the SEM the sample must first be covered with a thin coating. A coating serves a number of purposes including:

- increased conductivity,
- reduction of thermal damage,
- increased secondary and backscattered electron emission, and
- increased mechanical stability.

Conductivity is the single most important reason for coating a specimen. As the primary beam impinges on the specimen the increased electrical potential must be dissipated in some way. For a conductive specimen such as most metals this is not a problem and the charge is conducted through the specimen and eventually is grounded by contact with the specimen stage. On the other hand non-conductive specimens or "resistors" can not dissipate this excess negative charge and so localized build up charges cause a dielectric breakdown and gives rise to an artefact known as charging. Charging results in the deflection of the beam, deflection of some secondary electrons, periodic bursts of secondary electrons, and increased emission of secondary electrons from crevices. All of these serve to degrade the image. In addition to coating the sample, the specimen should be mounted on the stub in such a way that a good electrical path is established. This is usually accomplished through the use of a conductive adhesive such as silver or colloidal carbon paint.

During the process of spattering, a thin layer of metal is applied, whose purpose is to transmit the current and prevent surface charging. By using conductive silver, even better performance could be achieved. Conductive silver is a suspension applied to the objects' side before spattering. In this way the current may be more efficiently transmitted from the objects' surface to the conductive holder of the object.

When examining under the microscope with secondary electrons, the layer has to be as thin as possible in order to prevent altering of the surface topography. Spattering is performed inside high vacuum with introduction of small amount of argon. The sample is placed on anode and a metal plate used for spattering, e.g. made of gold, is cathode. It is also called target. High voltage is then applied between the two electrodes. The atoms of argon collide with the anode and loose one electron. Because of their positive charge, the argon ions are accelerated towards the target and collide at high speed with its surface. They hit the smallest particles of gold (around 3 nm), as well as the electrons from the cathode. The electrons are accelerated towards the anode, but one toroidal magnet prevents them from reaching it and

damaging the sample, i.e. the object being spattered. The golden particle falls onto the sample and forms a thin layer.

Instead of gold, some other metal can be used as well, e.g. platinum, aluminum, nickel, titanium, etc.

A conductive coating can also be useful in dissipating the heating that can occur when the specimen is bombarded with electrons. By rapidly transferring the electrons of the beam away from the region being scanned, one avoids the build up of excessive heat.

Because secondary electrons are more readily produced by elements of a high atomic number than by those of a low atomic number a thin coating of specimen can result in a greatly improved image over what could be produced by the uncoated specimen. In cases where backscattered electrons or characteristic X- rays are of primary interest a coating of heavy metal such gold or gold/palladium could obscure differences in atomic number that we might be trying to resolve. In this case a thin coating of a low atomic number element (eg. carbon) serves the purpose of increasing conductivity without sacrificing compositional information.

The fourth and final purpose of using conductive coatings is to increase mechanical stability. Although this is somewhat related to thermal protection, very delicate or beam sensitive specimens can benefit greatly from a thin layer of coating material that actually serves to hold the sample together. Fine particulates are a prime example of a case where a coating of carbon or heavy metal can add physical stability to the specimen.

Many of the negative effects of imaging an uncoated specimen can be reduced by using a lower energy primary beam to scan the sample. Whereas this will tend to reduce such things as localized charge build up, thermal stress, and mechanical instability it has the distinct disadvantage of reducing overall signal. By carefully adjusting factors such as accelerating voltage and spot size, many of these same effects can be reduced but a fine coating of the specimen is still usually required. [4-7]

The importance of clean specimens and clean specimen handling can not be overemphasized.

Each impurity disturbs the image generating and its quality due to electric charge accumulated on these fields; the charged components behave undefined, attract or repel each other, assembly, i.e. manipulation is very complicated or fast impossibly (increased adhesion). It shows the importance of the cleaning that are perform by rinsing in the acetone and than in the isopropyl alcohol dissolution.

- The main advantages of the scanning electron microscope:
  - high resolution
  - large working distance
  - large depth of field
  - enable instrument operating without the necessity of entering “clean-room” laboratories
  - SEM stage can be moved (x,y,z), rotated and tilted (to 60°)
- Disadvantages
  - high maintenance cost
  - high price
  - sample prepare necessary:

  - samples that produce a significant amount of vapour, e.g. biological samples, need to be either dried or cryogenically frozen
  - the not conductive samples must be sputtered
  - every sample must be cleaned
  - the samples must be electrically grounded
- processes involving phase transitions, such as the drying of adhesives or melting of alloys, liquid transport, chemical reactions and solid-air-gas systems in general could not be observed
- sample damage possible
- requiring extremely stable high-voltage supplies
- extremely stable currents to each electromagnetic coil/lens
- continuously-pumped high- or ultra-high-vacuum systems, and a cooling water supply circulation through the lenses and pumps
- very sensitive to vibration and external magnetic fields, microscopes aimed at achieving high resolutions must be housed in buildings (sometimes underground) with special services
- time and cost consuming operation

4.1.1 Fundamental terms

- Resolution

Depending on the instrument, the resolution can fall somewhere between less than 1 nm and 20 nm. The world's highest SEM resolution is obtained with the Hitachi S-5500. Resolution is 0.4nm at 30kV and 1.6nm at 1kV.

Resolution depends on the wavelength of the medium that participate in image formation. Since it is an electron beam in the SEM, its properties and wavelengths will be analyzed.

As well as the light, electrons also have wave properties. The electrons' wavelength depends on their energy but it is significantly smaller than that of visible light.

Figure 4.1-2 shows the comparison of the wavelengths of electrons at different acceleration pressures, as well as the related theoretical resolution.

Because of its marginal wavelength, defined by the Abbe limit, as in the case of the light microscopy, the theoretical power of resolution is considerably higher than that of the light. This fact enables the increase into nanometer domain. Because of the practical source of error, the theoretical power of resolution is impossible to achieve. [4-8]

Due to inherent defects and factors concerning lenses and electron optical systems, there are a variety of abnormalities or aberrations that must be corrected for in an electron microscope. If it were possible to completely correct for all of the lens aberrations in an electron microscope (EM) our actual resolution would very nearly approach the maximum theoretical resolution. In other words if all lens aberrations could be eliminated our numerical aperture number would equal 1.0 and Abbe's equation for calculating resolution would equal wavelength/2. Whereas we have been able to approach this in light optics, the nature of electro-magnetic lenses makes this goal much more difficult to obtain. [4-7]

Acceleration voltage (kV)	Wavelength λ (nm)	Resolution (nm)
20	0,0087	0,44
40	0,0061	0,31
60	0,0050	0,25
80	0,0043	0,21
100	0,0039	0,19
1000	0,00087	0,10

Figure 4.1-2: Resolution depending on acceleration voltage [4-8]

- Accelerating Voltage and Resolution

The acceleration voltage is the high voltage applied to the filament. Together with the application of a small current, it will cause the electrons to leave the filament. The size of accelerating voltages often used in SEM imaging varies between 5kV and 20kV. In general, increasing the accelerating voltage will decrease the spherical aberration of the system and therefore increase the resolution. But, varying the acceleration voltage will also have an effect on the beam-specimen interaction. If a higher accelerating voltage is used, the interaction volume between the beam and the specimen will become bigger because of the greater energy of the beam of electrons. With an increase in acceleration voltage the interaction volume becomes bigger, see Figure 4.1-3. This effect is more significant in specimens with low atomic number, such as most biological samples. The interaction volume of samples with a high atomic number is much smaller as compared to samples with a low atomic number, see Figure 4.1-4

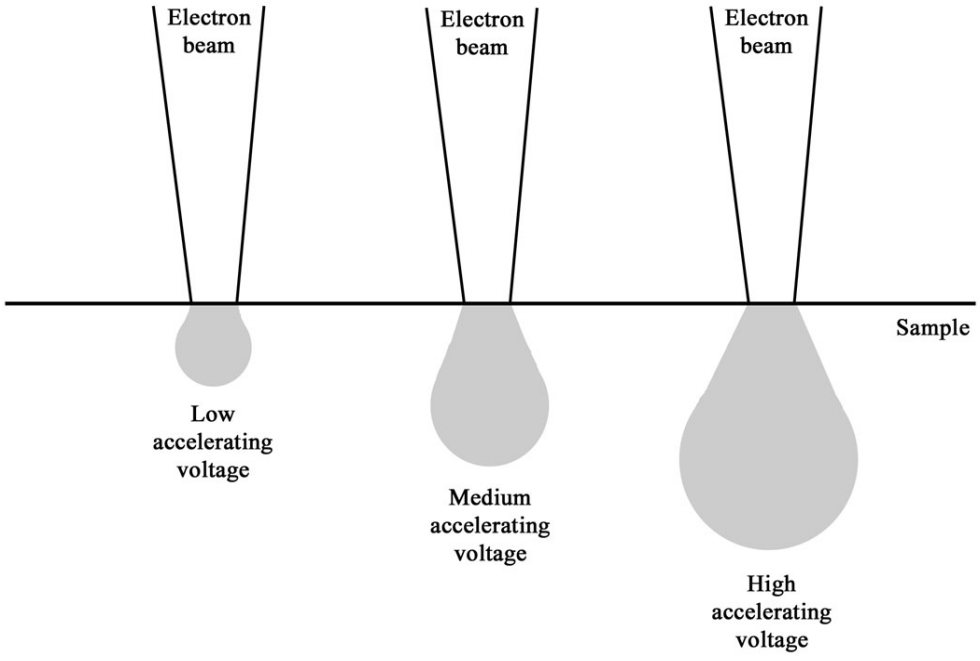


Figure 4.1-3: Effect of the acceleration voltage on the interaction volume [4-9]

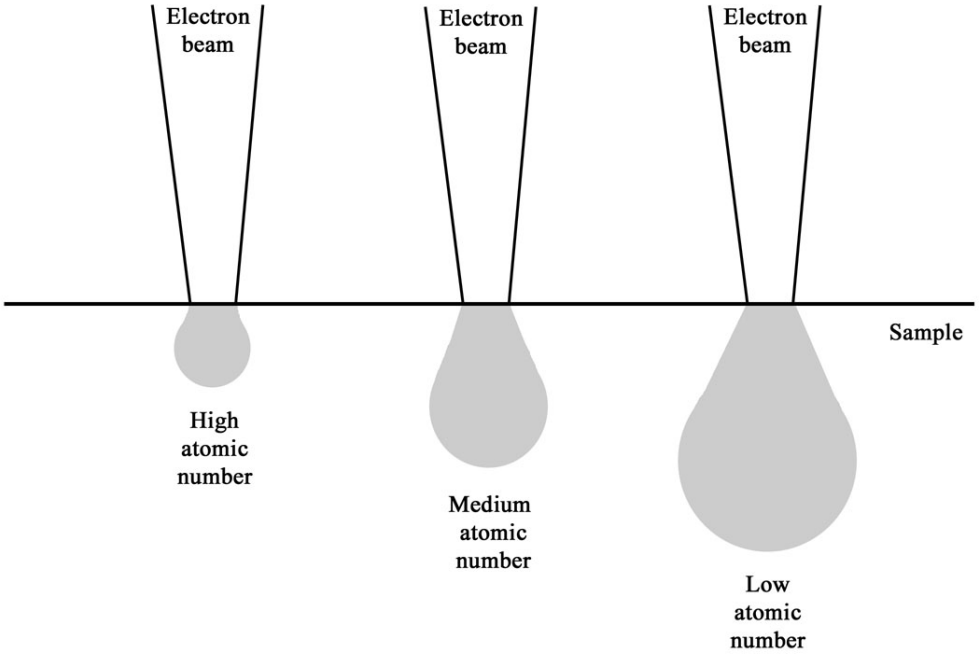


Figure 4.1-4: Effect of the acceleration voltage on samples with different atomic number [4-9]

Resolution is dependent on the area from which secondary electrons are produced. Normally this area would be defined by the spot size. By increasing the accelerating voltage, backscattered electrons, emitted from a larger area of the sample, interact with the sample on their way out, producing secondary electrons further away from the original spot size (Figure 4.1-5), thereby reducing the resolution of the image. This effect will be much less in a sample with high atomic numbers. [4-9]

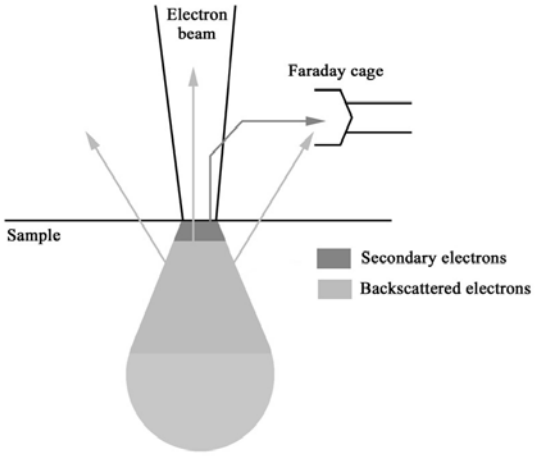


Figure 4.1-5: When interaction volume increases, more backscattered electrons will be able to escape from a bigger volume [4-9]

Both electron and light microscopes have resolution limitations, imposed by their wavelength. The greater resolution and magnification of the electron microscope is due to the wavelength of an electron, its de Broglie wavelength, being much smaller than that of a light photon, electromagnetic radiation.

The wavelength of an electron is given by the de Broglie equation

$$\lambda = \frac{h}{p}$$

Here h is Planck's constant and p the momentum of the electron. The electrons are accelerated in an electric potential U to the desired velocity:

$$v = \sqrt{\frac{2eU}{m_0}}$$

m_0 is the mass of the electron, and e is the elementary charge. The electron wavelength is then given by:

$$\lambda = \frac{h}{m_0 v} = \frac{h}{\sqrt{2m_0 eU}}$$

However, in an electron microscope, the accelerating potential is usually several thousand volts causing the electron to travel at an appreciable fraction of the speed of light. An SEM may typically operate at an accelerating potential of 10,000 volts (10 kV) giving an electron velocity approximately 20% of the speed of light. The wavelength of the electrons in a 10 kV SEM is then 12.3 x 10-12 m.

The spatial resolution of the SEM depends on the size of the electron spot, which in turn depends on both the wavelength of the electrons and the magnetic electron-optical system which produces the scanning beam. The resolution is also limited by the size of the interaction volume, or the extent to which the material interacts with the electron beam. The spot size and the interaction volume both might be large compared to the distances between atoms, so the resolution of the SEM is not high enough to image individual atoms.

Magnification in the electron microscope can be varied from hundreds to several hundred thousands of times. This is done by varying the strength of the projector lens. This can not be achieved with a light microscope.
Figure 4.1-6 shows comparison of the light nd electron properties. Light waves behaviour as particle and electron as waves.

	Light/Photon	Electron(in nonrelativistic approximation)
Energy	$E=h\cdot\nu=h\cdot c/\lambda$; $c=\nu\cdot\lambda$	$m\cdot v^2/2=e\cdot U=E$
Impuls	$\rho=h/\lambda=h\cdot\nu/c$	$m\cdot v=\sqrt{2}\cdot m\cdot E$
Wavelength	λ	$h/p=h/\sqrt{2}\cdot m\cdot E= h/\sqrt{2}\cdot m\cdot e\cdot U$
Effect	Light diffraction, Photo effect	Electron diffraction,

Figure 4.1-6: Wave–particle dualism [4-10]

- Working Distance and Resolution

The working distance is the distance between the final condenser lens and the specimen. Changing the working distance will have an effect on the spherical aberration of the imaging system and therefore will effect the resolution of the final image. Spherical aberration is the failure of the lens system to image central and peripheral electrons at the same focal point. Spherical aberration is due to the geometry of electromagnetic lenses. Electrons passing along the axis of the electron beam refract less than electrons passing through the periphery of the electron beam creating more than one focal point and therefore resulting in an enlarged, cloudy spot (Figure 4.1-7). When the working distance decreases, this effect of spherical aberration will become less, the spot striking the specimen will become smaller and therefore will improve resolution. [4-9]

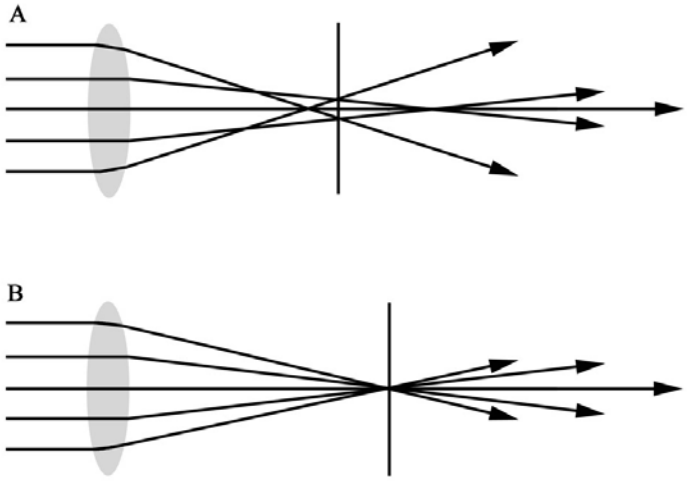


Figure 4.1-7: If spherical aberration is present the beam will scan with an enlarged, cloudy spot (A). If spherical aberration is absent, the beam will scan with the sharpest spot possible (B) [4-9]

- Working Distance and Depth of Field

The working distance has an effect on the depth in the sample that appears to be in focus or in other words, has an effect on the depth of field. At a short working distance the sample will be scanned with a wide cone of electrons resulting in an image with little depth of field. At a longer working distance the sample will be scanned with a narrow cone of electrons resulting in an image with an increased depth of field (Figure 4.1-8). A longer working distance does not give the optimal resolution (see above). If a sample with large topographical variation needs to be scanned it may be important to use a longer working distance to bring as much of the image into focus as possible; however, some of the resolution will be lost. If a relative flat sample is scanned it is possible to benefit from a better resolution using a shorter working distance since depth of field becomes less important. Depending on the sample and the contained features, a correct balance between working distance and depth of field needs to be found.

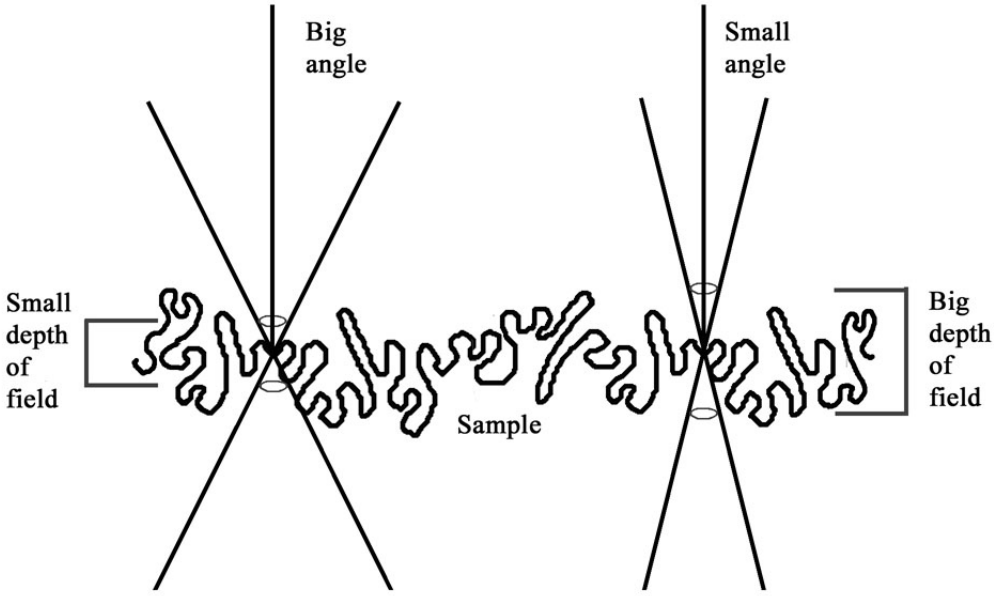


Figure 4.1-8: At a short working distance little of your sample appears to be in focus (A). At a long working distance, more of your sample appears to be in focus because of a greater depth of field (B) [4-9]

- Area of application
  - The components are very small and air resistance could make an obstruction
  - The air gaps must be avoided
  - The vacuum under assembled system must be obtained
  - The dust dimension is the same or larger then the micro components

Example of devices that have to be assembled in the vacuum:
- Field emitter arrays (Oxidation of Molybdenum Thin Films and Its Impact on Molybdenum Field Emitter Arrays printer)

4.1.2 Further trends

Environmental SEM (ESEM) is especially useful for non-metallic and biological materials because coating with carbon or gold is not necessary. Plastics and elastomers can be routinely examined, so as biological samples. Coating might reduce the value of the results obtained. For example very small details on the surface of the sample may be concealed by the coating, let alone that coating is done under vacuum, which drastically alters hydrated specimens. Problems of static build-up in non-metallic specimens are entirely removed by using environmental SEM. The internal pressure can be controlled within fine limits, and the gas used can be varied according to need. Working with the method is easier because the sample chamber is very large, and control is usually completely computer controlled. Coating is thus unnecessary, and X-ray analysis unhindered. Sample manipulation within the specimen chamber is always more difficult than in optical microscopy, however, and colour rendition is absent.
The first commercial development of the Environmental SEM (ESEM) in the late 1980s allowed samples to be observed in low-pressure gaseous environments (e.g. 1-50 Torr) and high relative humidity (up to 100%). This was made possible by the development of a secondary-electron detector capable of operating in the presence of water vapour and by the

use of pressure-limiting apertures with differential pumping in the path of the electron beam to separate the vacuum regions around the gun and lenses from the sample chamber. [4-11][4-12] [4-13] [4-14] [4-15] [4-16]

Novel SEM (FEI) Phenom work at low vacuum, while electron beam is being at high vacuum, so that the components those are not electrically conductive can be observed. Time required to evacuate the chamber is only 30 seconds. There is a touchscreen and all parameters can be adjusted automatically. [4-17]

4.2 Optical microscope imaging

Optical microscope has been used since 17th century for different applications, f.e. inspection of the living cells or quality control in semiconductor device fabrication. Although in resolution inferior to SEM, it is still oft used for manual assembly of micro motor or diode laser. Since it is compact and easy to handle and control, it is an integral part of different processing and test machines.

- The main advantages of the light microscope:
  - maintenance-free
  - low price
  - suitable for the magnification of living cells
  - no sample preparation
  - all methods of micro joining (processes with evaporating or outgassing are allowed)
  - set up changing is not time-consuming
- Disadvantages:
  - short working distance
  - small depth of field
  - low magnifications

4.2.1 Fundamental terms

- Resolution

Resolution is defined as the smallest distance at which two objects can be apart from one another and still be recognized as being separate objects. The very best of today's light microscopes offer a resolving power of about 0.2 m. This is about 500 times better than with the unaided human eye. [4-7]

The resolving power of the light microscope depends upon two factors:

- The absolute limit to resolution imposed by the wavelength of the light illuminating the specimen. No instrument which forms its image by wave interference can resolve detail which is smaller than about half the wavelength of the wave energy (light in the case of the microscope) is being used to examine the specimen. This is as true of the acoustic and the electron microscope as it is of the light microscope.
- The Numerical Aperture (N.A.) of the objective in use. Numerical aperture (NA) of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light. NA is important because it indicates the

resolving power of a lens. The size of the finest detail that can be resolved is proportional to λ/NA, where λ is the wavelength of the light. A lens with a larger numerical aperture will be able to visualize finer details than a lens with a smaller numerical aperture. Lenses with larger numerical apertures also collect more light and will generally provide a brighter image.

Resolution in a perfect optical system can be described mathematically by Abbe's equation.

$$d = \frac{0.612 * \lambda}{n \sin \alpha}$$

where:

d = resolution
λ = wavelength of imaging radiation
n = index of refraction of medium between point source and lens, relative to free space
α = half the angle of the cone of light from specimen plane accepted by the objective (half aperture angle in radians)
n sin a is often expressed as NA (numerical aperture)

The medium is usually air with a refraction index of n = 1. Angle α can never be bigger than 90° and thus the numerical aperture can never outgrow 1. Its largest actual size is 0.95, since the distance between objective and the surface of the cover glass cannot reach zero. The aperture of 0.95 corresponds to an angle α of roughly 72°. An increase of the numerical aperture can be achieved by the choice of a medium between objective and object with an index of refraction bigger than that of air. Special oil for immersion with an index of n = 1.515 has proved to be useful. Larger indexes of refraction do not make sense, because the index of refraction of the objective itself (n = 1.525) becomes limiting. Immersion oil can be used only with specially constructed immersion objectives. If α has the maximum of 67.5°, the aperture is accordingly 1.515 x 0.92 = 1.40. The degree of resolution (d) is set by the wavelength of light (λ) and the numerical aperture (A_{obj}):

$$d = \lambda / A_{obj}$$

If λ = 550 nm (green light) the formula runs the following way:

$$d = 550 \text{ [nm]} / 2 \text{ x } 1.40 = 200 \text{ nm} = 0.2 \text{ µm}$$

It means, 0.2 µm is the highest theoretical resolution that can be reached with a light microscope. A rough approximation shows that the power of resolution of a light microscope lies at about half the length of a light wave if a good immersion objective is used.

Using ultra-violet light is an expensive but increasingly popular approach to sub-micron microscopy. If the limit of resolution of a microscope is known, then the maximal useful magnification can be calculated. A magnification is called useful when two only just clear points are magnified so strongly that they are seen as separate unities by the human eye. At 250mm is the resolution of the human eye about 0.15 - 0.2 mm. The rule of thumb for a useful magnification is thus:

$$500 - 1000 \text{ x } A_{obj.}$$

Resolution is restricted by the wavelength of the power source in light microscopy; this is the wavelength of visible light between 400 and 700 nm. Different light emitting diodes that give almost monochromatic light can be used for illumination; using the blue light, the optical resolution of the system is to 0.8 μm. Electrons have a much shorter wavelength of about 0.005 nm and the scanning electron microscope is superior to the light microscope. [4-18][4-19] [4-20] [4-21]

- Area of application
  - The components are not very small and air resistance could not make an obstructiont
  - The materials, which are not suitable in vacuum, has to be used
  - The methods, that are not feasible in the SEM chamber, must be applied(gluing, soldering)
  - The assembly processes require many steps, what in SEM means a lot of „pump-vent" cycles

4.2.2 Further trends

The **Adaptive Scanning Optical Microscope** combines a custom designed scanner lens, high speed steering mirror, and MEMS deformable mirror to offer the advantages of a greatly expanded field of view, rapid image acquisition, and no agitation to the workspace or specimen. The ASOM concept serves as a crucial step towards realizing a fully operational and high performance ASOM to enable the observation of micro-robotic activities over a large workspace. [4-22]

Near Field Scanning Optical Microscopy (NSOM/SNOM) is a microscopic technique for nanostructure investigation that breaks the far field resolution limit. In the early 1870s, Ernst Abbe formulated a rigorous criterion for being able to resolve two objects in a light microscope:

$$d > \lambda / (2\sin\theta),$$

where d = the distance between the two objects, λ = the wavelength of the incident light, and 2θ = the angle through which the light is collected. According to this equation, the best resolution achievable with optical light is about 200 nm.

With the introduction of NSOM (near-field scanning optical microscopy, also known as SNOM, scanning near-field optical microscopy), this limitation no longer exists, and optical resolution of < 50 nm can be achieved. Light passes through a sub-wavelength diameter aperture and illuminates a sample that is placed within its near field, at a distance much less than the wavelength of the light. The resolution achieved is far better than that which conventional optical microscopes can attain. [4-23]
Improvement the performance of optical microscope can be achieved using confocale microscope. At present, the most efficient are laser scanning microscope, which have focussed laser beam (laser is focussed through the objective in a small point on the sample. Reflected light are detected and light information (a point tht control the display) is got. Confocal means that only the region of sample that is in focus is detected. By scanning the different focus levels, the real 3D image is obtained. Observation of processes with this method has not been done yet. [4-1]

4.3 Micro manipulation procedure

4.3.1 Manipulation of the micro disc and a micro gear

- The assembly task

The assembly task is to pick up the micro gear, inside diameter of a 350 μm, made of plastic, from the holder surface, insert it into a hole of the specimen holder and pick up the micro disc, inside diameter of a 500 μm, made of aluminium and put it onto the micro gear. The assembly process consists of following steps:

- Pick up a micro gear from a specimen holder
- Place a micro gear into the hole
- Pick up a micro disc of a specimen holder and place it onto the micro gear

The micro-assembly system consists of an x-y-z positioning table with two micro manipulators or one micro manipulator and a helping hand; it can be equipped with different micro grippers. The positioning accuracy of the micro-assembly system is 2 μm.

4.3.1.1 Micro components preparation

- The preparation procedure under a optical microscope includes dry blowing in order to remove dust
- The preparation procedure in the chamber of a SEM is as follows:
  - Sputtering with the gold the micro gear which is not electrically conductive.
  - Cleaning both of the components; this is very important step because each impurity disturbs the image generation and its quality due to the electric charge accumulated on these surfaces. Therefore, the components are firstly immersed into the acetone and afterwards in isopropanol.

4.3.1.2 Positioning the components

- Under optical microscope (OM)

The mechanical tweezers is not the best solution for micro manipulation; there is a high risk that the components jump out. Vacuum tweezers represents the better alternative.
During the assembly process, it is thoroughly feasible make the change of the position the components; it is not time consuming.

- In the chamber of a SEM

The micro components are positioned on the microscope stage, i.e. specimen holder; a very careful and quick handling with gloves is necessary in order to avoi contamination of the micro componenets. During the positioning the components must be protected from dirtiness (dust, fingerprint etc.). Every dirty section means target for electrostatic charging that influences both the image quality and the assembly process itself (charged components attract or retract each other and make the manipulation more difficult).
Changing the position of the components, after closing and evacuating the chamber is now time consuming and the assembly flow must be well considered.

4.3.1.3 Operation flow

- Under OM

The process can be observed through the lenses and by the camera on the monitor. There is problem with adhesion, especially when releasing the micro disc. The adhesion arises from primarily from capillary forces. Humidity is in principal larger than in the SEM chamber, since the vacuum is inside. With increasing humidity, the adhesive forces grow up and the releasing of the picked micro components becomes more complicated. When the air is dry, the conditions for the assembly are improved.

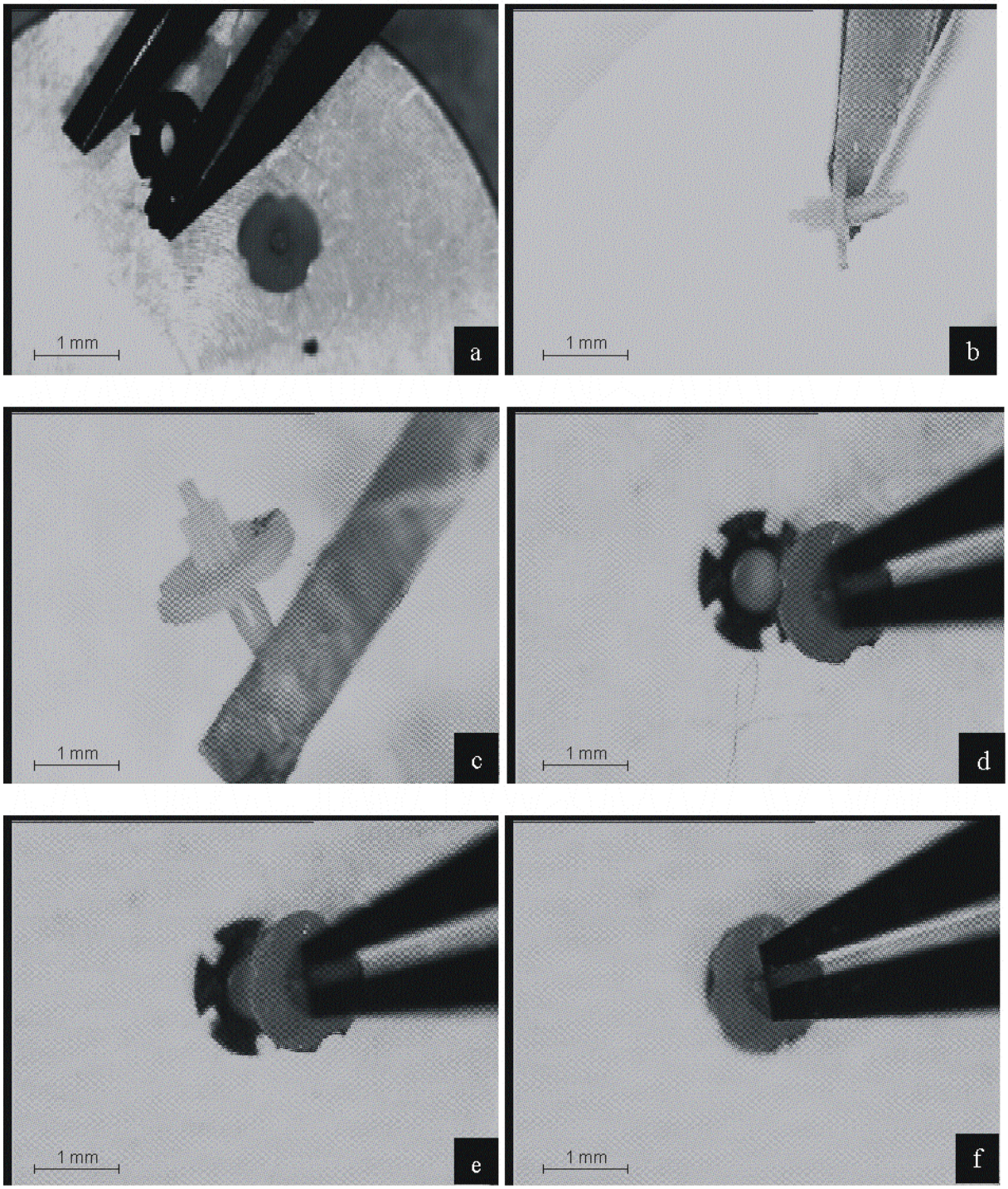


Figure 4.3-1: Micro manipulation under an optical microscope: a)pick up of the micro disc, b)pick up of the micro gear, c) micro gear adheres to the micro gripper; d), e), f) pick up and placing of the micro gear

The images (Figure 4.3-1) show the adhering of the components and the assembly process stepwise.

- In the SEM Chamber

After positioning, the chamber is evacuated, the electron beam is activated, the image is set and the assembly process begins, Figure 4.3 2.
Due to the electron beam, the electrostatic force is significantly greater in the SEM chamber than under the OM. Adhesive forces play a great role, especially the electrostatic force. There

are no capillary forces in vacuum and the adhesion has to be less than in the air, except for contaminated micro components.

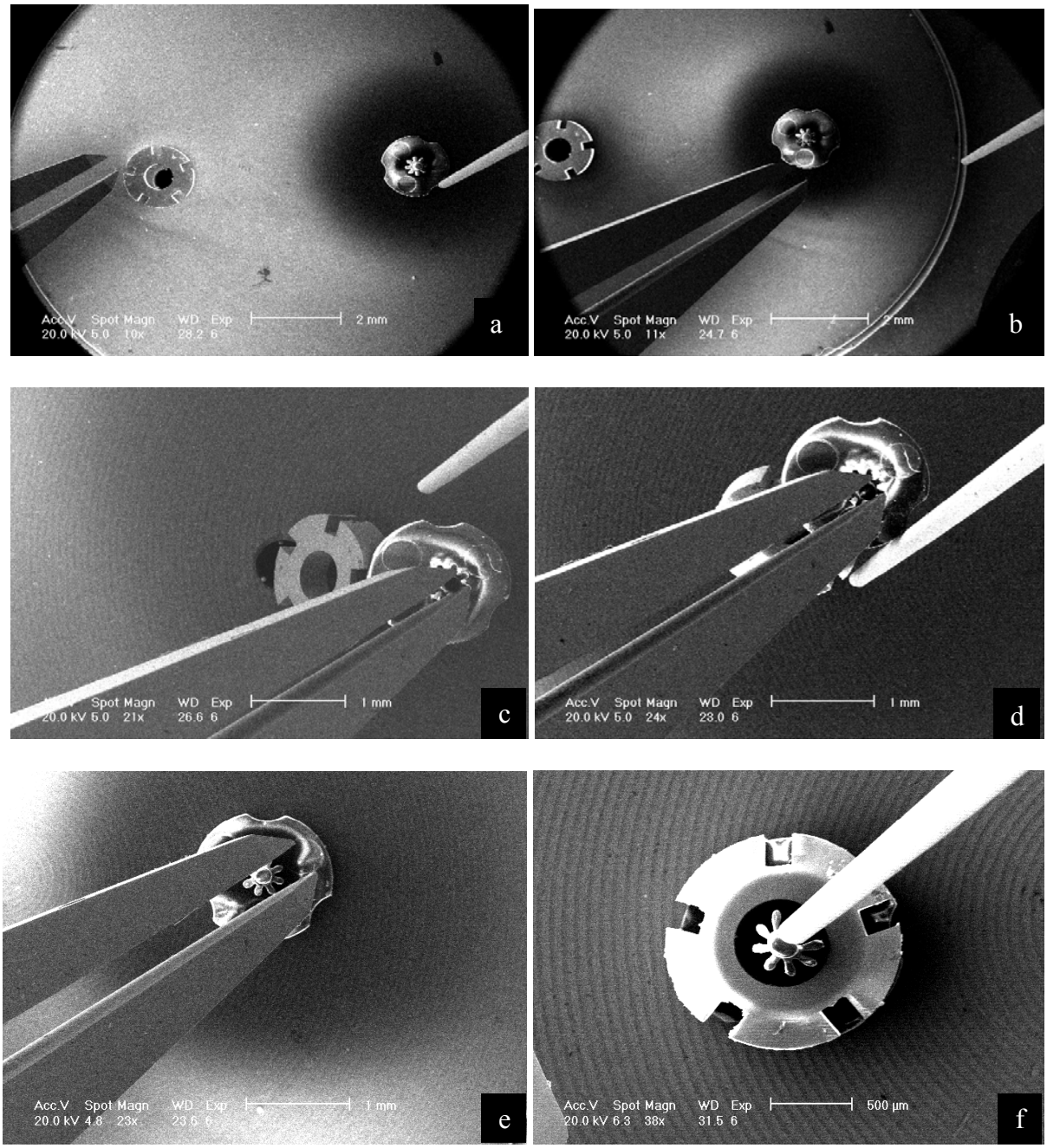


Figure 4.3-2: Micro manipulation in a SEM chamber: a) placing of the micro disc, b)pick up of the micro gear; c),d) micro gear adheres to the micro gripper; e),f)- system assembled

When the components adhere, as the images show (Figure 4.3-2), we can use the other micro gripper to help releasing.

4.3.2.7 Connecting the component

- Under OM

Generally, any joining process is possible, but the working distance is limited.

- In the SEM chamber

Many processes can not be carried out:

  - gluing (except special low outgassing adhesive),

- cell manipulation,
- magnetically processes or
- processes with evaporation

4.4 Technical evaluation

Figure 4.4-1 shows how to find the suitable microscope concerning each element of manipulation process – micro component, micro tools, environment, and assembly flow.

		Electron microscope		Optical microscope	
Microscope type		Scanning electron microscope SEM	Environmental scanning electron microscope ESEM	Optical microscope (Optical microscope in clean room)	Adaptive scanning optical microscope
Suitability	Optimal if	•Micro component size <50 µm •Micro component material –electrically conductive – non-magnetic – non-evaporable •Vacuum required •Aspect ratio small •Micro component form-no sharp tips •Large working distance	•Micro component material -evaporable - non-conductive	•Micro component size >50 µm •Micro component material –non conductive –magnetic –evaporable •Aspect ratio small •Dust-free atmosphere	•Micro component size <50 µm
	Not optimal if	•Micro component material magnetic •Evaporable		•Vacuum required •Large working distance	

Figure 4.4-1: Microscope selection

When evaluating micro assembly and manipulation process in the chamber of a scanning electron microscope and under the optical microscope, the next criteria must be considered:

- efficiency
- complexity
- reliability
- functionality
- technical feasibility
- design
- maintenance
- improvement cappabilities
- quality
- implementation
- development and support
- interoperability
- automation possibility
- portability
- equipment and facilities

4.5 Economical evaluation

In Figure 4.5-1 is reported the price per hour for both of the optical microscope and scanning electron microscope.
Considering an average use of SEM per year (based on lab-notebook), there are about 50 effective working hours per month. The total costs per working hour are 48, 67 €, the price of a new SEM was 248201 €.
Since the amortization time was 15 years, the purchase decision was well-founded.
The purchase is reasonable, if the performed tasks require use of a SEM due to its high resolution, working distanc, etc., see 4.1 and 4.2.

		unit	Optical Microscope **Olympus SZX 9**	Scanning Electron Microscope **Philips XL 40**
	Fix costs			
1	Price including Instalation	Eu	5000,00	248201,00
2	personal education costs	Eu	500,00	2000,00
3	**Fix costs summary(1+2):**	Eu	**5500,00**	**250201,00**
4	amortization period	years	15,00	15,00
5	amortization period	months	180,00	180,00
6	**Fix costs per month (3/5):**	Eu	**30,56**	**1390,01**
	Running costs			
7	required labor space	m2	4,00	15,00
8	price (rent per month per m2)	Eu	14,00	14,00
9	additional labor costs (special equipment - nitrogen supply), price per month,	Eu	0,00	250,00
10	labor costs (5*6+7)		56,00	460,00
11	service and maintenance interval	months	12,00	12,00
12	service and maintenance price	Eu	600,00	7000,00
13	service and maintenance price per month (10/9)	Eu	50,00	583,33
14	**Running costs summary per month (10+13):**	Eu	**106,00**	**1043,33**
15	**Summary costs per month (6+14):**	Eu	**136,56**	**2433,34**
16	effective working hours per month		50,00	50,00
17	**Total costs per working hour:**	Eu	**2,73**	**48,67**

Figure 4.5-1: Microscopes price comparison

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Chapter 5. A novel protective cover for the assembly of micro components in the chamber of the scanning electron microscope (SEM)

5.1 Introduction

Assembly of micro components can be realized under the optical microscope but in a SEM chamber. The assembly in the SEM chamber has its application in cases where a great resolution(ability of a microscope to distinguish between two objects, depends from the wavelength of the energy source that is used for specimen image) depth of field(area in front of and behind a focused subject in which the image appears sharp) as well as large working distance (distance from the front lens element of the objective to the closest surface of the specimen surface when the specimen is in sharp focus) is needed.
Nevertheless, there are a lot of restrictions concerning manipulation of micro components, its positioning and orientation in the given system. We mention only some of them: an evacuation decelerates the work and complicates it, samples preparation (drying, sputtering) takes time and many processes are not allowed: gluing (except special low outgasing adhesive), cell manipulation, magnetically processes or processes with evaporation (which are allowed only in environmental SEM). Further difficulties by assembling of the micro components, both in SEM and under the optical microscope, are the absence of the adequate standard tools for manipulation as well as the phenomena occurring in the range μm and nm in general. [5-1]
The presented system is standardized and can be mounted without additional time, modification or expenses into the SEM chamber. It enables, on the one hand, easier manipulation of the micro components that do not need to be glued on the specimen holder and, on the other hand, introduces further automation in the manipulation process in the SEM chamber since it creates thus a necessary basis for modular assembling system.
Furthermore, it is very important for the automated assembly process that the micro components are exactly positioned. The standardisation in the micro world becomes more and more essential. The uniformity of micro components, operations and tools strongly supports an automatic assembly system. The application of the novel protective cover is conceivable in all devices that evacuate the air from the working chamber, f.e. sputter machine.

It is well known that the vacuum pumps, especially turbo one, which evacuated a SEM chamber, are highly sensitive to foreign object damage. This is the one of the reason why the micro components are glued on the specimen holder in the SEM chamber. On the other hand, the micro grippers that have to pick, lift and place the micro components in a desired system (position, orientation) are very fragile. They can not overcome the adhesive force of the glue and remove the particle from the specimen holder.

During evacuation of the SEM chamber and, particularly in the beginning of the process, it is possible that the micro components which have to be manipulated will be sucked into the pump, due to the produced air stream. This possibility increases as the size of the micro components decreases. Furthermore, the occurring van der Waal's force is stronger in the case of more polished micro components due to adhesion. This means that manipulations with the micro gripper are more complicated. Therefore this phenomenon has to be prevented since it is highly undesirable.

5.2 System overview

The novel system is presented in Figure 5.2-1 and consists of three units:
The novel cover plate (1) with dimensional adjusted perforations: the design of the plate enables the user to open some specimen holders while others remain covered. With an allocation, an optimum cover without using repeating “vent-pump” procedure of SEM is provided.
The platform (2) made in the TU Vienna is dimension-compatible with any SEM. The specimen holders have different shape (grooves, holes or smooth), so that different specimen secures the appropriate position. The material is aluminum, diameter of 65, 5 mm, thickness of 14 mm.
The holder system (3): makes the perforated cover plate irremovable in relation to the rotating platform. Therefore the same specimen holder can be either covered or opened. When the platform moves in x, y or z direction, the whole system moves as well since everything is fastened on the same stage in the SEM chamber.
Assembly of the entire system is shown in Figure 5.2-2.

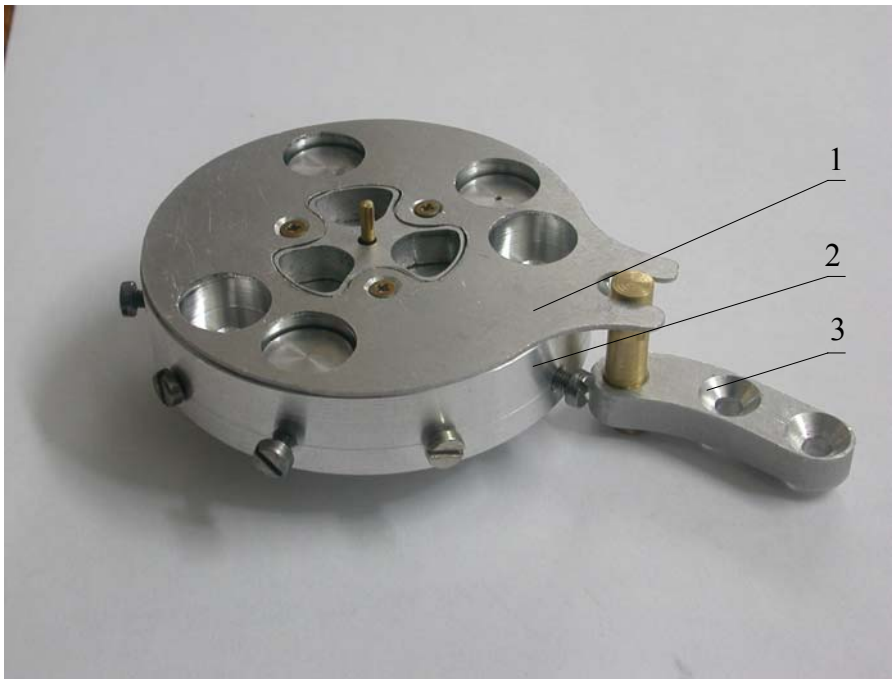

Figure 5.2-1: The novel protective system

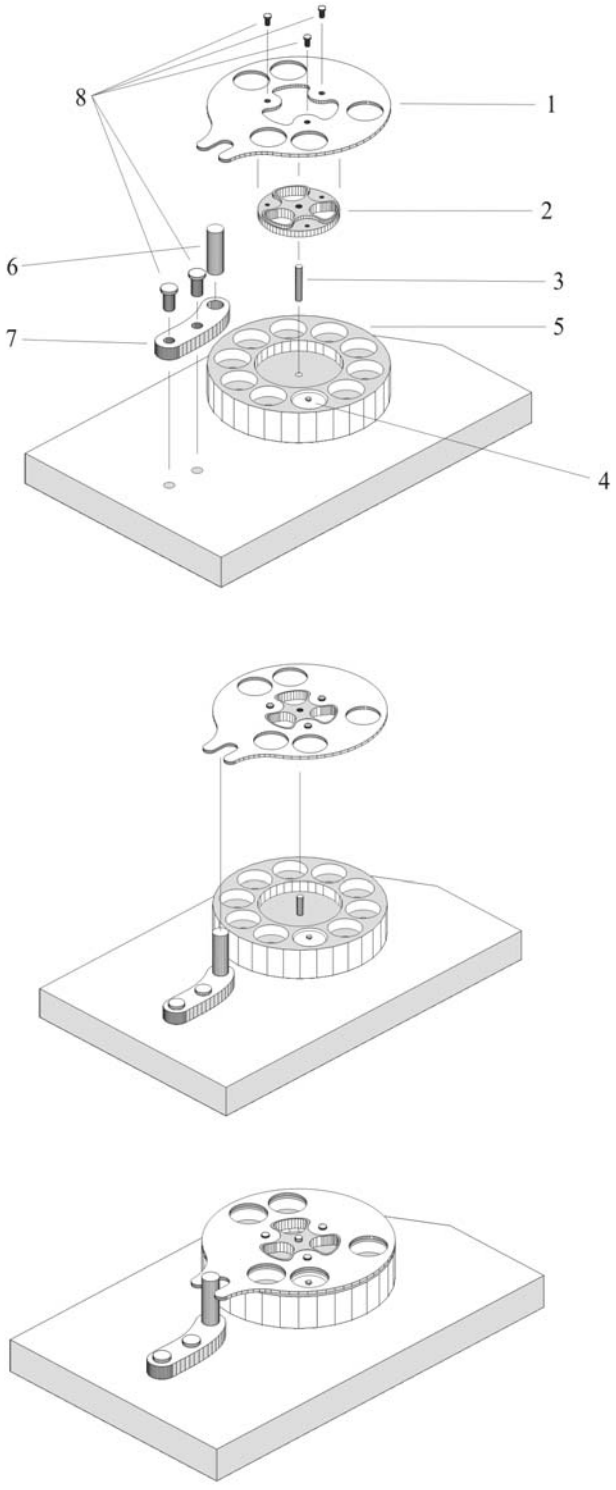

Figure 5.2-2: The novel protective system: assembly

5.3 Working principle

The system operates as follows:
First, the micro components are placed on the specimen holder that will be covered with the cover plate. The cover plate is screwed (fixed) in the middle together to the platform.
After the SEM chamber is evacuated, the cover opens by rotation of the platform below it.

Then, the micro components covered will be exposed to the electron beam, and can be picked up. All assembly tasks on any other specimen holder are then performed accordingly to the a.m. procedure. Opening the cover is shown in Figure 5.3-1, a 15 µm Al wire is positioned under the cover.

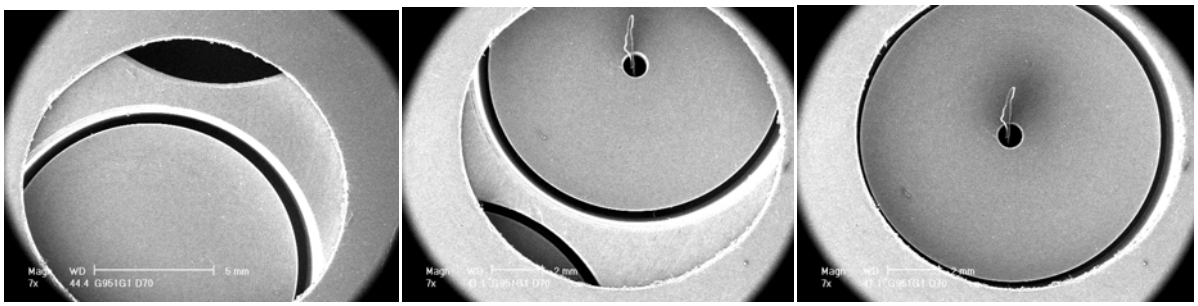

Figure 5.3-1: Moving the protective cover

Since it is highly challenging to analytically determine when or even whether the components will be sucked, a comparison with and without the protective cover, was examined.

5.4 Efficiency analysis: Case 1 – SEM chamber without protective cover

In general, the danger for the micro component to be sucked is greater if the air stream velocity v_1 is very high. The velocity v_1 is exactly determined by the velocity v_0.
Velocity v_0 is the velocity of the air stream caused by pumping. Pumping is determined by the flow rate through the vacuum pump, or - even better - by the dynamics of the pressure loss at the connection point between the chamber and the vacuum pump. (See Figure 5.4-1) First step is to define pressure behavior on that point. The equivalent electric circuit is shown in Figure 5.4-2 [5-2], [5-3] B_1 and B_2 are the atmosphere and the vacuum pump, respectively. The capacitor C_1 represents the chamber; the resistor R_1 is the resistance to air streaming through the pipe that is led from the chamber to the pump (proportional to the pipe length and inversely proportional to its cross-section). The batteryB_2 is the vacuum pump and the tension in point K is the pressure at the exit of the chamber. The switch p represents the door of the SEM chamber.

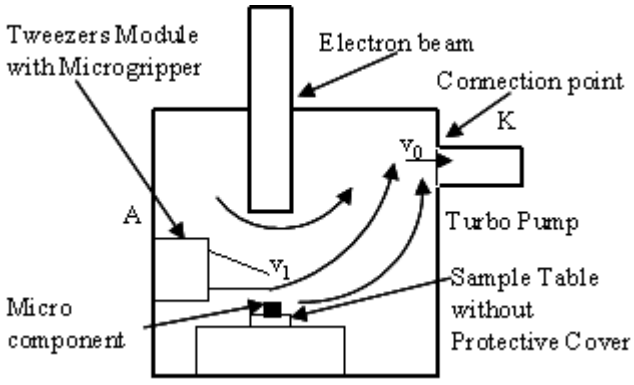

Figure 5.4-1: Chamber without protective cover

When the p is closed, the door of the chamber is open and the pressure in the chamber is equal to the atmospheric pressure ($u_k = u_a$). When the p is opened, the chamber door is closed (no contact between the chamber and the external environment) and evacuation starts. Precisely this moment is interesting to begin the analysis of the system. [5-4]

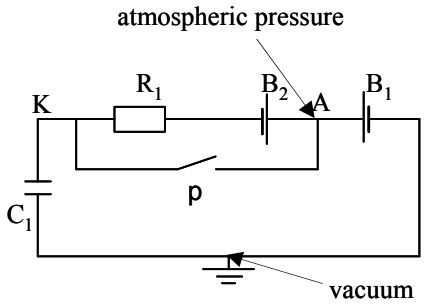

Figure5.4-2: Chamber without protective cover: equivalent schema

Analysis:

$$u_k(t) + R\, i_{c1} = 0,\ u_k \text{ - tension at point K}$$

$$i_{c1} = C_1 \frac{du_k}{dt},\ i_{c1} - \text{current at point K}$$

$$u_k(t) + R_1 C_1 \frac{du_k}{dt} = 0$$

$$u_k(t) = -R_1 C_1 \frac{du_k}{dt}$$

$$-\frac{1}{R_1 C_1}\int_0^t dt = \int_{u_k(t=0)}^{u_k(t)} \frac{du_k}{u_k}$$

$$e^{-\frac{t}{R_1 C_1}} = \frac{u_k(t)}{u_k(t=0)}$$

$$u_k(t) = u_k(t=0)\, e^{-\frac{t}{R_1 C_1}}$$

$$\frac{du_k(t)}{dt} = -\frac{1}{R_1 C_1} u_k(t=0)\, e^{-\frac{t}{R_1 C_1}}$$

$$v_1 \leftrightarrow v_0 \sim -\frac{\partial p}{\partial t} = \frac{1}{R_1 C_1} U_a\, e^{-\frac{t}{R_1 C_1}} \qquad (1)$$

Judging from Eq.1, where for t=0 → exp=1, it is concluded that the possibility for the micro components to be sucked in is maximum at the beginning of the evacuation process when the air flow rate is a maximum. While analyzing the following approximations are made:

1. The air stream through the door of the SEM chamber is neglected.
2. Air cooling due to expansion is not considered.
3. The vacuum pump is ideal, there is no air drain and for $t=\infty$ the vacuum in the chamber could be absolute.

Since C_1 is constant, it is obvious that the risk of components suction would decrease with increasing resistance R_1 (by decreasing the pipe cross-section or by its lengthen), but the evacuation time would be unacceptably increased since it makes the work too slow.

5.5 Efficiency analysis: Case 2 – SEM chamber with protective cover

In Figure 5.5-1 is showed a schematic of a SEM chamber with a protective system. It is important to mention that the covering plate must not be hermetically sealed on the platform, because in that case it would cause rapid pressure changes which could suck in the micro components or disturb the stability of the electron beam, when the cover opens

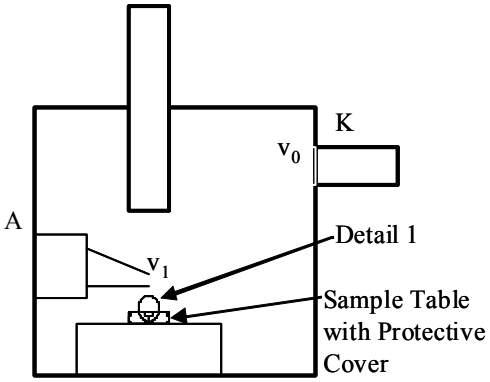

Figure 5.5-1: SEM chamber with protective cover

The system "cover plate-platform" has predefined tolerances thus preventing rapid pressure changes which could suck off the micro components or disturb the stability of the electron beam, see Figure 5.5-2.

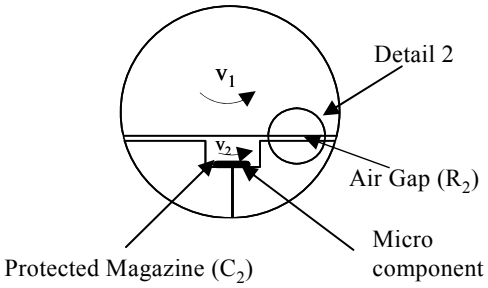

Figure 5.5-2: Detail 1 protected specimen holder

The capacitor C_2 represents the protected (covered) section; the resistor R_2 represents the resistance to air stream through the channel that leads from the protected magazine to the chamber (proportional to the channel length and inversely proportional to its cross-section), see Figure 5.5-3.

Because the channel that connects the protective magazine is very narrow, the resistance to the air stream is very high; i. e. the current through the resistor R_2 will be low, so that the capacitor C_1 will discharge faster than the capacitor C_2. That means that the derivation of the air pressure in response to time will be quicker in the SEM chamber than in the protected magazine and automatically it will be a rate of air stream through the magazine slower than in the SEM chamber.

It is observed that in this case the danger of the micro components to be sucked in is less and therefore the air stream is faster than in the case where the protective cover is not present.

When the chamber is evacuated (vacuum is established), no air stream exist so far and the cover can be opened without exposing the micro components in the danger of being sucked in.

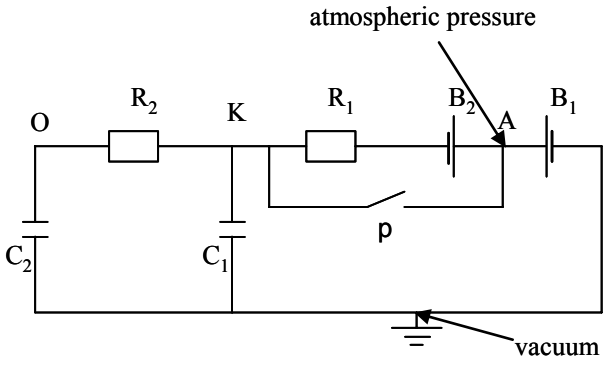

Figure 5.5-3: SEM chamber with protective cover

Analysis:

$$i_{c2} = -C\frac{du_{c2}}{dt}\text{, } i_{c2} - \text{current at point K } u_{c2} \text{ - tension at point K}$$

$$u_{c2}(t) - R_2 i_2 = U_a e^{-\frac{t}{T_1}}\text{, } T_1 = R_1 C_1$$

$$u_{c2}(t) + R_2 C_2 \frac{du_{c2}}{dt} = U_a e^{-\frac{t}{T_1}}$$

U_a - tension at point A (chamber door), atmospheric pressure

$$T_2 \frac{du_{c2}}{dt} = -u_{c2}(t) + U_a e^{-\frac{t}{T_1}}$$

$$u_{c2}(t) = f(t) e^{-\frac{t}{T_2}}\text{, } T_2 = R_2 C_2$$

$$\frac{du_{c2}}{dt} = \frac{df(t)}{dt}e^{-\frac{t}{T_2}} - \frac{1}{T_2}f(t)e^{-\frac{t}{T_2}}$$

$$\frac{df(t)}{dt}e^{-\frac{t}{T_2}} = \frac{1}{T_2} U_a e^{-\frac{t}{T_1}}$$

$$df(t) = \frac{1}{T_2} U_a e^{t(\frac{1}{T_2}-\frac{1}{T_1})}dt$$

$$\int_0^t df(t) = \frac{1}{T_2} U_a \int_0^t e^{t(\frac{1}{T_2}-\frac{1}{T_1})} dt$$

$$f(t) = U_a \frac{T_1}{T_1 - T_2} e^{t(\frac{1}{T_2}-\frac{1}{T_1})} + C$$

$$u_{c2}(t) = (U_a \frac{T_1}{T_1 - T_2} e^{t(\frac{1}{T_2}-\frac{1}{T_1})} + C) e^{-\frac{t}{T_2}}$$

Initial condition: u_{c2} (t=0) = U_a

$$\rightarrow U_a = (U_a \frac{T_1}{T_1 - T_2} + C), \qquad C = -U_a \frac{T_2}{T_1 - T_2}$$

$$u_{c2}(t) = U_a \left(\frac{T_1}{T_1 - T_{2)}} e^{-\frac{t}{T_1}} - \frac{T_2}{T_1 - T_2} e^{-\frac{t}{T_2}}\right) \tag{2}$$

The gap between the surface edge of the protective cover plate and the platform is defined by the surface quality. The smaller the micro component is, the flatter (smoother) surface edge is necessary. The surface roughness corresponds to the micro components dimensions. It is possible to make different covering plates with different surface quality for different dimensions of micro components, see Figure 5.5-4.

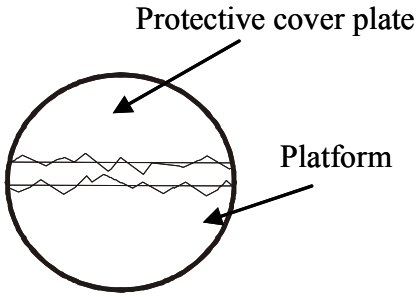

Figure 5.5-4: Detail 2 Air gap between protective cover plate and platform in relation to surface quality

5.6 Graphical comparison between Case 1 and Case 2

The pressure which could suck in the micro component is considerably lower when the micro component is in the chamber without the protective cover, particularly in the beginning, which causes more chances for suction of the micro component. The pressure decreases in the chamber faster than in the protective magazine, towards equations (1) and (2). Figure 5.6-1 shows pressure change in the SEM chamber with and without protective cover. It is assumed that the gap width b = 5 µm (cover made by milling) and other measured dimensions length l = 3 mm, specimen holder diameter d = 12, 8 mm, magazine deepness h = 2 mm. There are always five specimen holders exposed (opened) and five covered, in an appropriate way. The chamber dimension is a = 30 cm, the cover diameter D = 65, 5 mm, the pipe diameter d = 100 mm and length L = 2 m. Correlation between the analogical parameter in electric circuit:

$R_1 \leftrightarrow$ Vpipe
$R_2 \leftrightarrow$ Vgap

Vpipe = 15700 mm³
Vgap = 3, 085 mm³
Vpipe / Vgap = 5, 089 103

$C_1 \leftrightarrow$ Vchamber
$C_2 \leftrightarrow$ Vmagazine

Vchamber = a³ = 303 cm³ = 27 106 mm³
Vmagazine = 253, 23 mm³
Vmagazine / Vchamber = 0,105 106

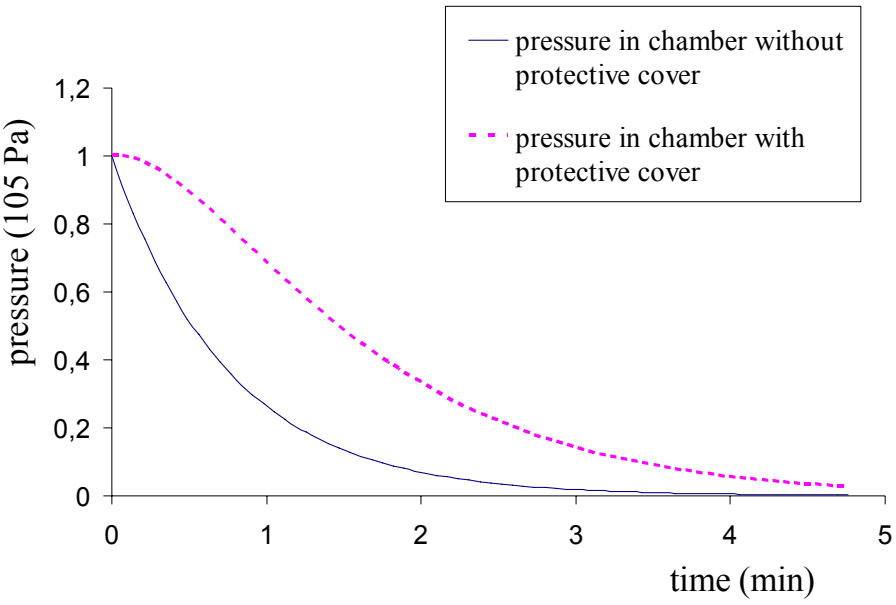

Figure 5.6-1: Comparison between case without protective cover and case with protective cover

5.7 Experimental results

Figure 5.7-1 shows samples, a ferric powder 40-60 µm and a wire Φ = 15 µ on the specimen holder before and after the two "pump-vent" cycles. There is no difference in the position of the objects. There was no specimen being sucked in. This observation confirms the efficiency of the protective cover for this order of magnitude.

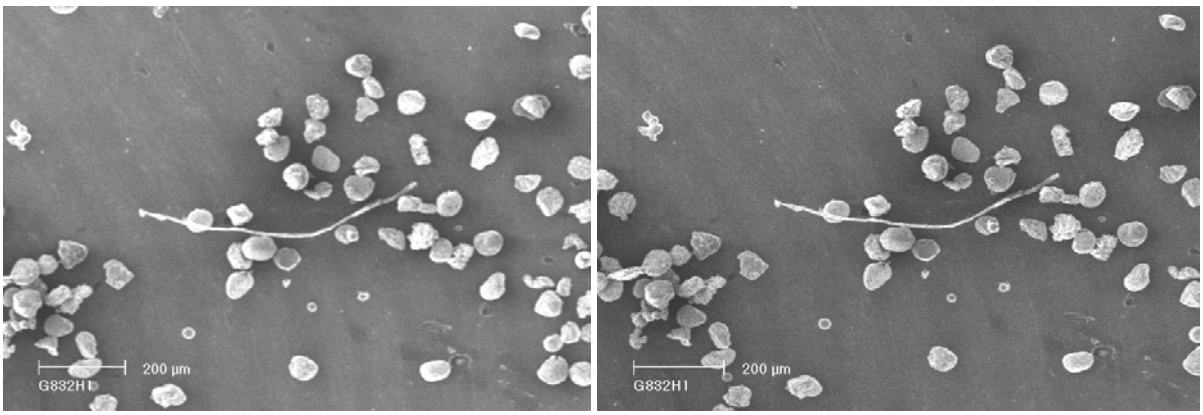

Figure 5.7-1: Before and after exposing

5.8 Algorithm of assembly

Three actuators for the automation of process are used:

- microgripper control, open/ close position
- microgripper control, up/ down position
- specimen holder control, rotation

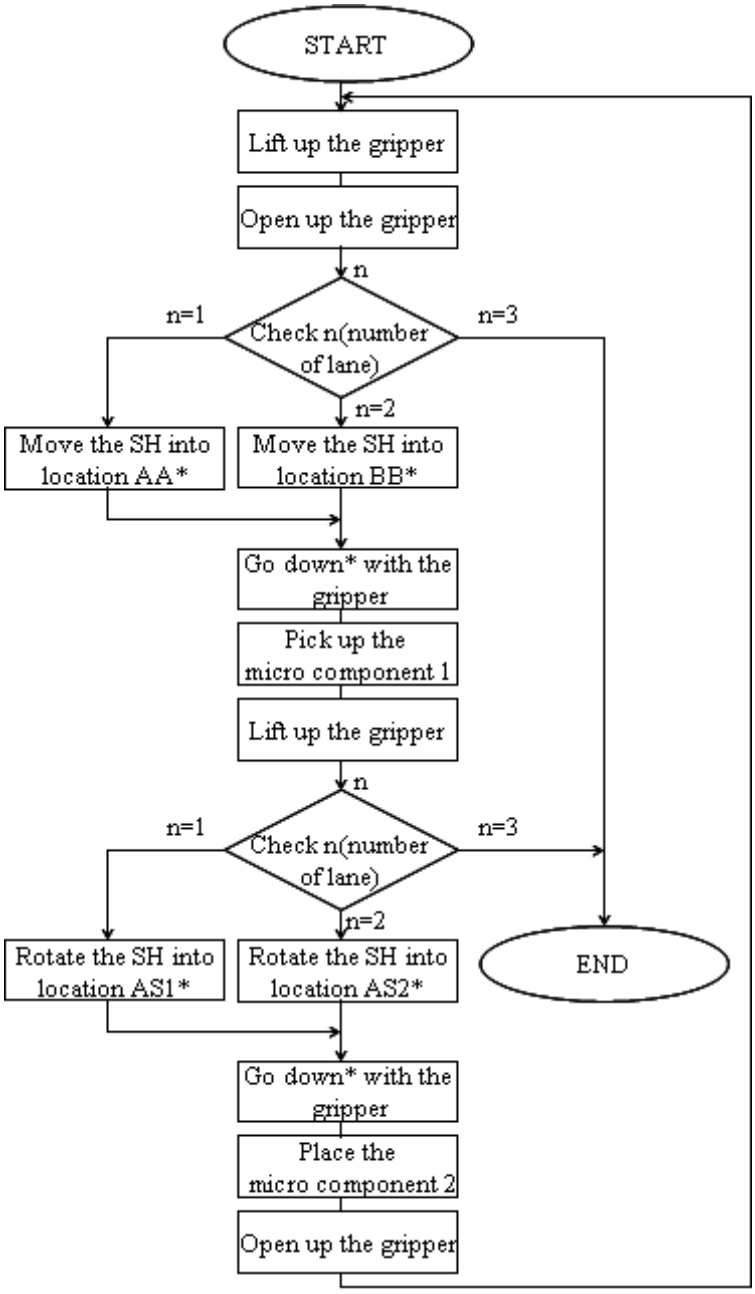

Figure 5.8-1: Assembly algorithm for twp micro components

Figure 5.8-1 describes the working principle for one sequence (one micro assembly process) with two micro components, at which are the characters:

AA*- preadjusted position of micro component 1 on the specimen holder (SH)
BB*- preadjusted position of micro component 2 on the specimen holder (SH)
AS1*- defined position for assembly micro component 1
AS2*- defined position for assembly micro component 2
down*- collision between micro gripper and specimen holder have to be prevented.
SH – specimen holder

[5-5]

5.9 References

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Chapter 6. Design of a novel visual system for collision prevention during the micro handling in a SEM chamber

6.1 Introduction

In order to perform the micro manipulation tasks, a microscope is necessary. During manipulation of the micro components both in the SEM chamber and under the optical microscope, no information is provided about the z-position of the micro gripper in relation to the level of the specimen holders on which the micro components are located. Since this information is essential for gripping and handling the components in the chamber of an SEM, the phenomenon is analyzed and a a novel visual method for monitoring the distance between micro gripper and micro component is developed.

This chapter presents a video system for preventing a collision of the micro gripper and the stage on which the micro component is located during micro manipulation in the chamber of a scanning electron microscope. The system consists of a micro manipulation station, micro camera with magnification lenses and a reflective specimen holder. Special focus is given to the approach procedure of the micro gripper toward the micro component, a sequence that is crucial during a micro manipulation process.

The presented optical system is aimed at controlled manipulating of objects measuring a few tens of micrometers. Manipulation of objects larger than 100 μm does not cause serious problems, since gravitational force is dominant and the manipulation procedure is better understood. Gripping of the nanometer-sized objects demands, however, a different approach as contact manipulation becomes problematic for objects smaller than a few tens of μm. The focus is the micro manipulation procedure in a scanning electron microscope (SEM) environment, but the system is applicable for the work under the optical microscope, too. Micro handling in a SEM is an advantageous procedure in manipulation cases where a dust-free working and vacuum environment (which is important when air gaps must be avoided) with high resolution, large working distance, large depth of field and high magnification are required. However there are a few disadvantages such as the high maintenance costs, need for skilled staff and special prepared samples. Further limitation of monitoring with either SEM or optical microscope arises when information about depth is needed. Horizontal information is obtained by monitoring from above, but vertical information, i.e. distance from micro gripper to micro component, generally cannot be obtained. In order to establish more effective micro handling procedure in the SEM chamber and protect the micro components and micro gripper from collision and damaging, a novel concept is suggested.

It is based on mirror principle and teleoperated visual control of the micro manipulation procedure. The mirror principle means that an image of the micro gripper will appear on the reflective surface so that the relevant information about the distance between micro gripper tips and mirror surface, i.e. micro component, can be obtained. An operator has to know the position of the micro gripper in relation to the micro component in order to successfully perform an assembly process or manipulation step. Teleoperation gives a tremendous quantity of information and a human operator can effortlessly recognize the micro objects, their relation to each other, interpret all relevant dates and define a manipulations task.

Imperative was continuously monitoring of the relationship between the micro gripper and the micro components. Precision in the nanometer range is not required, because immediate prevention of collision is made possible by observing with the camera and the SEM

simultaneously. This includes an optimal cost-performance ratio, what makes commercialization feasible.

The system configuration being presented has been mounted as a module in a conventional SEM, using standard tools, which does not influences its accuracy or proper operation. During micro handling with this system, specific skills are not required and manipulation is simple and safe. By changing the end-effectors and the micro camera, it can easily be adapted to the needs of new applications.

Additionally the presented system operates without disturbing influences on the handling process and can be adapted to any manipulating procedure.

6.2 State of the art

There are several research groups that attempted to solve to the collision problem, because the micro gripper's approaching the micro object makes a key issue for an effective micro manipulation operation.
So far different systems for micro manipulation monitoring have been reported, such as laser triangulation [6-1], stereoscopic depth detection [6-2], autofocus for micro assembly [6-3], concentrated visual fields [6-4], optical vision feedback [6-5], using AFM and STM as sensing devices [6-6] [6-7] [6-8].
Buerkle and Fatikow [6-1] introduced the concept of depth measuring by micro triangulation using a line laser. When the object under the microscope moves, a variation of standard triangulation is used, called sheet of light triangulation. The best accuracy obtainable depends on image processing, microscope magnification, CCS camera resolution and fidelity, and the angle between sheet of light and camera. The main advantage of the system is flexibility regarding the size of the micro object and necessary working area. Some limitations are: the dependency of the object's surface properties, dark and transparent materials have to be coated with a luminescent material, micro gripper vibrations disturbing the signal from the reflection, and deflection in z direction.
Jähnisch and Schiffner [6-2] proposed a stereo algorithm which compares intensity values or their rank values within a small image patch of the two images. By means of two cameras, the third dimension can be calculated by stereoscopic approach; two images from two different perspectives are required and a stereo algorithm to determine the relative depth. After the generation of stereo images (which are needed to calculate the third dimension), suitable algorithms are needed for determining the depth information. Stereoscopic images are generated by tilting the sample concentrically between the two images or tilting the electron beam. The disadvantage of the first method is that the handling station, consisting of the handling object, robot and tools, has to be tilted, which takes several minutes and the risk that the object changes its position is high. The advantage of the second method is the fast image acquisition without any impact on the process. The main problem is the increasing noise level of the images, which has a negative effect on accuracy, particularly for images of technical handling processes, which are different from images of surfaces. Disadvantages are insufficient robustness against shifted and rotated images and of the texture-based filter for nosy images. The calculation time for 256x192 pixel size images is about 1 second.
Allegro et al. [6-3] presented autofocus for automated micro assembly under a microscope; the optical microscope with a CCD camera serves as an optical sensor for the acquisition of 3D information in the μm range, and for visual control of the assembly process. The optimal focus location can be obtained by varying the distance between the microscopic objective and the object, and determining where the object appears sharpest. This method is more applicable for domains of biology and medicine, because there is only one focal plane, and the samples

to be observed are always planar. In micro assembly, neither the griper nor all of the gripping devices are planar, so a technique was developed to determine and distinguish the different focal planes. The resolution of this system is up to 4 μm. A priori knowledge about the shape of the objects and their approximate position along the x, y and z is initially necessary for identification of the focal plane. Special markers are used for identification of the non-planar objects. The main problem is focussing the objects that are not oriented horizontally and objects with continuous features to which a marker cannot be assigned. This autofocus system can measure height in the micrometer range. Further problems: finding the focal plane when the object area is very small in comparison to the background or any other visible object is difficult, and distinguishing focal planes which are too close together. Focusing occurs slowly when done manually, because of limitation with respect to the time for acquiring the images and moving the z-drive of the microscope. However, precision and repeatability are much better.

Koyano und Sato [6-4] used a micro object handling system which consisted of two microscopes (i.e. a SEM observes from above and an optical microscope observes from the side), two manipulators (needle like, tip diameter of 2 μm; and micro griper, tip diameter of 20 μm) and a work table, and proposed new skills crucial for micro manipulation concerning the control of adhesive forces using both manipulators. The dimensions of the system are 300x180x200 mm³. The optical axes of the microscopes coincide in the work space. Solder balls with a diameter 20-30 μm are manipulated. The system is large and cannot be mounted in every SEM.

Sulzmann et al. [6-5] assembled a LIGA micro motor (a rotor, 250 μm in diameter, was mounted on the axis with 2-3 μm of space between the components) using high- resolution camera calibration, a passive auto focus algorithm and 2D-object recognition of the robot's position in order to guide the micro assembly process. However, this concept can be performed under an optical microscope only.

There are different approaches of teleoperated micro manipulation of nanoscale objects, by using AFM (atomic force microscope) and STM (scanning tunnelling microscope). An AFM can be used with all materials; STM is suitable for conducting materials only. An AFM gives topology and interaction data, a STM topology only. For nanoscale-object manipulation, two systems have utilized an AFM or STM with haptic and visual displays: Hollis et al. [6-6] used a STM for tactile feedback, and Taylor et al. [6-7] used an AFM and commercial haptic devices and introduced virtual reality graphics and networked manipulation systems. In the AFM system, mechanical vibration, hysteresis and thermal drift in the piezoelectric positioners, humidity in the air, air flow, acoustic pressure and temperature changes are the main sources disturbance [6-8]. During teleoperation, time delay can be a significant disturbance. The working space is restricted to the maximum expansion of the piezo elements. During micromanipulation under the optical microscope or in the chamber of the SEM, the information about location of the micro tools and micro object in 3D space is necessary. Getting the information should be quickly, precisely, simply and without disturbing influences on the handling process. Since the microscope does not provide measure of the variation in height and gives no indication of the vertically relation between the micro gripper and the object, it is necessary to integrate a monitoring system, i.e. to ensure the visual feedback.

6.3 Collision risk during approaching

In a typical micro assembly situation the main problem is depth estimation. Neither the relationships between the micro components and the micro gripper and the distance between the micro gripper nor the specimen holder are known.

Figure 6.3-1 shows the image when the electron beam is on. Both the relation between the object and the micro gripper and distance between the micro gripper and the holder is not known.

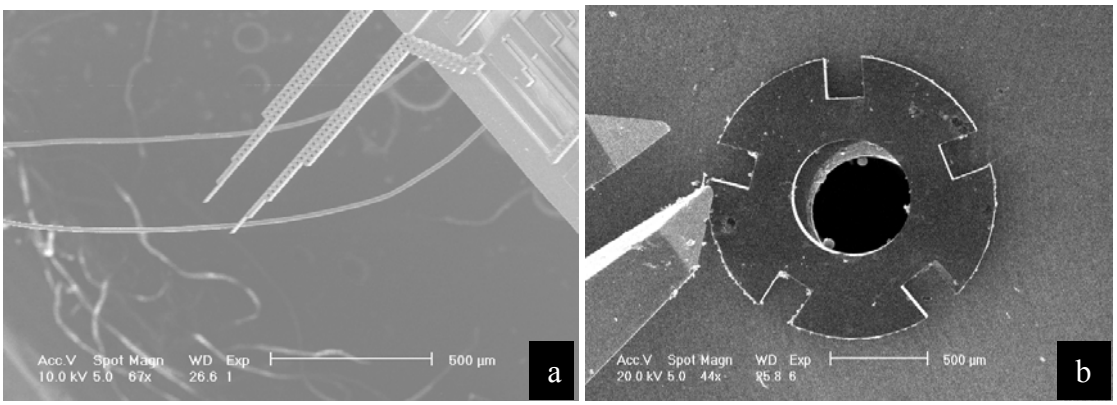

Figure 6.3-1: SEM images: a) Al wire, diameter 15 µm; b) micro disc, radius 250 µm

The operator moves the micro gripper down but has poor information about the vertical distance to the specimen holder. As a result the micro gripper can break after colliding with the stage or specimen holder. The stage with the specimen holders could be tilted to 60°, but it is not sufficient to permit observation of the micro gripper tips' approach and prevent the micro gripper and the specimen holders from colliding. When the micro components are not glued on the specimen tilting is not recommendable, because the components will slip away.

6.4 Analysis and possible solutions

During the micro-handling procedure under the optical microscope or inside the SEM vacuum chamber, it is indispensable to obtain accurate information on the relative position of micro tools and micro object in all tree spatial dimensions. The information should to be obtained quickly, accurately, simply and without any impact on micro handling.

Since it is difficult to obtain information from the microscope with regard to the altitude, the integration of second monitoring system is essential, i.e. to provide visual feedback, more exactly 3D information.

Requirements for successfully integration of the visual system in the SEM chamber are:

- electron beam compatibility
- vacuum compatibility
- small size and weight
- Resolution in the µm range is the essential in the selection of the sensor we could apply for prevent the collision. The resolution is related to the precision with which the measurement is made.
- Contactless working principle is desired because the micro components and the micro gripper are delicate and fragile
- Simply mounting and use must be considered, because in the scanning electron microscope different experiment research taking place. It is necessary that the whole system is simply to install und reinstall every time when required.
- Very short reaction time-high sensitivity is crucial for the sensor in order to prevent the collision

- Since different kinds of micro grippers and specimen holders are being applied for manipulation operations, the sensor should not be integrated either in the micro gripper or in the holder

For application in the system for collision prevention, a sensor and a micro camera have been considered.

6.4.1 Sensor limitation

Several distance sensor principles cannot be employed as their working principles are not valid under the conditions of the chamber of a SEM or they might cause undesirable interactions or phenomena.

- Sensors based on temperature changes as they are too slow.
- Sensors register the change in magnetic or electric signals, or electromagnetic radiation, because this could result in disruption of the electron beam, i.e. lower image quality.
- Sensors that register sound changes, because there is no sound propagation in the vacuum.

Distance sensors with optical working principle (infrared-reflected light or triangulation) may be used to measure distance inside the SEM chamber.

Using linear variable differential transducers (LVDT) in a vacuum environment is possible, but certain factors such as outgassing and heat dissipation need to be addressed, and the main point is that its working principle is not contactless.

A capacitance sensor can be used in the chamber, under an electron beam, since its electrical and magnetic field are weak, but the capacitance is very difficult to register because both the tips of the micro gripper and the dimensions of the micro component are in the μm range. In additional the mounting is problematic.

6.4.2 Micro camera limitation

Several factors must be considered in setting up the multiple-view system. Firstly, due to the limited working distance of the microscope objective, the space between the micro component and the camera objective is quite limited. It is therefore important to avoid collision among the objectives (lenses), micro component and micro manipulator. Secondly, since multiple views with vastly different magnifications are concentrated in this limited space, lighting must be controlled separately.

Integration of the micro camera into micro manipulation system provides a different view to the human operator. Together with the other two views, a vertical view for micro component pickup and a global view of the entire assembly scene, one is well equipped for the challenges of the micro manipulation. Very small cameras or endoscopic systems are really interesting from a size point of view but are today limited to the visualisation (for applications requiring image processing) of more than 500 μm in size components. [6-9]
It is necessary that micro camera fulfils the following demands:

- Vacuum capability
- Additional magnification integrated
- IR sensitivity: In particular, the micro camera has to be IR sensitive because:
- Visible light in the SEM chamber disturbs the function of the detector of the secondary electrons
- Reflectivity of the coated mirror film is excellent for IR light
- Small sized
- Lightweight

6.4.3 Selection

By considering not only above mentioned sensor requirements but also efficiency, time required to purchase, installation and optimisation, in this work is suggested a concept of visual following of manipulations process using the micro camera.
Sensors are essential to perform micromanipulation tasks in teleoperated mode and indispensable for automatic mode. Up to now very few force sensors (compromise between resolution and size) have been developed for micromanipulation needs showing the difficulties of this problematic. [6-9]

Taking into account all the before mentioned conditions, the financial profitability, time of acquisition, assembly, optimization and so on, this dissertation has proposed the concept of visual monitoring of the manipulation process by the means of micro camera, USB, which has its advantages:

- Together with the micrometer scale that provides more precisely determination of griper-object distance, micro camera has been implemented as a system for collision prevention.
- Simple to mount and manipulate since it is compatible with the existing equipment (micro assembly station)
- Easy availability
- Compatible with the conventional SEM chamber
- It is a robust system consisting of only a few parts, making it easier to use
- Maintenance free
- The configuration of the whole system is quickly changeable, depending on the micro assembly process mode (size and number of micro objects, manipulation flow, etc)
- Use of a micro camera instead of an optical sensor (what is the most similar method), offers the opportunity to simultaneously monitor any other movement in the SEM chamber, for example that of a robot.
- Electronic measuring devices are not required for the interpretation of the results
- Applicable under the optical microscope

In combination with the micrometer scale that provides more precisely determination of griper-object distance, micro camera has been implemented as a system for collision prevention. [6-10].
The micro camera is vacuum capable and infrared sensitive so as to enable continuous monitoring of the inside of the chamber. The micro camera utilized is a USB micro camera with infrared sensitivity and a resolution of 640 x480 pixels. Its mass (20 g) and its dimensions of 26 x 22 x 16 mm³ make it suitable for mounting on the micro assembly station. Magnification can vary from 20-40X depending on the micro component's dimension.

6.5 Working principle

The mirror principle means that the micro gripper will reflect completely and accurately on the reflective surface so that the relevant information about distance between micro gripper tips and mirror surface, i.e. micro component can be visual obtained. An operator wants to know the position micro gripper in relation to micro component in order to successfully perform an assembly process or manipulation step.
In order to achieve optimum results, the specimen holders are coated with a conductive, reflective material. The coating material is aluminium; the material must be conductive, in order to avoid the electrostatic charging on the isolated surfaces in the SEM chamber during the images generating. Both the micro gripper's image and its mirror image must to appear in focus.

Figure 6.5-1 and Figure 6.5-2 show the mirror image on the coated specimen holder in the dark with an infrared light source, the condition that dominates in the SEM chamber.

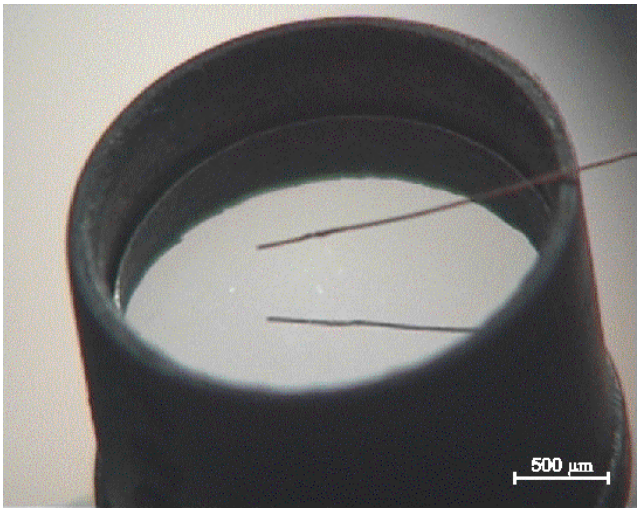

Figure 6.5-1: Wire, 50 µm and its image on the aluminium coated specimen holder

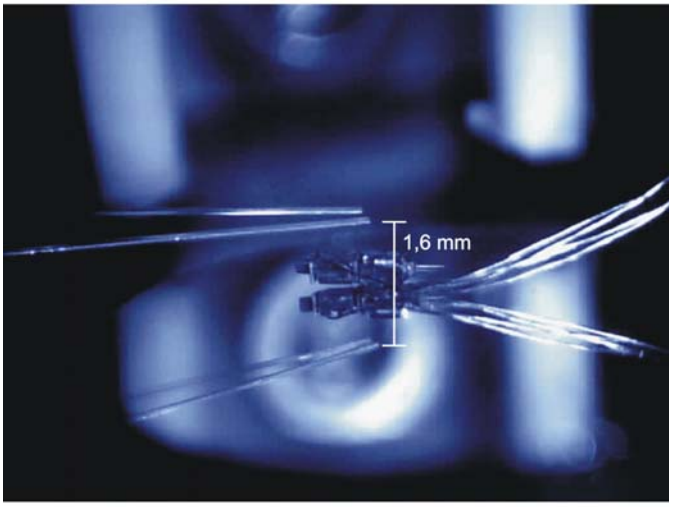

Figure 6.5-2: Mirror effect. Micro gripper and micro object are reflected on the coated specimen holder

Coating of the Si with Al was done in a sputtering machine (Ardenne LS 320S). The first layer is made of Ti (one minute, 100 W, in order to increase the adhesion of the Al layer). The second layer is made of Al (two minutes, 50 W, thickness of about 80 nm). If this deposition procedure is employed, a pure aluminium film is formed, which serves as a good reflector (approximately 92%) of visible light and an excellent reflector (up to 98%) of medium and far infra red. [6-19]
The chosen infra red emitters operate in 950 nm wavelength and provide an optimal working range. The roughness of the mirror surface is about 0, 4 nm.
The micro gripper and micro component are reflected on the specimen holders and one can observe the micro gripper in the mirror as it approaches the micro component.

6.6 Depth of field

The most important requirement for the camera's position is reaching a compromise between magnification and depth of field. Both the micro gripper's image and its mirror image must appear in focus.
The system's design is shown in Figure 6.6-1. It is not proportional, so that the whole system can be shown.

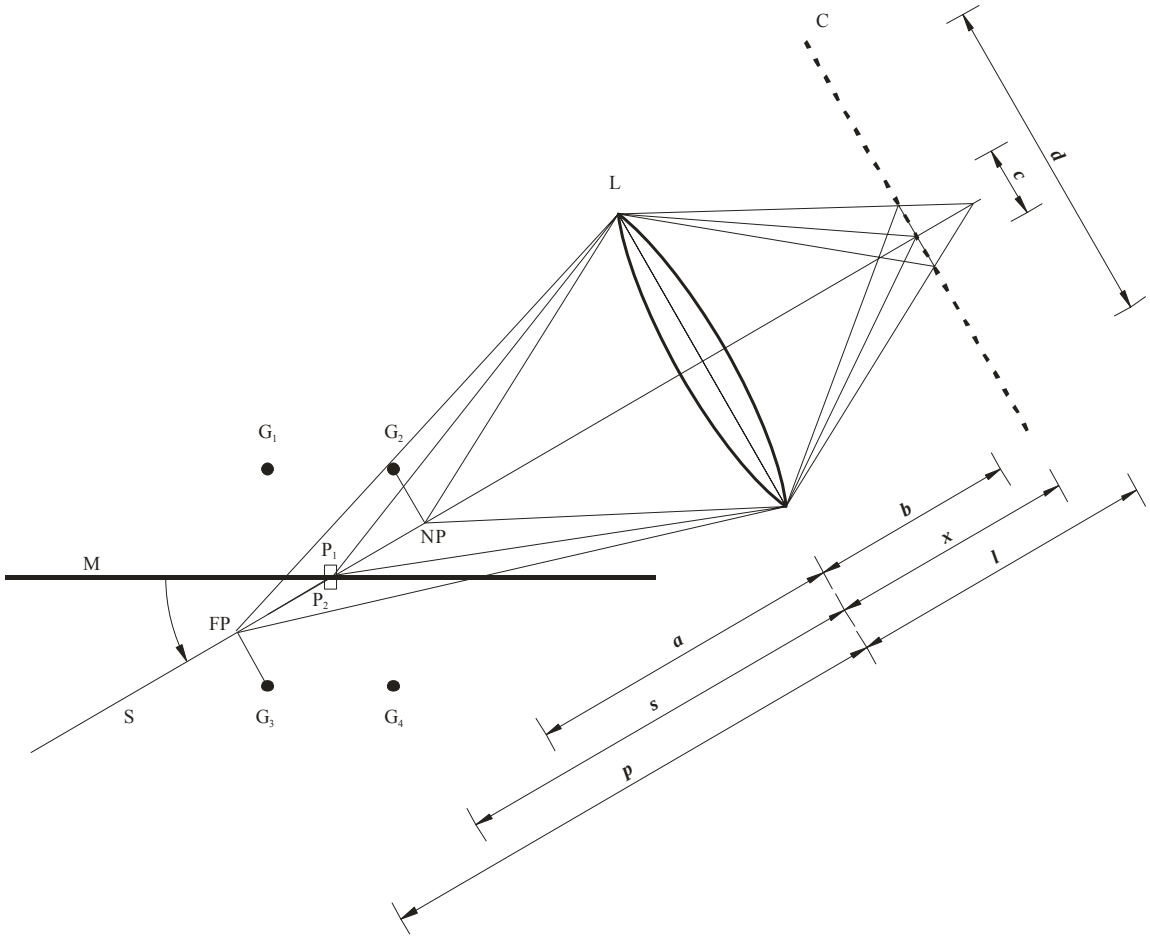

Figure 6.6-1: System micro camera-micro component-micro gripper

System parts and symbols:
G1, G2 – micro gripper's fingers
G3, G4 – micro gripper's mirror image
P1 – micro component
P2 – micro component's mirror image
M – mirror
S – symmetric axis of the optical system
C – plane of the camera's CCD chip
c – size of the CCD chip's single cell. This is the maximum permissible circle of confusion (to calculate a camera's depth of field one needs to know the maximum permissible size of the circle of confusion in what can still be considered an acceptable focus)
d – lens diameter

NP –projection of G1 to the system's symmetric axis; lower boundary of the area that has to have satisfactory depth of field (near point)
FP –projection of G3 to the system's symmetric axis; upper boundary of the area that has to have satisfactory depth of field (far point)
L – lens. In this simplified representation, only one lens is shown and its parameters are defined as parameters of the equivalent lens for the lens system used in the experiment.
a - distance between the near point, NP, and the lens' symmetric axis
b - distance between the mirror image of the near point, NP, and the lens' symmetric axis
p - distance from the far point FP to the symmetric axis of the lens
l - distance between the mirror image of the far point, FP, and the lens' symmetric axis
s – distance between the micro component and the lens' symmetric axis
x - distance between the micro component's mirror image and the lens' symmetric axis
α – slope of the optical system's symmetric axis to the mirror plane

$$\frac{1}{l}+\frac{1}{p}=\frac{1}{f} \tag{1}$$

$$\frac{1}{s}+\frac{1}{x}=\frac{1}{f} \tag{2}$$

$$\frac{1}{a}+\frac{1}{b}=\frac{1}{f} \tag{3}$$

The following can be written on the basis of the similarity of triangles (Figure 6.6-1):

$$\frac{c}{d}=\frac{l-x}{l} \tag{4}$$

$$\frac{1}{l}=(1-\frac{c}{d})\frac{1}{x} \tag{5}$$

(1) and (2) into (5)

$$\frac{1}{f}-\frac{1}{p}=(1-\frac{c}{d})(\frac{1}{f}-\frac{1}{s})$$

$$p=\frac{dsf}{cs+f(d-c)} \tag{6}$$

$$\frac{c}{d}=\frac{x-b}{b} \qquad \frac{1}{b}=(1+\frac{c}{d})\frac{1}{x} \tag{7}$$

$$\frac{1}{b}=(1+\frac{c}{d})\frac{1}{x} \tag{8}$$

(2) and (3) into (8)

$$\frac{1}{f}-\frac{1}{a}=(1+\frac{c}{d})(\frac{1}{f}-\frac{1}{s})$$

$$a=\frac{dsf}{-cs+f(d+c)} \tag{9}$$

The next equation represents the distance between the NP and FP from the lens. Now the depth of field can be calculated in the same way as its difference:

$$p-a=dof=\frac{dsf}{cs+f(d-c)}+\frac{dsf}{cs-f(d+c)} \tag{10}$$

[6-11] - [6-17]

Determining the value of s in this equation would give us information about the micro component's distance from the lens axis, and the depth of field can be defined in this way. "Lens" refers to the equivalent lens, which is a combination of two or more lenses (micro camera lens and magnification lenses).
This equation presents dependence depth of field to the lens' focal length and the distance between the lens and the micro components. Figure 6.6-2 is obtained on the basis of the equation (9) and shows the distance at which the micro camera must be positioned to obtain a satisfactory depth of field. It is necessary to calculate the focal length of the equivalent lens. The depth of field is a function of the equivalent lens' focal length, the distance between micro component and lens, the lens diameter (aperture size) and the size of the CCD chip's single cell. We had five different lenses and the depth of field could be calculated by combining them.
It is supposed that, for use in order of magnitude one hundred to ten µm, a depth of field of 500 µm provides a satisfactory image because both the micro gripper and its mirror image are reproduced sharply. From Figure 6.6-2 follows that, for the lens' focal length 4 mm, d=3mm (the equivalent lens as combination of two lenses f_1=25mm, d_1=12mm and f_1=7mm, d_1=3mm) the micro camera had to be positioned 25 mm from the micro component because this permits a 500µm depth of field.

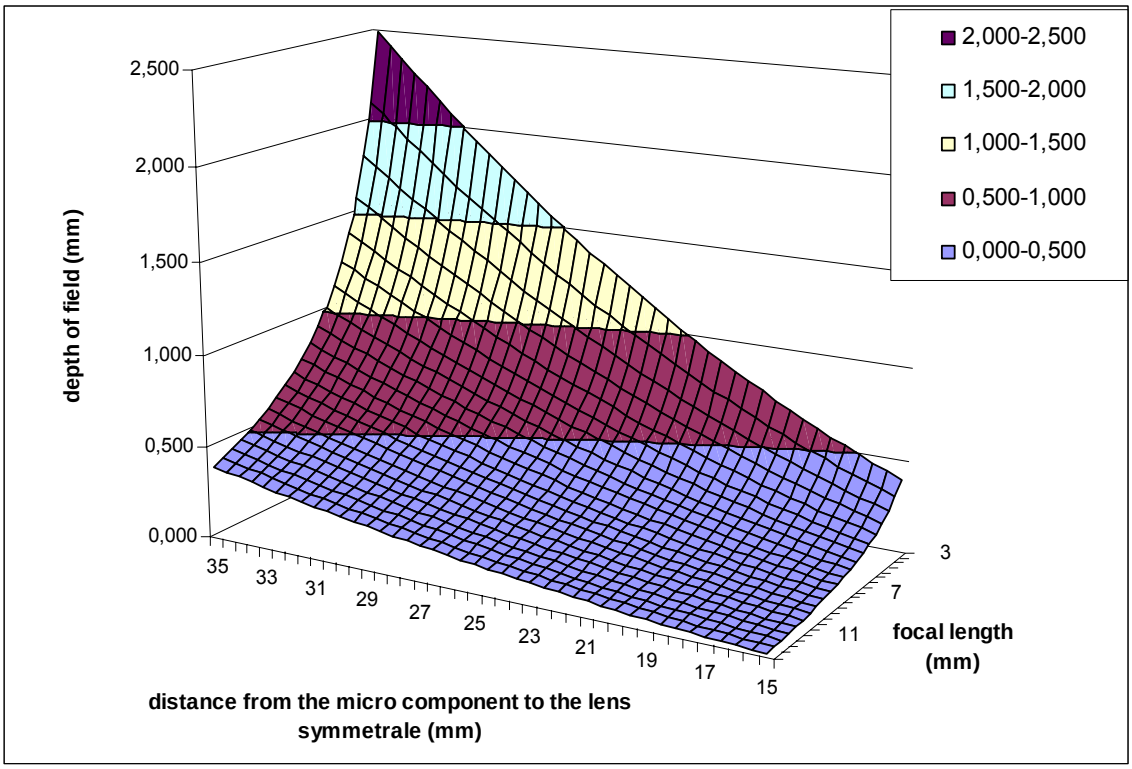

Figure 6.6-2: Depth of field distribution

A compromise between the required magnification and a satisfactory depth of field represents an optimum result, which is manifested in the image sharpness both of micro gripper and its images.

6.7 Distance between the micro gripper and the mirror

The approach can be inspected in detail using micrometer scale, which is also reflected. [6-10]
The distance between the micro gripper's finger and its mirror images is twice that between the micro grippers and the mirror.
In order to get the satisfactory depth of field is necessary that the images of the furthest object (G3) and the nearest object (G1) are sharp, see Figure 6.7-1 and Figure 6.7-2.

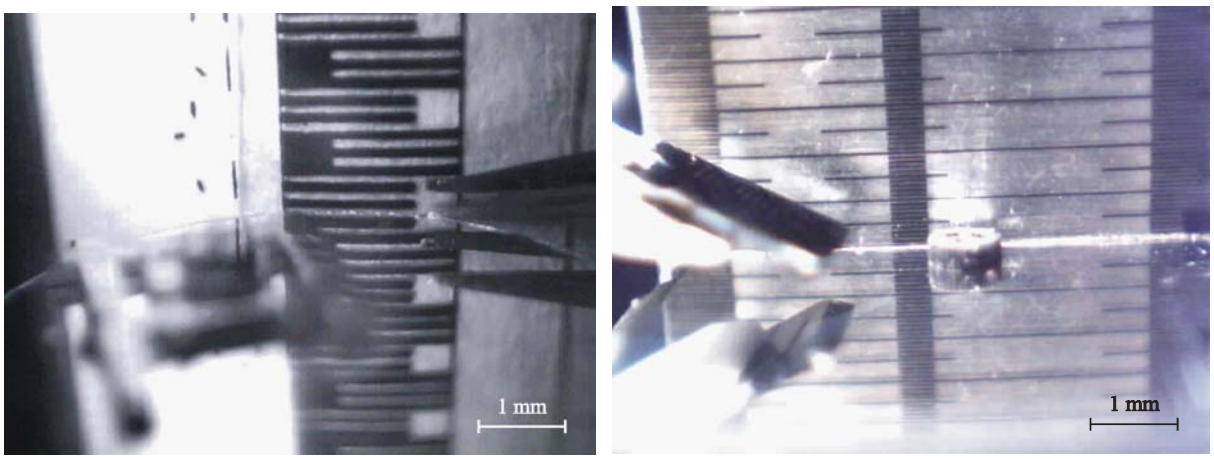

Figure 6.7-1: Micrometer scale is focused

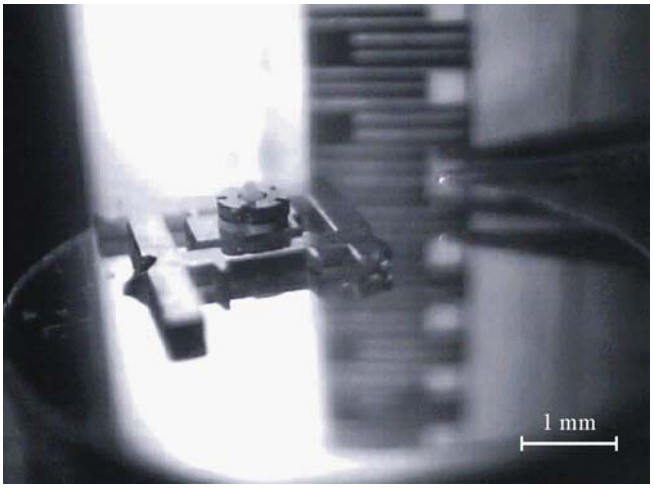

Figure 6.7-2: Micro component is focused

The calculation of the distance micro gripper-micro component is carried out according to Figure 6.7-3.

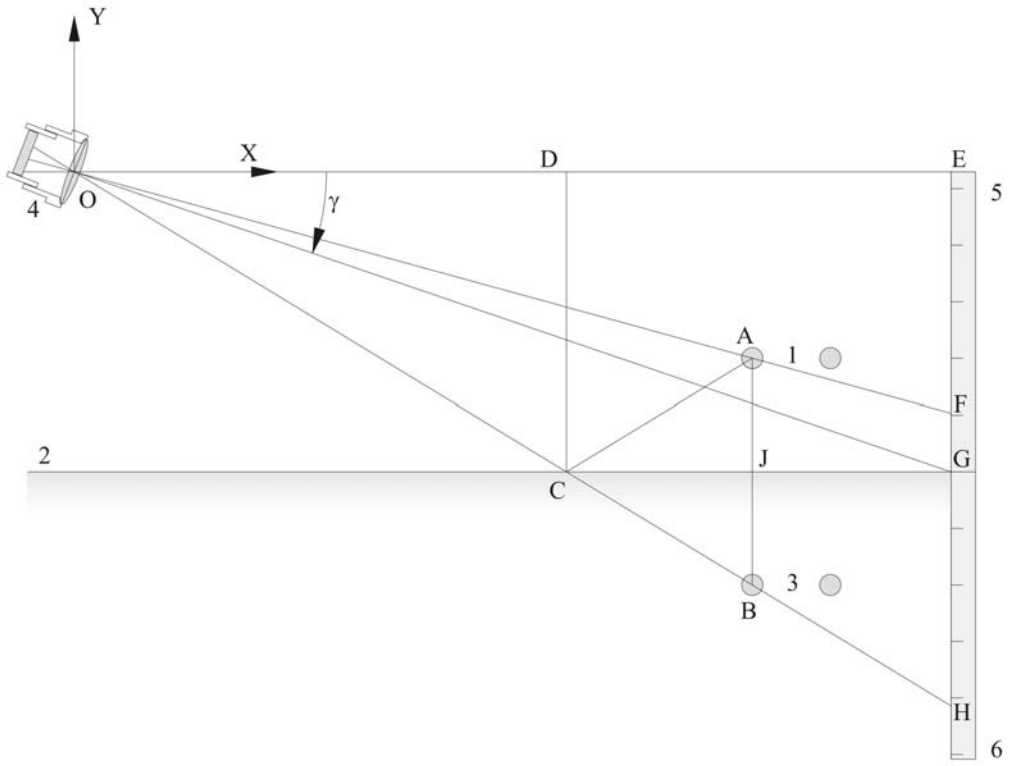

Figure 6.7-3: Distance micro gripper-mirror

P: γ, F_y, G_y, H_y

$$E_X = \frac{G_y}{tg\gamma} \tag{1}$$

$$C_y = G_y \tag{2}$$

$$D_x = C_x \tag{3}$$

$$\frac{D_X}{C_y} = \frac{E_X}{H_y}$$

$$D_X = \frac{E_X}{H_y} C_y$$

(1), (2) → (4)

$$C_X = \frac{\frac{G_y}{tg\gamma}}{H_y} G_y$$

$$C_x = \frac{G_y^2}{H_y \operatorname{tg}\gamma} \tag{4}$$

OF: $y = \frac{F_y}{E_x} x$

$$y = \frac{F_y}{G_y} \operatorname{tg}\gamma x \tag{5}$$

γ, F_y, G_y, H_y

AC: $y = kx + u$

ΔOEH

$$k = -\frac{H_y}{E_x}$$

ΔACJ

$$k = -\frac{H_y}{\frac{G_y}{\operatorname{tg}\gamma}} = -\frac{H_y}{G_y} \operatorname{tg}\gamma$$

$$k = -\frac{H_y}{G_y} \operatorname{tg}\gamma \tag{7}$$

C → (6)

$$C_y = kC_x + u$$

$$u = C_y - kC_x$$

(8)

(7) → (8)

$$u = C_y + \frac{H_y}{G_y} \operatorname{tg}\gamma \cdot C_x \tag{9}$$

(2), (4) → (9)

$$u = 2G_y \tag{10}$$

(7), (10) → (6)

$$y = -\frac{H_y}{G_y} \operatorname{tg}\gamma \cdot x + 2G_y \tag{11} \quad / \cdot F_y$$

(5):

$$y = \frac{F_y}{G_y} \operatorname{tg}\gamma \cdot x \tag{12} \quad / \cdot H_y$$

A:

$$A_y \cdot F_y = -\frac{H_y F_y}{G_y} \operatorname{tg}\gamma \cdot x + 2G_y F_y \tag{13}$$

$$A_y \cdot H_y = \frac{H_y F_y}{G_y} tg\gamma \cdot x$$

$$A_y(F_y + H_y) = 2G_y F_y$$

$$A_y = 2\frac{G_y F_y}{F_y + H_y}$$

$$h = A_y - G_y$$

$$h = \frac{2G_y F_y - (F_y + H_y)G_y}{F_y + H_y}$$

$$h = \frac{F_y - H_y}{F_y + H_y} G_y \tag{14}$$

6.8 Measurement precision

Precision refers to the repeatability of measurement. It does not require us to know the correct or true value. [6-15]

Measurement repeatability is measurement precision under repeatability conditions of measurement.[6-16] These conditions include same locations, same operators, same measuring systems and replicated measurements for a measurement of the same measurand (the quantity intended to be measured) carried by a same material (matrix). [6-17]
The precision of determining the distance between mirror and micro gripper is defined by an imperfection of the orthogonal position between the micrometer scale and the camera as shown in Figure 6.8-1.
In detail:

α defines the angular deviation from the orthogonality between the plane of angle γ and the plane of the micrometer scale. It indicates that measurement beam is not collinear with the axis orthogonal to the micrometer scale.

δ is the angle between micro camera axis and micro gripper tip and defines the position error

γ describes micro camera horizontal inclination that is necessary to enable correct mirror image observation and depends on the size of the micro components and micro grippers. This angle is defined on the plane that is orthogonal to the plane of the specimen holder.

Point “A” is identified as the middle of the micro camera lens.
Point “D” is the point on the micrometer scale where the micro gripper would have been projected if it had been exactly above the micro component.

Since the micro gripper needs not to be positioned above the micro component, its projection is at point “F” (see Figure 6.8-2 for detail).

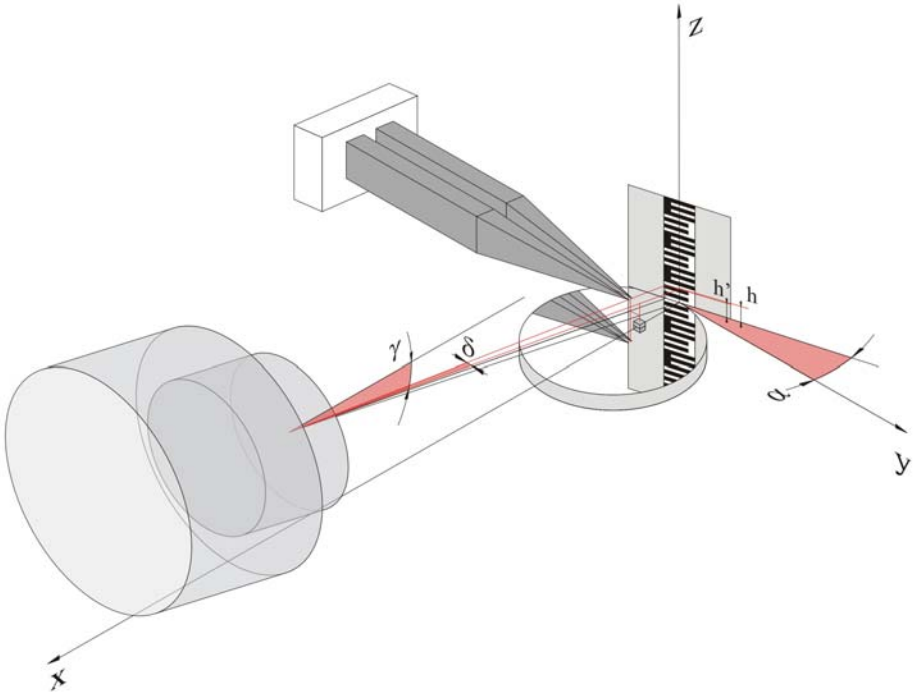

Figure 6.8-1: Measurement precision: components of the system

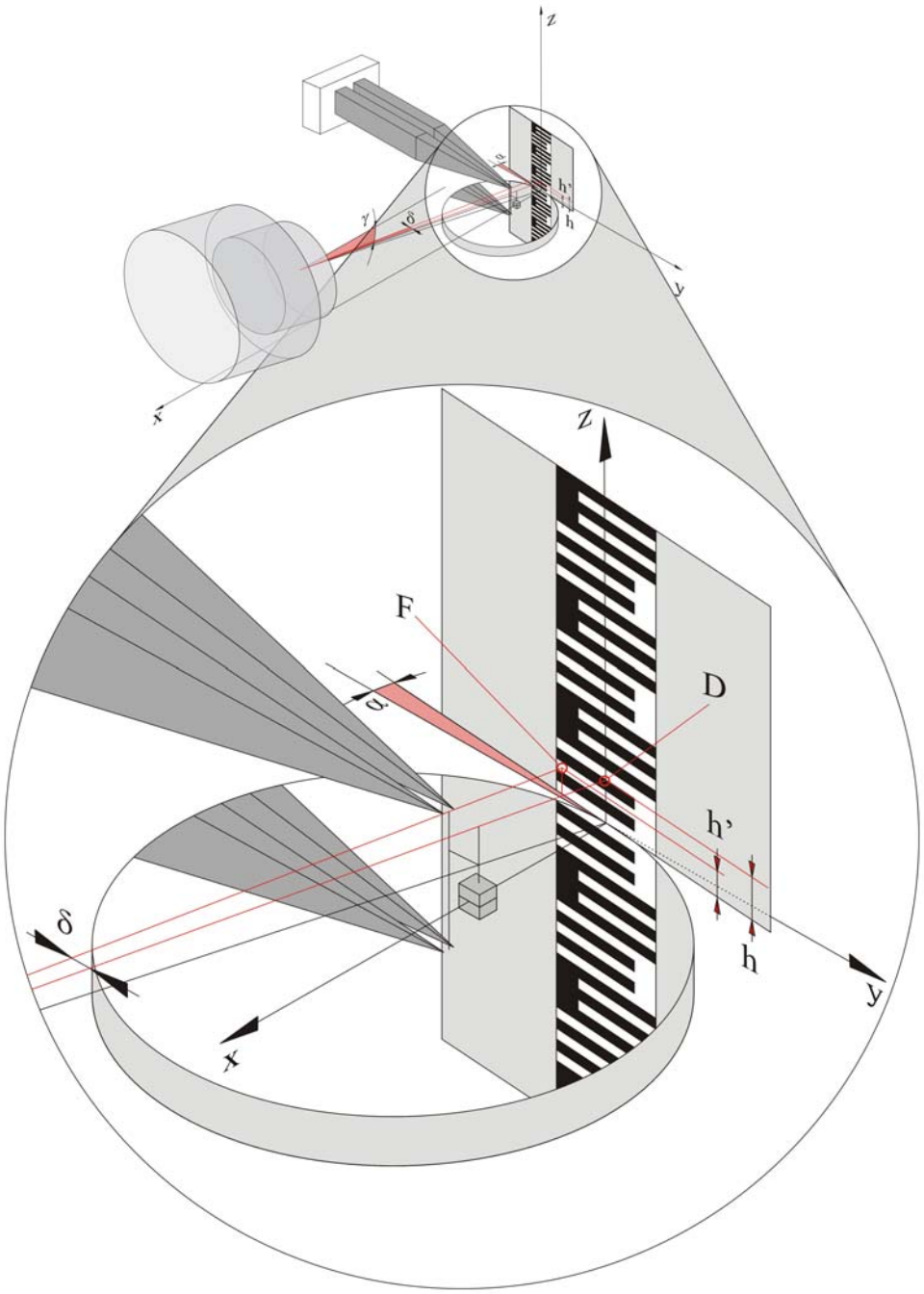

Figure 6.8-2: Error in measurement estimation, system's position and orientation in the three dimensional space

3.2.2 The optical system and its components:

The optical system consists of a micro camera, mirror and micrometer scale, and enables continuous monitoring of the micro gripper approaching the micro object. External influences are not present during the manipulation process, and the system is functionally independent of the micro object's design. The micro camera and micro gripper are mounted on the micro assembly station and are controlled by Lab VIEW.

Figure 6.8-4 and Figure 6.8-6 demonstrate the elements of the system and the relationship (angles, distances) which is relevant for the following calculation. Point "G" means micro gripper tips, "cam" is micro camera,"rul" is micrometer scale (rule), "mir" is mirror.
Angle γ is the anle between the straight line AG and horizontal line. Point I is the intersection point of the AG line and horizontal plane of the mirror.

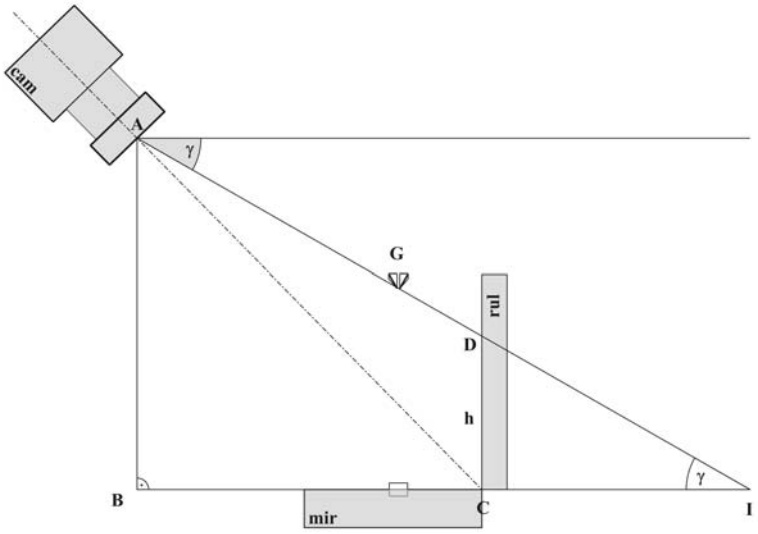

Figure 6.8-3: System micro camera (cam) - micro component- micro gripper (G) - micrometer scale (rul) - mirror stage (mir), side view

In order to simplify the description, mico gripper, micro camera and micrometer scale are removed and the system in the ABI plain is showed in Figure 6.8-4

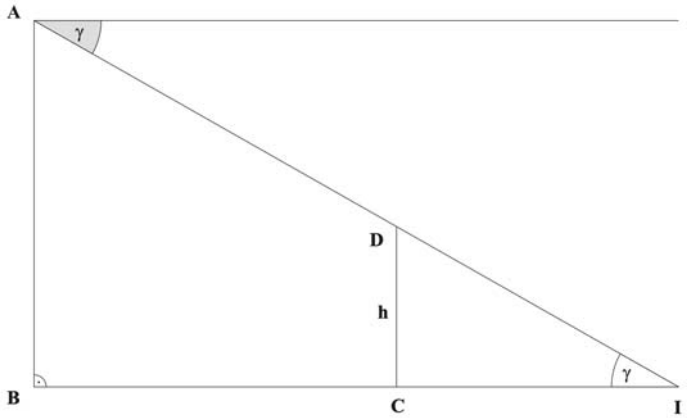

Figure 6.8-4: Error in measurement estimation, system's position and orientation in the plane, side view.

The system in the plain AFI (view from above) is shown in Figure 6.8-5.

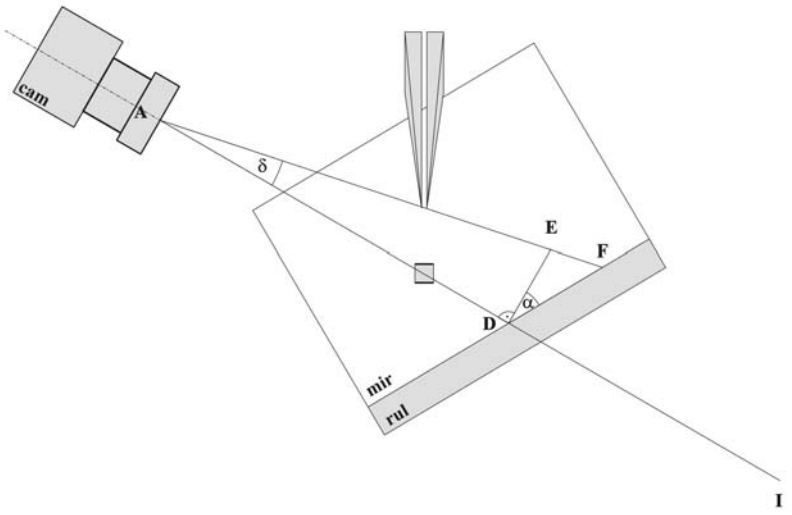

Figure 6.8-5: System micro camera (cam) - micro component- micro gripper (G) - micrometer scale (rul) - mirror stage (mir), top view

Removing the components, as above explained, the optical system is shown in Figure 6.8-6

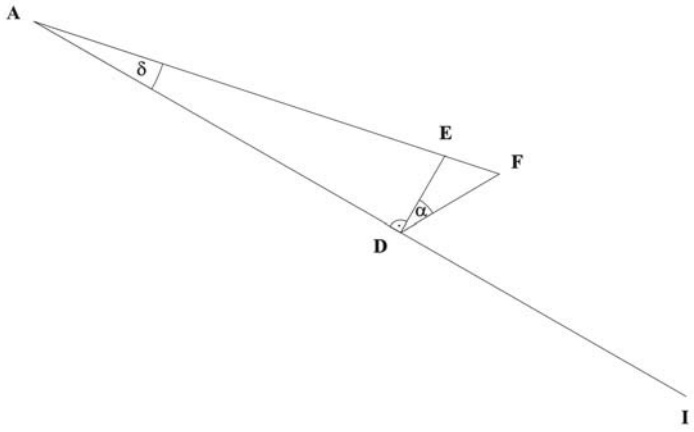

Figure 6.8-6: Error in measurement estimation, system's position and orientation in the plane, top view.

The projection of the plane AFI on the plane ABI (rotation around the line AI) are presented in Figure 6.8-7

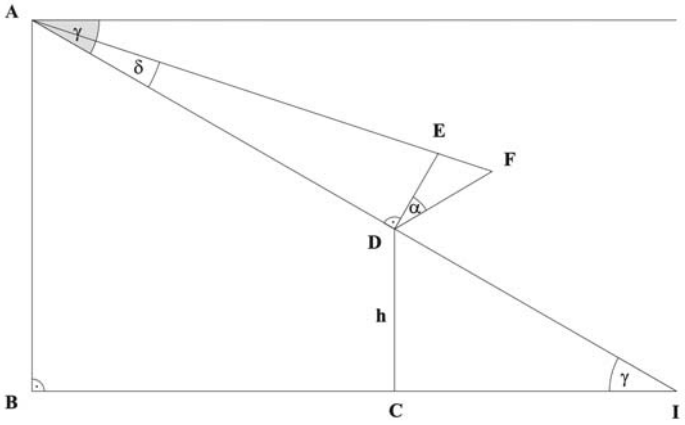

Figure 6.8-7: The projection of the plane AFI on the plane ABI by rotating around the line AI

Transferring the AF line on the AI line, gives the point G, see Figure 6.8-8.

The distance between the point G and BI line is height h', i.e. the read distance. The height h is the height that would have read if the micro gripper had been exatcly above the micro component.
Let the lines and points be transferred into plain ABI

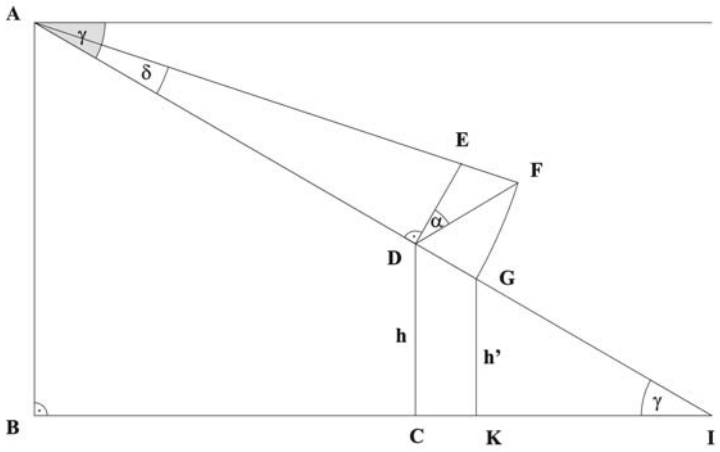

Figure 6.8-8: Error in measurement estimation, system's position and orientation in one plane

It can be written

$$\Delta h = \frac{h'-h}{h} = 1 - \frac{h'}{h}$$

Similarity of triangle DCI and GKI:

$$\frac{AI - AD}{h} = \frac{AI - AG}{h'}$$

$$\Delta h = \frac{h'-h}{h} = 1 - \frac{h'}{h} \tag{1}$$

Since the trianges DCI and GKI are similar, relation between h and h' is:

$$\frac{AI - AD}{h} = \frac{AI - AG}{h'} \tag{2}$$

Eq. (2) can be transformed:

$$h' = \frac{AI - AG}{AI - AD} * h \tag{3}$$

On substituting equation (3) in equation (1), it is obtained:

$$\Delta h = 1 - \frac{\frac{AI - AG}{AI - AD} * h}{h} = 1 - \frac{AI - AG}{AI - AD} = \frac{AI - AD - AI + AG}{AI - AD} = \frac{AG - AD}{AI - AD}$$

$$\Delta h = \frac{AG - AD}{AI - AD} \tag{4}$$

Considering that:

$$AG = AF \tag{5}$$

On substituting equation (5) in (4), equation (4) becomes:

$$\Delta h = \frac{AF - AD}{AI - AD} \tag{6}$$

The relation between AF and AD can be defined with sinus theorem – triangle ADF:

$$\frac{AD}{\sin\left[\frac{\pi}{2} - (\alpha + \delta)\right]} = \frac{AF}{\sin\left(\frac{\pi}{2} + \alpha\right)} \tag{7}$$

Equation (7) can be transformed in the following way:

$$AF = \frac{\sin\left(\frac{\pi}{2} + \alpha\right)}{\sin\left[\frac{\pi}{2} - (\alpha + \delta)\right]} * AD \tag{8}$$

$$AF = \frac{\cos\alpha}{\cos(\alpha + \delta)} * AD \tag{9}$$

On substituting (9) in (6), it is obtained:

$$\Delta h = \frac{\left(\frac{\cos\alpha}{\cos(\alpha + \delta)} * AD\right) - AD}{AI - AD} = \frac{AD}{AI - AD} * \left[\frac{\cos\alpha}{\cos(\alpha + \delta)} - 1\right] = \frac{1}{\frac{AI}{AD} - 1} * \left[\frac{\cos\alpha - \cos(\alpha + \delta)}{\cos(\alpha + \delta)}\right]$$

$$\Delta h = \frac{2}{\frac{AI}{AD} - 1} * \frac{\sin\left(\alpha + \frac{\delta}{2}\right) * \sin\frac{\delta}{2}}{\cos(\alpha + \delta)} \tag{10}$$

The percent error:

$$\Delta h[\%] = \frac{2}{\frac{AI}{AD} - 1} * \frac{\sin\left(\alpha + \frac{\delta}{2}\right) * \sin\frac{\delta}{2}}{\cos(\alpha + \delta)} * 100$$

Empirically are taken the following dimensions:
AI = 50, AD = 25

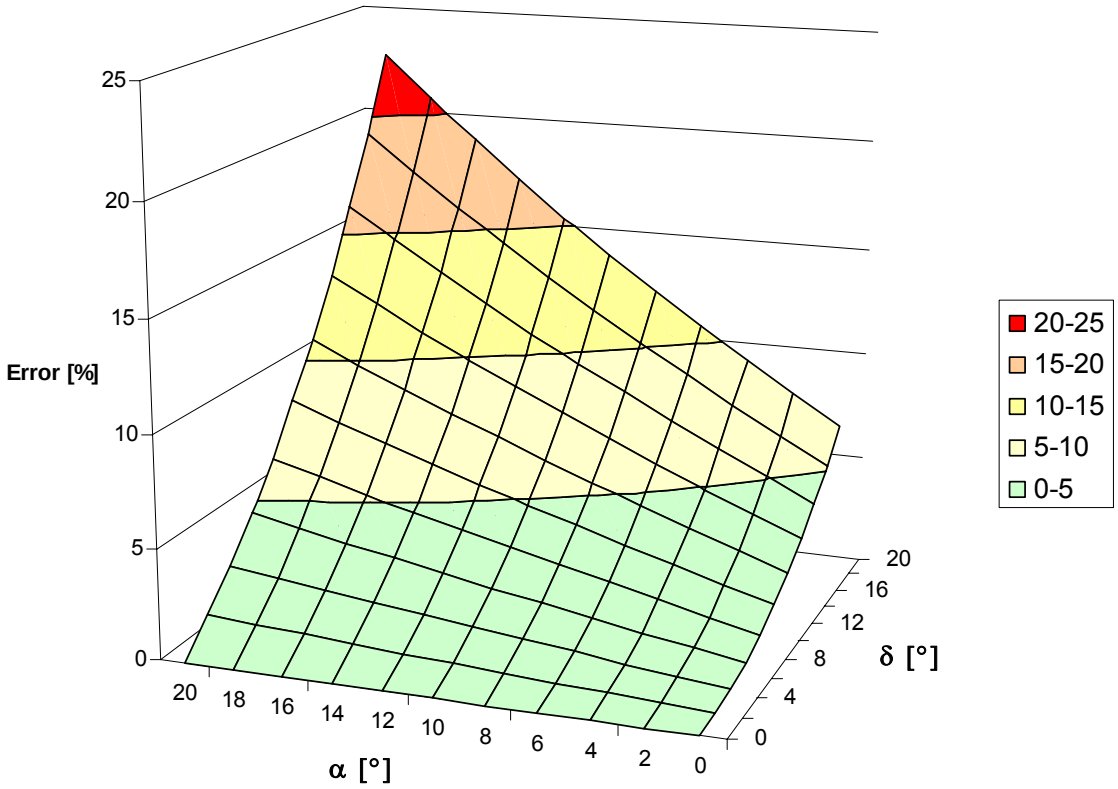

Figure 6.8-9: Measurement error: distribution

It can be concluded from the chart (Figure 6.8-9) that:

- For extreme case: maximal value of the angle δ, at the micro gripper yet reflects in the mirror (δ=13, 5°) and relative high deviation from the orthogonally of the measure scale with reference to the camera axis (α = 15°), the error value is within 10%.
- For normal expected deviations (α=10°, δ =10°), the error value is less than 5%, and it can be neglected, as follows:

Measurement System Analysis (MSA), also known as Measurement System Evaluation (MSE), as part of ISO9000:2000 and AIAG 2002 standards, the Measurement system analysis (MSA) is defined as an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability.
A general rule for measurement system acceptability is:

- Under 10 percent error is acceptable.

- 10 percent to 30 percent error suggests that the system is acceptable depending on the importance of application, cost of measurement device, cost of repair, and other factors.
- Over 30 percent error is considered unacceptable, and you should improve the measurement system. [6-18]

6.9 Experimental tests

The novel video system was tested using different micrometer scales and micro grippers, see Figure 6.9-1. The results were achieved with the micrometer scale of a 100 µm subdivision, surface chrome image. The limit of the resolution was 20 µm.
The accuracy that can be achieved with the described method depends on the line segmentation accuracy (image processing) and the micro camera's resolution and credibility. The micro camera has an integrated magnification of 20-40 X. The magnification must not be too great in order to maintain the depth of field. The micro camera used in the first experiments had a resolution of 640x480 pixels and a mass of 20 g.

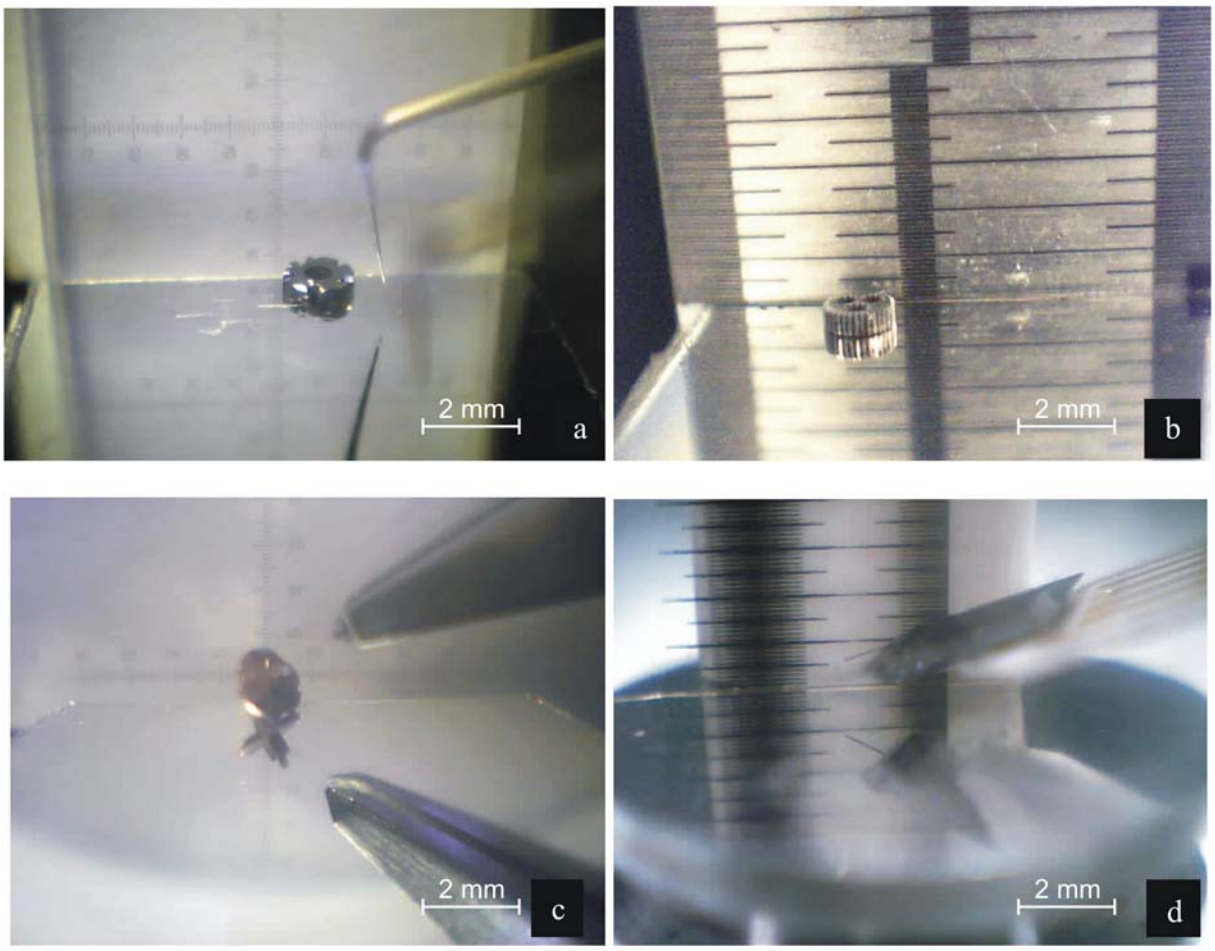

Figure 6.9-1: Experimental testing with different micrometer scales and micro grippers

Figure 6.9-2 shows Cu micro balls, 40-60 µm and micro grippers, with and without micrometer scale.

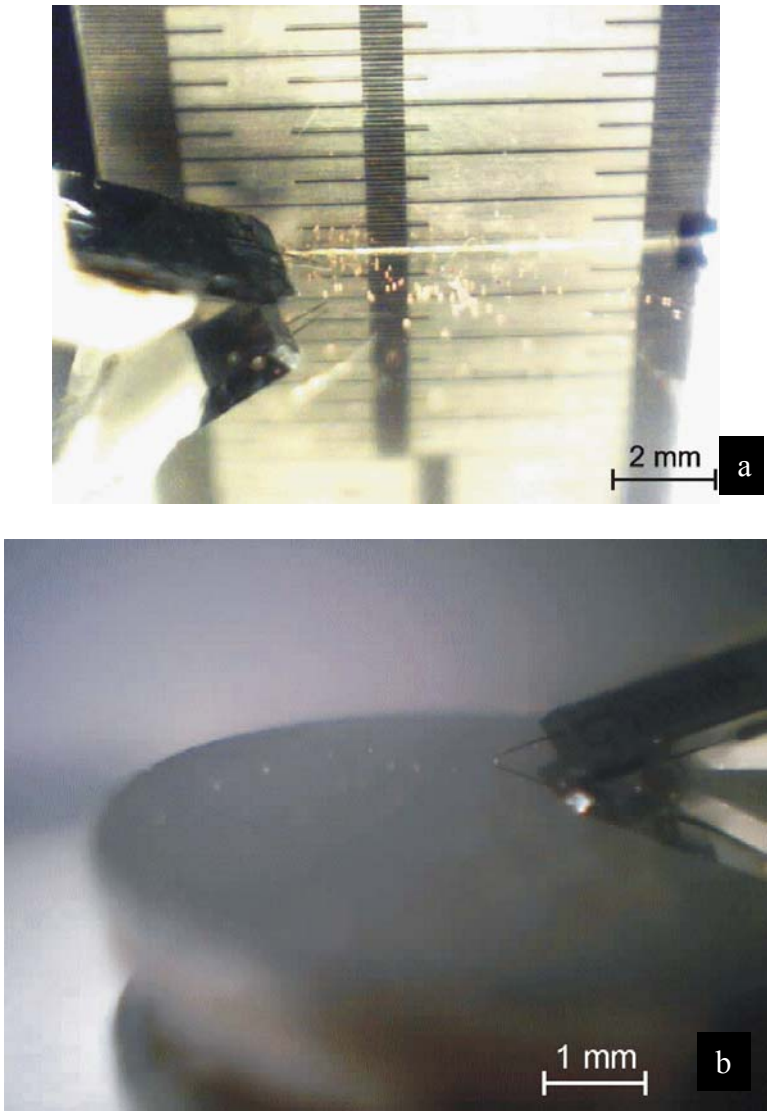

Figure 6.9-2: Micro gripper and Cu spheres, 40-60 µm: a) with micrometer scale, b) without micrometer scale

The thickness of the finest micro gripper's tips used in the experiments was 2, 5 µ, Figure 6.9-3.m. The micro objects were polymer spheres measuring about 2 µm, Figure 6.9-4.

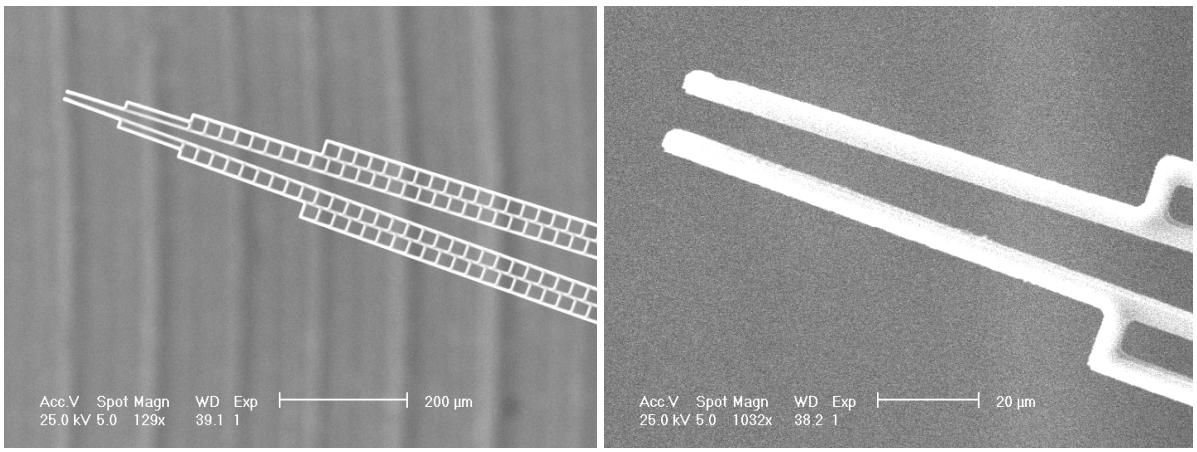

Figure 6.9-3: SEM photos of the micro gripper's tipps

The algorithm for the handling procedure is described in the following steps:

- At first the micro gripper approaching the micro component is focused.
- The distance to the micro component on the x-y plane (gripping center) is controlled by the SEM or optical microscope,
- The difference in working distance when the micro gripper or micro object is focused provides information about vertical distance.
- The measure grid is focused when the micro gripper approaches the micro componentand the distance is read und calculated, Figure 6.9-4.
- This value provides information about the distance. Then the micro gripper is focused again and is driven further down, checking the position on the x-y plane.
- The grid is refocused and the distance is read.
- The procedure is iterated so the micro component can be reached and gripped from the base (specimen holder).

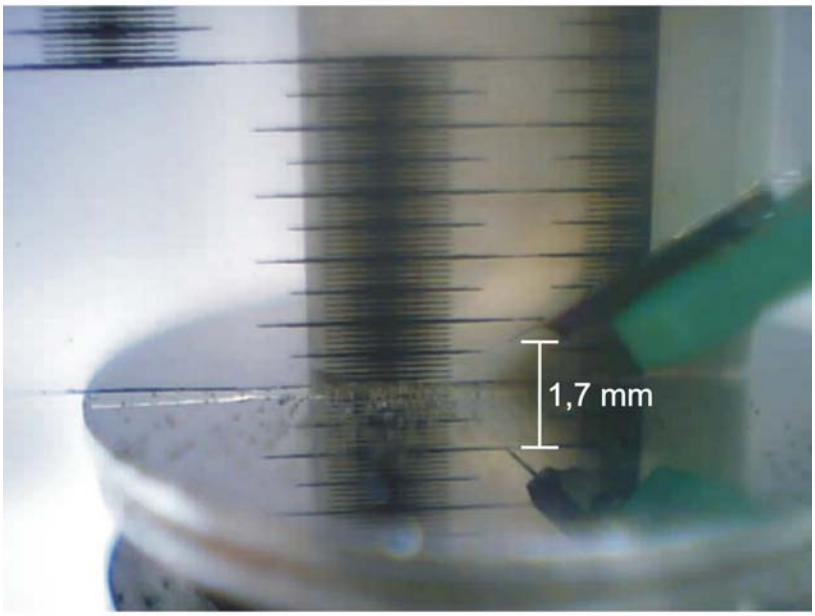

Figure 6.9-4: Approach of the micro gripper to the micro object. The distance is read at the scale and then calculated

Similar is the operation under the optical microscope, f.e. manipulation of micro spring, see Figure 6.9-5

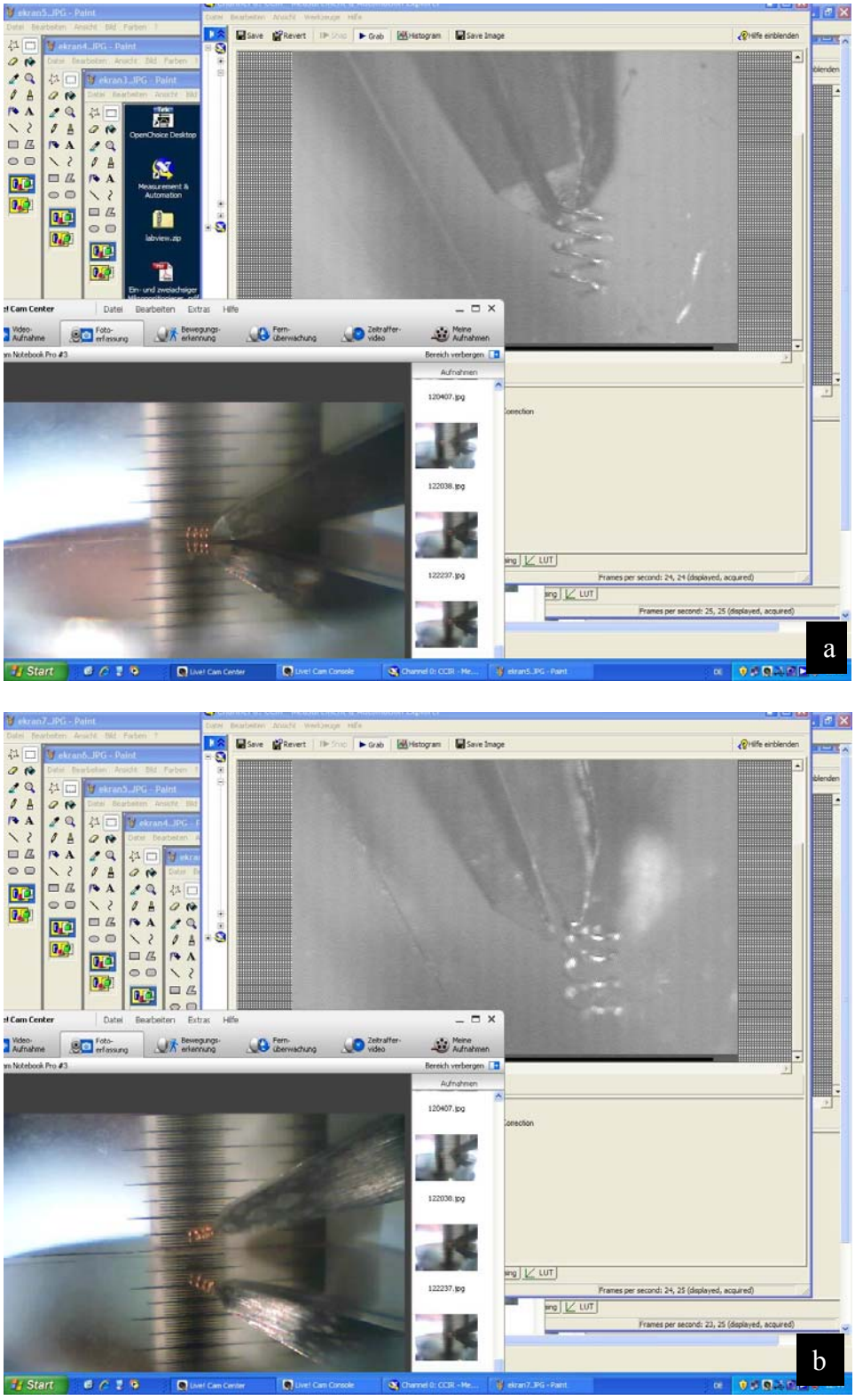

Figure 6.9-5: Manipulation task under the optical microscope: a- approaching the micro component, b- pick up the micro component

Based on the equipment used in this experiment a resolution of 10-20 μm was achieved. Considering the use of the best cameras with high resolution photo sensor (10-20 MP), maximal resolution to 5μm can be expected.

6.10 Mounting the system

Micro camera is mounted on the existing tweezers-gripper module and driven by three piezo motors (Figure 6.10-1).

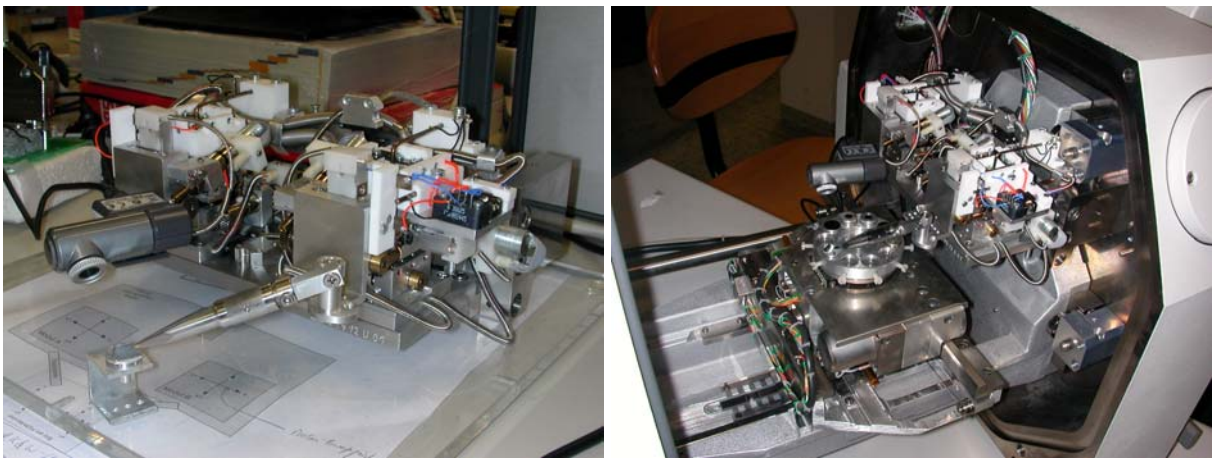

Figure 6.10-1: Camera and griper in a micro assembly station and mounted in the SEM

The whole system is screwed onto the SEM chamber's interior and can be controlled by Lab View (Figure 6.10-2).

Figure 6.10-2: LABView control system for tweezers-gripper module [6-20]

6.11 References

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Chapter 7. Real-time optimization of the assembling of the mechanical devices by combined regulation of the assembling path using 3-axis manipulator and rotational table

7.1 Introduction

In this work an optimization of the assembly process of the mechanical systems in real time by a combined control of the three axis stage and the rotational platform of the SEM chamber has been investigated. The analysis is general and could be implemented in any process concerning mechanical systems assembly. In the presented case, this optimization was employed during an assembly process which was carried out in the SEM Philips XL 40 chamber. A microassembly station with an integrated micro gripper fabricated by Kammrath &Weiss was positioned in the SEM chamber. For the optimization the expected velocity of the automatic assembly of the microsystems in the SEM chamber was elaborated depending on the number of micro componentwhich comprised the system. The number of the components is limited to 10 (by the number of the specimen holders on the platform). It was shown how the assembly process can be expedited with synchronization of the platform and stage motion compared to the assembly of the components which are conveyed on the assembly stub only by rotation of the platform (this occurs often in automatic assembly systems with mechanisms based on the rotational table) or with the assembly only by translation of the stage, i.e. manipulator (in the case of the automatic assembly systems with mechanisms based on the translation).
The given system is shown in Figure 7.1-1(view from above) and Figure 7.1-2 (view inside the chamber):

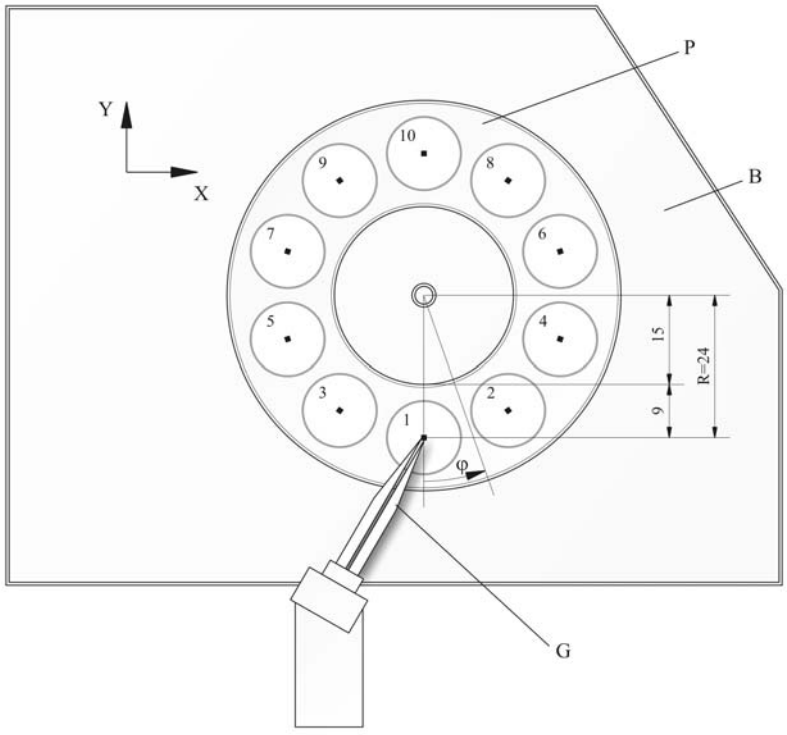

Figure 7.1-1: Stage and platform with specimen holders and micro gripper; P-platform, B- stage, G-micro gripper, φ-rotation angle

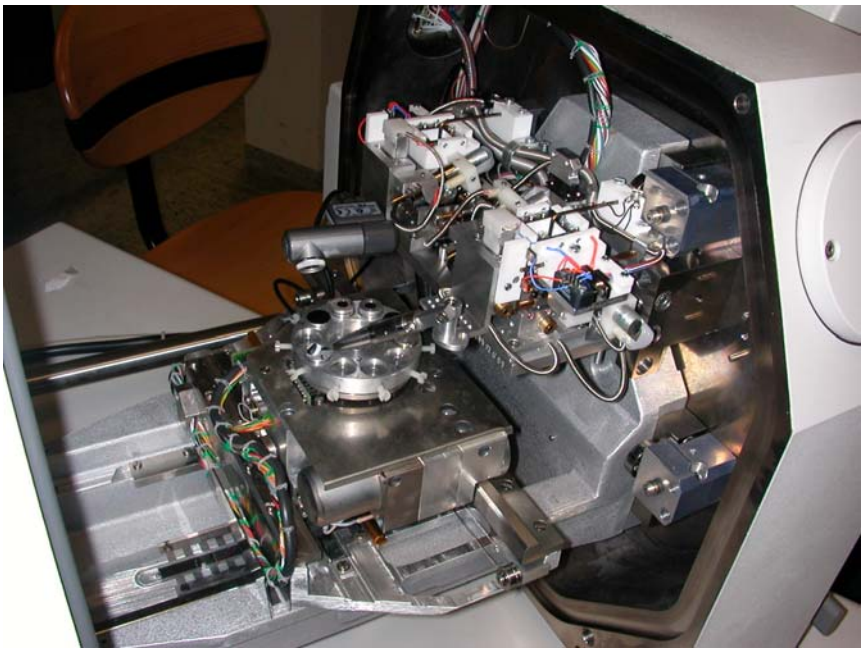

Figure 7.1-2: A view into the SEM chamber when micro montage station is mounted

Stage (B) can be driven in X, Y and Z directions; for this analysis only X and Y coordinates are of interest. The maximum velocity of the stage is v_b = 3 mm/s for x and y axis. Platform (P) can rotate in φ direction with a velocity of ω_p=0, 25 rad/s. The assembly task is performed using the micro gripper (G). The specimen holders (1 to 10) are fixed on the platform (P); the components of the micro system which will be assembled are represented as a small black quadrate. The distance between components of the micro system and the rotational centre is R=24 mm. In the case of the micro system with less of 10 components they should be near the micro gripper in order to reduce the time needed to assembly the system. For example, when the system consists of five components, they are arranged on the stubs 1-5 in such a way that the first micro componentare placed on the stub 1, second on the stub 2, etc.

The velocity of the micro gripper (in x and y directions) is 0, 48 mm/s, which is several times less than the velocity of the stage; its influence in this analysis is neglected. The times needed to grip and release the components as invariant to the control of the stage are neglected. Also the times needed to start and stop the platform are very short compared to the time needed for the assembly process and are ignored.
The component's location is supposed to be in the centre of its respective stubs. The micro system is assembled by successive transport of the components to the stub 1 where the basic micro componentof the system is positioned. The components are assembled in the system in the following way: the stub with the demanded micro componentis brought under the micro gripper; the micro gripper is driven downwards and is picking up the component. Afterwards it is driven upwards, the stage moves and when the stub 1 is under the micro gripper again, the micro gripper is driven down and the micro componentis assembled.
The algorithm of the assembly is shown in the flow chart, see Figure 7.1-3; the input value is n- number of the assembled components.

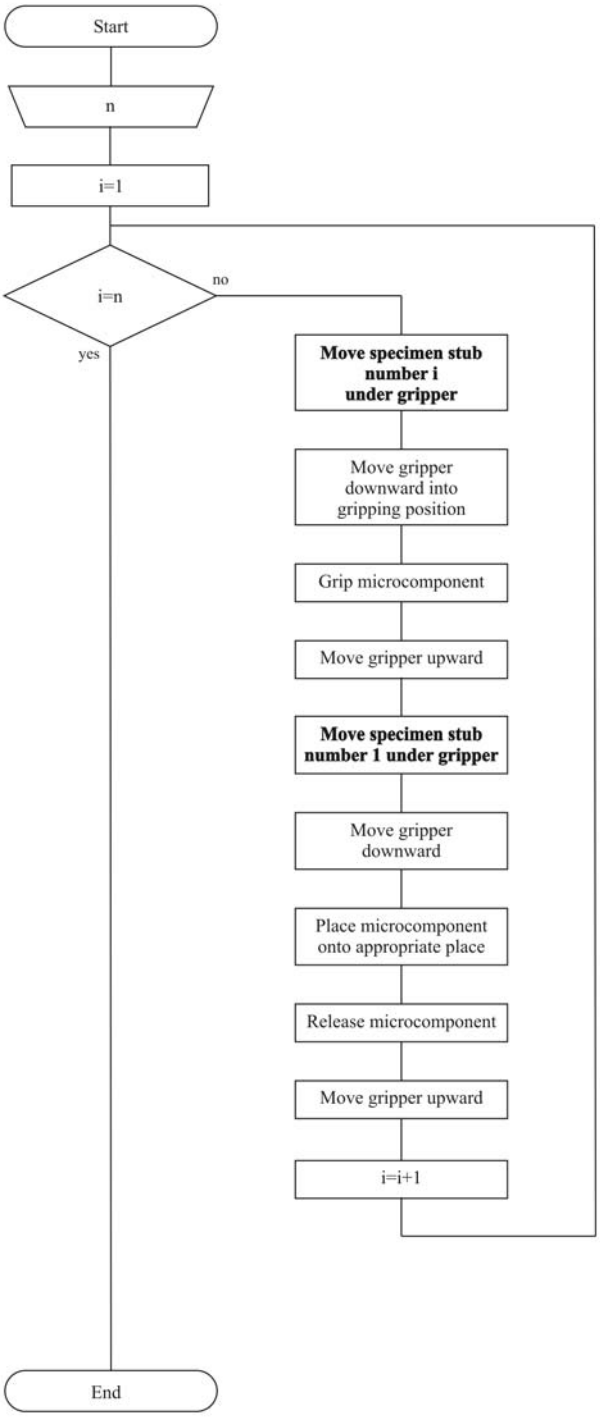

Figure 7.1-3: Assembly flow chart

The zero point is on the top of the micro gripper that means that coordinates of the stub's centre in the moment t=0 are

$$X_{b0} = 0$$
$$Y_{b0} = R$$

X_{b0}- initial x coordinate of the specimen holder's centre (for t=0)
Y_{b0}- initial y coordinate of the specimen holder's centre (for t=0)

The coordinates of each micro component are given in the polar coordinate system referred to the centre of the specimen holder (see Figure 7.1-1).

$$X_c = X_b + R\sin\varphi_p \quad (1)$$

$$Y_c = Y_b - R\cos\varphi_p \quad (2)$$

X_b- x coordinate of the stub's centre
Y_b- y coordinate of the stub's centre
φ_p- the stub's rotation, as mention in the Figure 7.1-1

$$X_b = X_{b0} + \int v_{bx}\,dt \quad (3)$$

$$Y_b = Y_{b0} + \int v_{by}\,dt \quad (4)$$

$$\varphi_p = \varphi_{p0} + \int \omega_p\,dt \quad (5)$$

φ_{p0}- initial rotation of the specimen holder, referred as in the Figure 7.1-1(for t=0)
v_{bx}- x component of the velocity of the stage B
v_{by}- y component of the velocity of the stage B

By replacing the equations 3, 4 and 5 in 1 and 2 is obtained:

$$X_c = X_{b0} + \int v_{bx}\,dt + R\sin(\varphi_{p0} + \int \omega_p\,dt) \quad (6)$$

$$Y_c = Y_{b0} + \int v_{by}\,dt - R\cos(\varphi_{p0} + \int \omega_p\,dt) \quad (7)$$

If the motion of the stage (B) is uniform (as assumed):

$$X_c = X_{b0} + v_{bx}t + R\sin(\varphi_{p0} + \omega_p t) \quad (8)$$

$$Y_c = Y_{b0} + v_{by}t - R\cos(\varphi_{p0} + \omega_p t) \quad (9)$$

By replacing t = 0 in equations 8 and 9 the initial coordinate of each micro component are defined:

$$X_{c0} = X_{b0} + R\sin\varphi_{p0} \quad (10)$$

$$Y_{c0} = Y_{b0} - R\cos\varphi_{p0} \quad (11)$$

[7-1]

The initial coordinates of the components are shown in Figure 7.1-4:

specimen holder	φ_{p0} [rad]	X_{c0} [mm]	Y_{c0}[mm]
1	0,00	0,00	0,00
2	0,63	14,11	4,58
3	-0,63	-14,11	4,58
4	1,26	22,83	16,58
5	-1,26	-22,83	16,58
6	1,88	22,83	31,42
7	-1,88	-22,83	31,42
8	2,51	14,11	43,42
9	-2,51	-14,11	43,42
10	3,14	0,00	48,00

Figure 7.1-4: Initial coordinates of the micro system components

According to the Figure 7.1-3(flow chart of the assembly system) the time t can be defined as time necessary to assembly the components into a system:

$$t = \sum_{i=2}^{n} 2t_i \tag{12}$$

t_i - time needed to get the stage from its initial position, defined with coordinates X_{c0}, $Y_{c0,}$ to the zero point, i.e. to the position where the micro gripper can grip the component. For each micro componentthe time is calculated twice, because the micro componenthas to be brought to the micro gripper in order to be picked up and return to the original position; then the specimen holder 1 is positioned again under the micro gripper tip's, which is the basic position of the system. These steps are written in bold in the algorithm of assembly.
A fundamental problem is the time necessary to place the defined micro componentin its position in the system. There are three cases examined:

- Assembly of the system if feeding the components occurs only by translation of the stage (B) in the x and y direction
- Assembly of the system if feeding the components occurs only by rotation of the platform (P)
- Assembly of the system if feeding the components is both by translation of the stage (B) and platform (P)

7.2 Assembly of the system if feeding of the components occurs only by translating the stage (B) in the x and y direction

In this case, equations (1) and (2) yield:

$$X_c = X_{c0} + v_{bx} t \tag{13}$$

$$Y_c = Y_{c0} + v_{by} t \tag{14}$$

Since the gripping, i.e. assembly occurs in the zero point, is valid:

$$X_c = 0 \tag{15}$$

$$Y_c = 0 \tag{16}$$

By replacing (15) in (13) and (16) in (14) it is obtained:

$$t_x = \frac{|X_{c0}|}{v_x} \tag{17}$$

$$t_y = \frac{|Y_{c0}|}{v_y} \tag{18}$$

Time t_i can be calculated as

$$t_i = \max(t_x, t_y) \tag{19}$$

By replacing (19) in (12), it is obtained:

$$t = \sum_{i=2}^{n} 2\max(t_x, t_y) \tag{20}$$

Time necessary for assembly of the micro system, depending on the number of the components, is shown in Figure 7.2-1 and Figure 7.2-2.

specimen holder	X_{c0} [mm]	Y_{c0}[mm]	t_x[s]	t_y[s]	t_i[s]	t[s]
1	0,00	0,00	0,00	0,00	0,00	0,00
2	14,11	4,58	4,03	1,31	4,03	8,06
3	-14,11	4,58	4,03	1,31	4,03	16,12
4	22,83	16,58	6,52	4,74	6,52	29,17
5	-22,83	16,58	6,52	4,74	6,52	42,21
6	22,83	31,42	6,52	8,98	8,98	60,16
7	-22,83	31,42	6,52	8,98	8,98	78,11
8	14,11	43,42	4,03	12,40	12,40	102,92
9	-14,11	43,42	4,03	12,40	12,40	127,73
10	0,00	48,00	0,00	13,71	13,71	155,16

Figure 7.2-1: Time needed for assembly of the micro system depending on the number of the components, if feeding the components occur only by translation motion the stage (B)

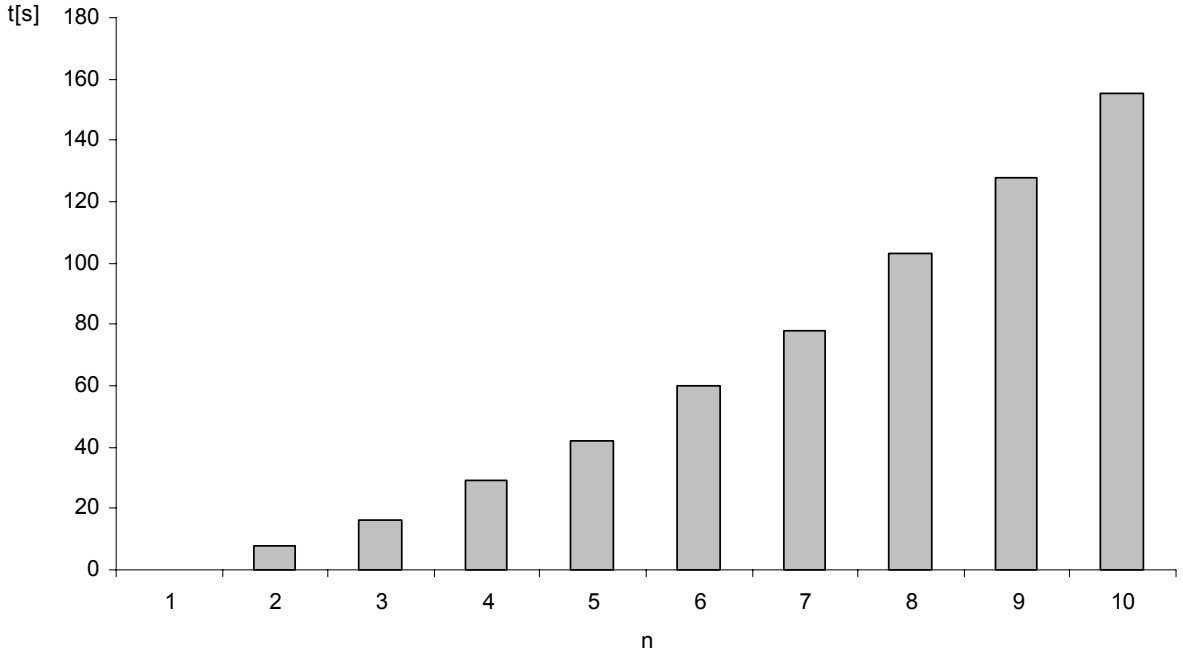

Figure 7.2-2: Time needed for assembly of the micro system depending on the number of the components, if feeding the components occurs only by translation the stage (B)

7.3 Assembly of the system if feeding of the components occurs only by rotation of the platform (P)

In this case the stage does not translate; transport of the components to the micro gripper is performed by rotation of the platform.
Thus equation (19) yields

$$t_i = \frac{\left|\varphi_{p0}\right|}{\omega_p} \tag{21}$$

By replacing (21) into (12):

$$t = \sum_{i=2}^{n} 2\frac{\left|\varphi_{p0}\right|}{\omega_p} \tag{22}$$

The necessary time for assembly of the micro system, depending on the number of the components is given in Figure 7.3 1 and Figure 7.3 2:

specimen holder	φp0 [rad]	ti[s]	t[s]
1	0,00	0,00	0,00
2	0,63	2,51	5,03
3	-0,63	2,51	10,05
4	1,26	5,03	20,11
5	-1,26	5,03	30,16
6	1,88	7,54	45,24
7	-1,88	7,54	60,32
8	2,51	10,05	80,42
9	-2,51	10,05	100,53
10	3,14	12,57	125,66

Figure 7.3-1: Time necessary for assembly of micro system, depending on the number of the components if feeding the components occurs by rotation of the platform (P)

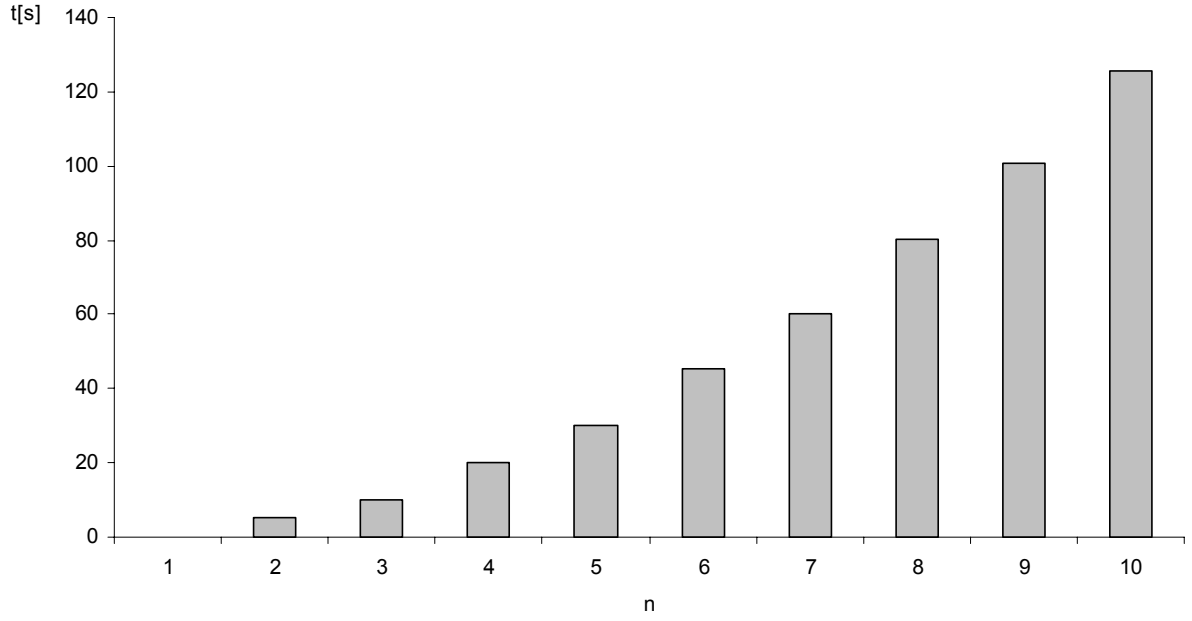

Figure 7.3-2: Time requiered to assembly the micro system, depending on the number of the components if feeding the components occurs by rotation of the platform (P)

7.4 Assembly of the system if feeding of the components occurs both by translation motion the stage (B) in the x and y direction and by rotation the platform (P)

This is the most effective and simplest case. Additionally the assembly is fastest and most precise.
Since the assembly system is symmetric, only specimen holders 2, 4, 6, 8 and 10 will be considered. The assembly of the components on the specimen holders 3, 5, 7 and 9 underlies the same analysis but with the changed sign for x-axis.
The peripheral velocity vector of the stage (B) induced by rotation is defined as:

$$\vec{v}_p = \vec{R} \times \vec{\omega}_p \tag{23}$$

The maximum value of the velocity is:

$$v_p = 24\text{mm} * 0{,}25\frac{\text{rad}}{\text{s}} = 6\frac{\text{mm}}{\text{s}} \tag{24}$$

The maximum value of the velocity of the stage (B) is

$$v_b = \vec{v}_{bx} + \vec{v}_{by} = \sqrt{\left(3\frac{\text{mm}}{\text{s}}\right)^2 + \left(3\frac{\text{mm}}{\text{s}}\right)^2} = 4{,}23\frac{\text{mm}}{\text{s}} \tag{25}$$

It is obvious that the peripheral velocity of the micro component (rotation) is considerably bigger than the maximum velocity of the stage (B) (translation).
For an optimal assembly process the rotation of the platform (P) is more important than translation of the stage (B).
Theoretical, the maximum transport velocity of the components to the micro gripper is summary of the vectors of the maximum velocities of the translation of the stage and peripheral velocity of the stub at distance R=24 mm from the stubs centre. The most convenient case is the one, when both the translation and peripheral velocities vectors have the same direction, i. e. if $\varphi_p=\pi/4$, $3\pi/4$, $5\ \pi/4$ or $\varphi_p=-\pi/4$.
The assembly of the micro systems by feeding of the components with combined motion - translation of the stage and the rotation of the platform without control of its velocities is not feasible because an error will occur that the micro componentcannot be gripped. To illustrate this, the trajectories of the components over time are simulated. Figure 7.4-1 shows the trajectories of the components over time when there is no velocity control. It can be noticed that no components will come in the origin point, which is the condition for succesful gripping.

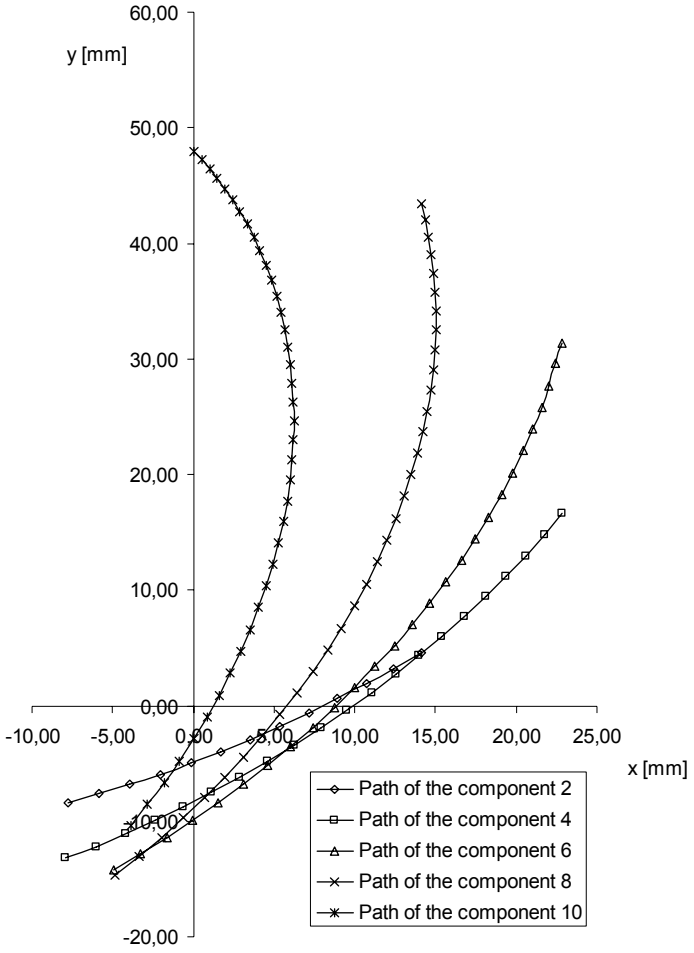

Figure 7.4-1: Trajectories of the components without motion synchronisation for the system stage - platform

The problem could be solved if the motion in the x or y axis is stopped, when the x or y dimensions are equal to null. Further positioning of the micro componentis realized only by motion of the platform: the other coordinate gets the zero value. Obviously, this solution is not the optimum one. The time calculation for this case is as follows:

By substituting in the (8) and (9) X_c=0, Y_c=0, X_{b0}=0 i Y_{b0}=24, the following equations are obtained:

$$0 = v_{bx} t_x + R \sin(\varphi_{p0} + \omega_p t_x) \tag{26}$$

$$0 = 24 + v_{by} t_y - R \cos(\varphi_{p0} + \omega_p t) \tag{27}$$

Numerical solving of the equations (26) and (27) gives the times t_x i t_y. The time t_y is shorter than the time t_x for any components, see Figure 7.4-1. The time needed for the transport of one component to the micro gripper is calculated as:

$$t_i = t_y + \frac{x_c(t_y)}{v_x} \tag{28}$$

The trajectories in this case are shown in Figure 7.4-2 and Figure 7.4-3:

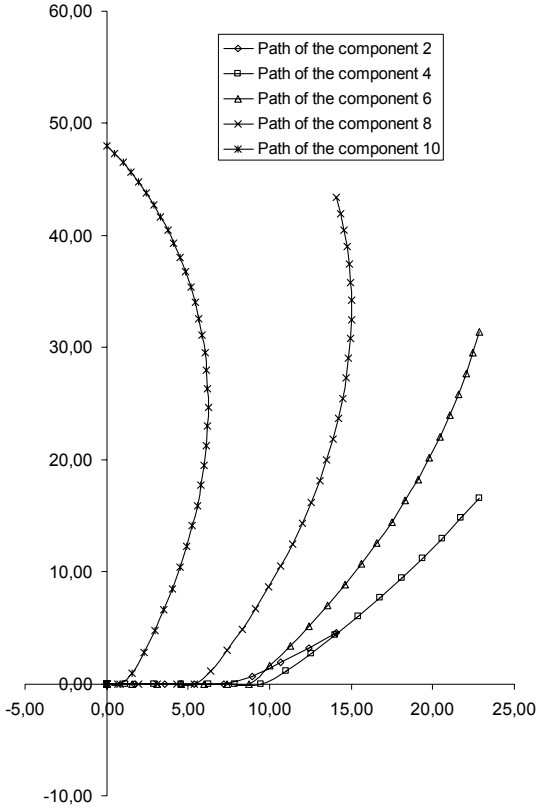

Figure 7.4-2: Trajectories of the components without optimisation

specimen holder	t_i[s]	t[s]
1	0	0,00
2	2,8	5,60
3	2,8	11,20
4	4,7	20,60
5	4,7	30,00
6	5,9	41,80
7	5,9	53,60
8	6,5	66,60
9	6,5	79,60
10	6,8	93,20

Figure 7.4-3: Trajectories of the components without optimisation

Comparing Figure 7.2-1 and Figure 7.3-1 it is clear that this solution is not the optimum. Rather, the assembly of the components 2 and 3 is faster when only rotation of the platform is used. The explanation of this fact is as follows: compared with the linear velocity of the stage, the peripheral velocity of the stub is considerably bigger. For systems with a less number of the components this methods is not very useful. However, for the systems which have a large number of components this method is effective, because the tenth micro componentis brought to the gripper almost twice as fast as by rotation of the platform.

7.5 Assembly of the system if feeding of the components occurs both by translation motion of the stage (B) in the x and y direction and by rotation of the platform (P) with optimization of the trajectory in real-time

From Figure 7.4-2 it can be observed that the coordinate y always gets to the null before the x coordinate. The motors for the coordinate y and rotation are stopped and only the motion in x direction is present. Therefore the velocity v_y will be modified in order to get the coordinates x and y to the zero point at the same time.
That means the stage will be slower driven in the y direction, but the platform will rotate constantly. Since the peripheral velocity of the stub by rotation is considerably bigger than the translation velocities of the stage, the process is less time consuming.
In order to drive the platform to the zero point as fast as possible, the following control process has to be performed:

- While the stub is far from the point of origin, all motors are driven at a maximum speed
- When the stub is close to the point zero, the feed back that will control the velocity in real time, in the motor control system for motion in y direction, will be activated, so as the resultant velocity of the micro component ($v_x = v_{bx}+\omega_p R\sin\varphi$, $v_y = v_{bx}+\omega_p R\cos\varphi$) are directed to the point zero, i.e. the micro component translates to the gripping position, see Figure 7.5-1.

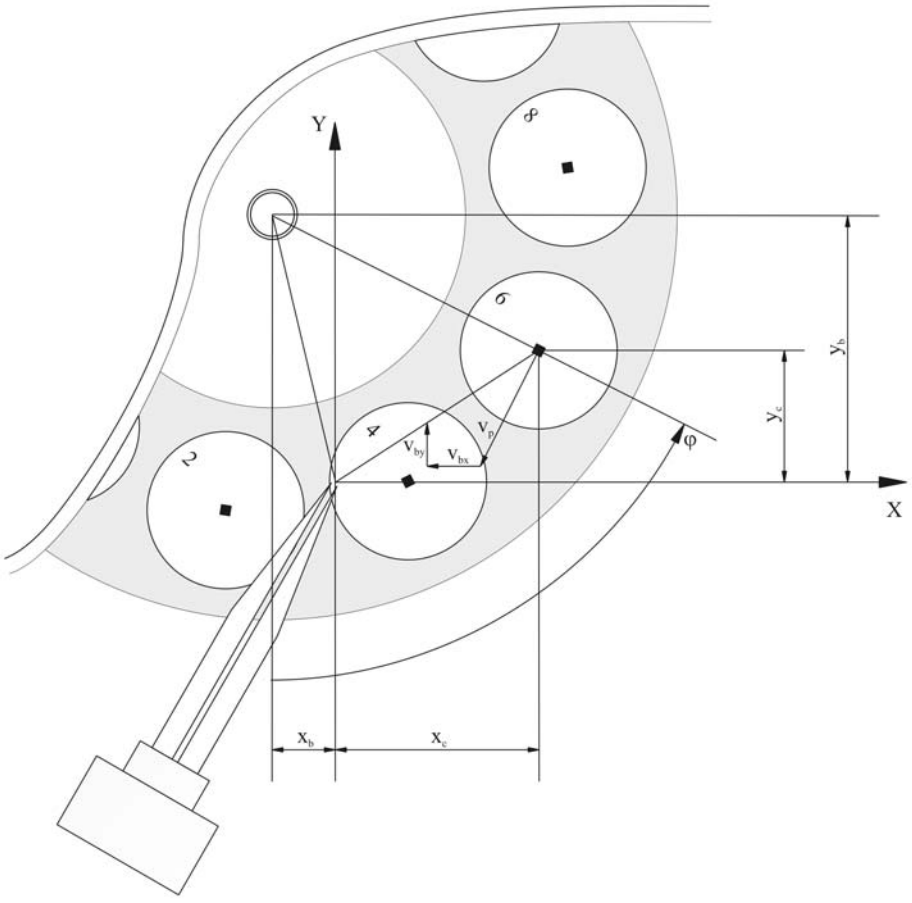

Figure 7.5-1: Trajectory compensation by controlling the velocity v_y in real time

In this case the following must be satisfied:

$$\frac{y_c}{x_c} = \frac{v_{bx} + \omega_p R \sin\varphi_y}{v_{by} + \omega_p R \cos\varphi_y} \tag{29}$$

From Eq. (29) the y component of the velocity can be calculated:

$$v_{by} = \frac{y_c}{x_c}(v_{bx} + \omega_p R \sin\varphi_y) - \omega_p R \cos\varphi_y \tag{30}$$

This control is switched on at the moment when the resultant velocity of the stub is directed to point zero and the value of its X component is smaller than 2, 5 mm/s.

Figure 7.5-2 illustrates the trajectories:

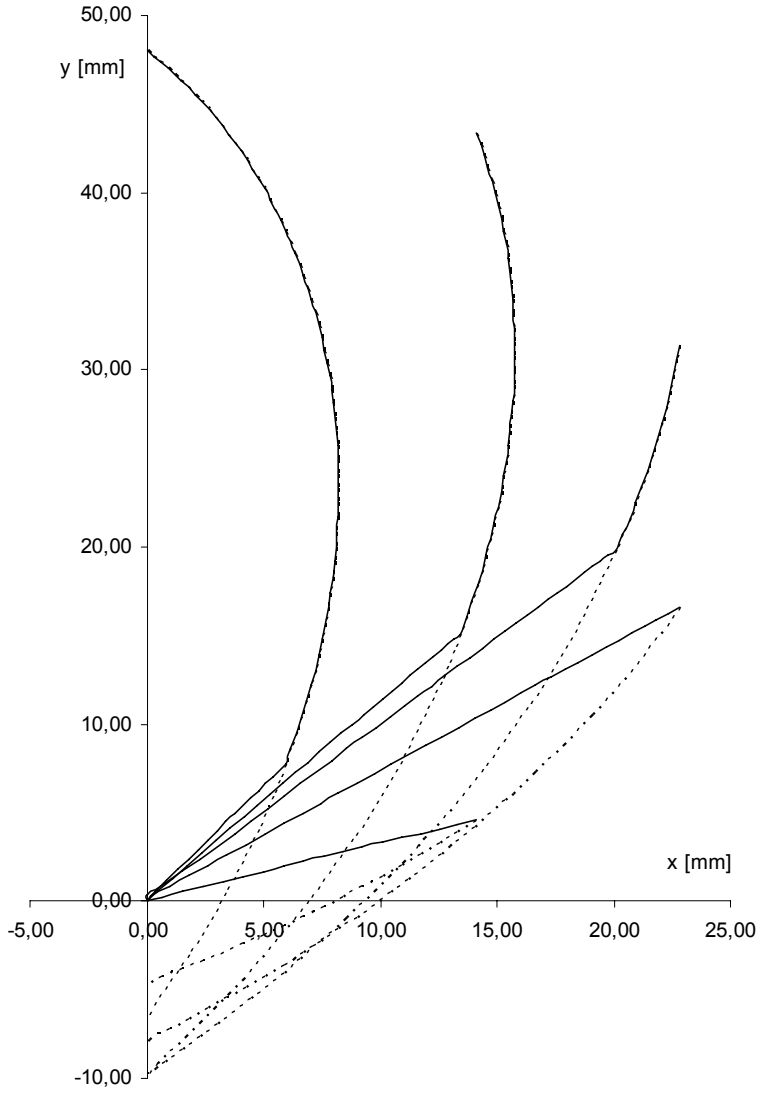

Figure 7.5-2: Optimized trajectories by control of the velocity vy in real time

It can be observed that the control on the stubs 2 and 4 right from the start is activated. On the stubs 6, 8, 10 the velocity control is switched on later, since the stubs are primarily driven at a maximum speed.
The dashed lines represent the trajectories when the velocity control is not activated.
Figure 7.5-3 illustrates how the control is activated and its effect on the velocities v_{bx}, v_{by}, v_{wx} i v_{wy} of the micro component on the specimen holder 10.

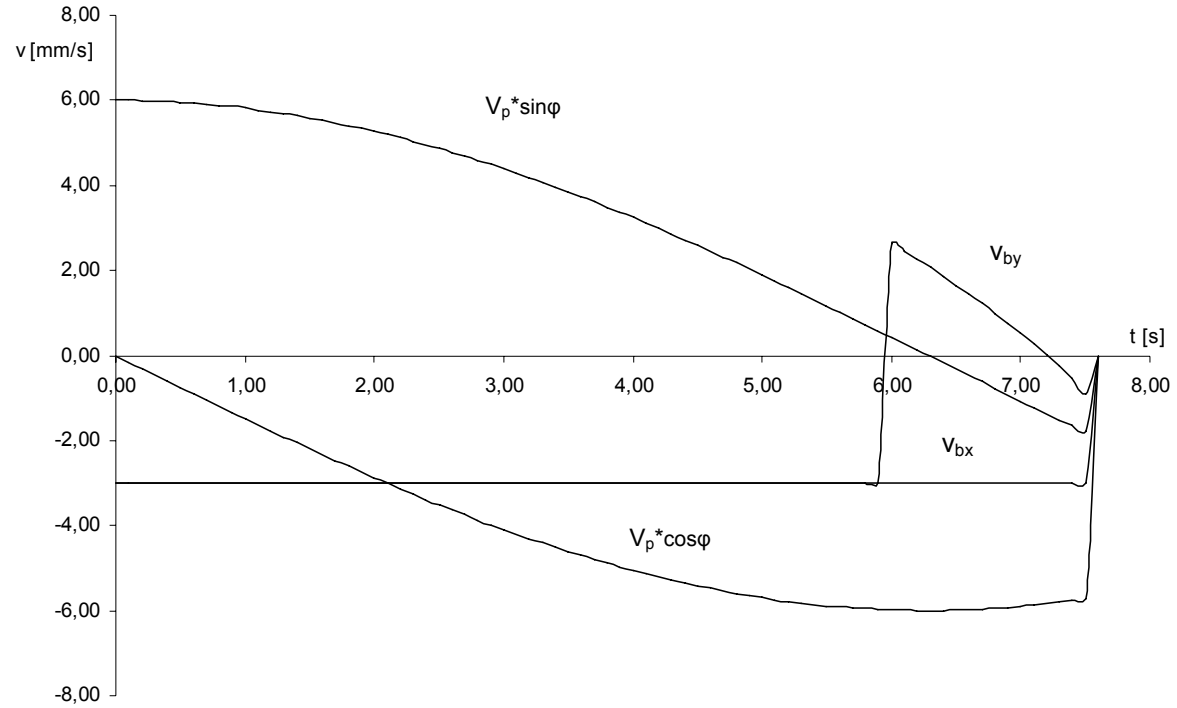

Figure 7.5-3: Velocities of the stage and platform during assembly of the tenth component

The time needed for the assembly depending on the number of the components is shown in Figure 7.5-4:

specimen holder	ti[s]	t[s]
1	0,00	0,00
2	1,70	3,40
3	1,70	6,80
4	3,40	13,60
5	3,40	20,40
6	5,00	30,40
7	5,00	40,40
8	6,40	53,20
9	6,40	66,00
10	7,60	81,20

Figure 7.5-4: Assembly time depending on the number of the micro components when the trajectory is optimized

7.6 Comparison of the assembly velocity for the analysed cases

Finally, the assembly time comparison for all examined cases is presented in Figure 7.6-1 and Figure 7.6-2.

number of components	translation assembling (1.)	rotatio assembling (2.)	combined assembling (3.)	controlled assembling (4.)
1	0,00	0,00	0,00	0,00
2	8,06	5,03	5,60	3,40
3	16,12	10,05	11,20	6,80
4	29,17	20,11	20,60	13,60
5	42,21	30,16	30,00	20,40
6	60,16	45,24	41,80	30,40
7	78,11	60,32	53,60	40,40
8	102,92	80,42	66,60	53,20
9	127,73	100,53	79,60	66,00
10	155,16	125,66	93,20	81,20

Figure 7.6-1: Assembly time comparison; tabelle

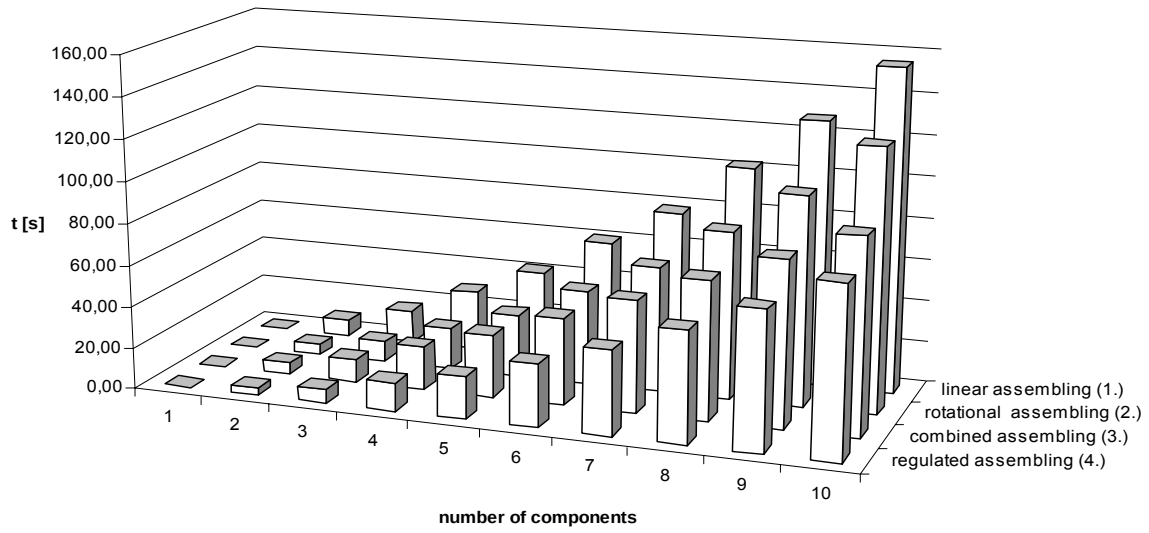

Figure 7.6-2: Assembly time comparison; chart

7.7 Conclusion

In this chapter a method for reduction of the assembly time in the case that feeding of the components occurs both by translation motion of the stage (B) in the x and y direction and by rotation of the platform (P) with optimization of the trajectory in real-time is presented. The time reduction for micro system which consists of ten components is almost 50% (81, 2 s compared to 155, 16 s).

The improvements achieved from using this method in the production are multiple:

- Reduction of working hours of the assembly equipments
- Higher productivity

- More flexibility, applicable for different systems
- Cost reduction of the assembled product

7.8 References

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Chapter 8. Conclusion und further work

In the previous chapter, several solutions of existing problems in the micro manipulation process have been presented.
The novel system for micro component protection, the visual system for collision prevention and a calculation of the best way for introduction of the automation of the micro assembly process in the SEM chamber were presented as general contribution not tailored to any specific application.
In Chapter 5 was dealt with solving the problem of adhesion of micro components on the specimen holder when a glue film is used in order to avoid suction of the micro components by the pump. A protective cover plate was developed to enable the usage of a finest gripper. It was proven that there is no risk of breaking during remove of the micro components from the specimen holder because no adhesive force, which in these dimensions can mean insuperable barrier to assembly attempt, is present anymore. Finally, easier manipulation in the sense of releasing the micro components from a specimen holder is established.

A novel visual and control system for the prevention of the collision during the micro handling in a SEM chamber is proposed in Chapter 6. The new control system simplifies the micro manipulation in a SEM chamber and makes it more reliable. It consists of a micro camera, mirror and micrometer scale, and enables continuously monitoring the approach procedure micro gripper to the micro object. External influences are not present during the manipulation process, and the system is functionally independent of the micro objects design.

In Chapter 7 a method for reduction of the assembly time with optimization of the trajectory in real-time is presented. The time reduction for micro system which consists of ten components is almost 50% (81, 2 s compared to 155, 16 s).
The improvements achieved from using this method in the production are multiple reductions of working hours of the assembly equipments, higher productivity, more flexibility, applicable for different systems, as well as cost reduction of the assembled product

A part of work was concentrated on the description of the microscope types, because they are essential part in micro manipulation. Another important element in the field of micro handling and assembly is scaling law and the physical phenomena arise when the size of the components are smaller than 100 μm. Using of conventional manipulation methods is very difficult even impossible. This phenomenon is discussed in the Chapter 3.
In combination with Chapter 2 ,where the state of the art in the field of micro manipulation, Chapter 3 and Chapter 4 give an overview of all relevant aspects to be considered when performing a micro manipulation procedure.

There are many ways in which these solutions can be further developed and find the comprehensive application: f. e. further development of the protective cover is in the direction of feeding and transport system, which will be automated on the base of the calculation given in the Chapter 7.
The visual system has the future potential in the direction of the increased resolution, based on the progressive image techniques. Additionally, this system can also be automated and made more efficient.
The results obtained up till now show great potential to enhance the performance of the current micro manipulation procedure.

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