Department of Precision and Microsystems Engineering

Title: Design of a millimetre sized gripper for biological sample handling for cryo-electron Microscopy

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Delft University of Technology

Challenge the future

Master Thesis

Design of a millimeter sized gripper for handling biological samples for Cryo-electron

by

Shubhonil

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This thesis is confidential and cannot be made public until December, 2025.

TU Delft

Preface

This thesis provides an opportunity for me to explore the world of microscopy with the help of Delmic BV to develop solution for scientists and researchers to improve research development into biological sciences.

During the eleven months of research and development at Delmic, I received daily support and guidance from my company supervisor Mr. Hoedt and my faculty supervisor Mr. Spronck and Hasan Hossenia.The combined vision of all the people into developing engineering solutions for some of the most smallest(in size) yet consequentially big(in effect) had made me realise the dimensions mechanical engineering can really influence

I could not have achieved the progress in my academic or personal life without all the support from them, my supervisors, my colleagues, my family and friends.

First I would like to thank my daily supervisor Sander for giving me an opportunity to work on such an interesting project.Recognizing the potential in me to work on this multidisciplinary project.The regular guidance with presentations and feedback on them , giving an equal importance on practical matters and overall development as a team , together realizing a common goal.

My faculty supervisor, Jo Spronck and Hasan Hossenia, thank you very much for your important question which you have asked me and keep on asking me for every argument I have ever presented.The regular monday meeting with important feedback sessions and personal hours when I was lost in the complexities of the project.

My colleague Bas Bikker and Xuanmin He, who shared a table with me in Delmic, working with you people was a good experience . We worked towards a common goal and always were ready to help each other during our monday STUP and any other time necessary.Porject ideas, solutions,doing presentations together and having a very interesting times for the whole year.

All my colleagues in Delmic,it was my first time expiriencing Dutch work culture and it sure made me convinced about the amazing work culture you have. Believing in efficiency and doing a 6 hour work day and also implementing innovative concepts for employee satisfaction was very refreshing to see.The hackathons gave me insights to a plethora of problems which a young tech company can face.The face to face review meeting exposed me to different people and their work in the company be it application specialist, software engineering etc.

My parents, for giving me the opportunity to study on the other side of the world,experiencing new cultures, not being afraid of taking risks, caring for me and motivating me to push ahead all the time

Thank you everybody

Executive summary

Shubhonil
Delft, November 2018

This paper presents a design project on a sample transfer system for a correlated light and electron microscopy (CLEM) workflow, which is a graduation project commissioned and supervised by Delmic B.V. and Delft University of Technology's 3mE faculty. Due to the disadvantages of the current transfer processes which heavily rely on manual operation, and the lack of a dedicated/integrated transfer device in the market, a user-oriented, pragmatic strategy is used to generate a solution space and create the final concept of a new system to improve the low yield of the current sample transfer workflow. A new workflow is designed and proposed to improve the yield, imaging quality and user experience of CLEM.

The goal of this project is to design a sample transfer system which protects the delicate cryo samples used in a CLEM workflow from damages caused by heating and contamination during the process of being transferred from the sample preparation device (Vitrobot) to the imaging chambers of the Focused Ion Beam Scanning Scanning Electron Microscopes (FIB/SEM) and Transmission Electron Microscopes (TEM).

Cryo-immobilized samples (at a temperature lower than $-165°C$) exhibit a large temperature gradient with its surroundings (27°C) when being transferred in the current workflow and will hence attract water molecules and other particles from their surroundings. Drastic heating which can be as fast as 2.7°C/s then causes a transition of the form of ice on the samples. The contaminants, such as cubic ice accumulated on sample surfaces, have a very negative influence on the imaging results of FIB/SEM and TEM: almost 90% of the samples transferred in this workflow end up being wasted.

Therefore, an integrated sample transfer system which fits the interfaces of CLEM devices and protects the samples from heating and contamination in transfer has been designed to conquer the problems, ensure better imaging results and increase the process yield. A literature research which covers relevant research contributions in areas such as electron microscopy, cryogenics, sample transfer systems and vacuum technologies is carried out to theoretically support the design. Based on the analysis of the literature, a set of research questions is proposed for designing as well as choosing each component. The main research question is 'what is the cheapest, easiest, most damage-free workflow for cryo sample transfer systems?'.

Answering these questions ultimately pushes forward the overall design of the system: a plunging bath is designed for sample preparation, a shield to shield the samples from heating and contamination, a vacuum box for vacuum generation and connection, a Delmicup to transfer and shield the samples, a cooling rod to actively cool the samples. A feedthrough pushing rod is selected to replace most of the human handling, a cryogen circulation & draining circuit for cryo cooling and a pumping system are integrated to reach cryo high-vacuum condition. The thermal simulations have proved the effectiveness of the passive and active cooling of the new workflow and the improvements over the old workflow. The mechanical simulations have shown the system's structural strength. The vacuum calculation suggests the pumping efficiency and time of the system. The new transfer system provides a faster, easier, more contamination-free, more temperature-stable, more user-friendly workflow that can increase the yield of sample transfer from 10% to 90%.

There is also room for improvements due to the limit in time and equipment of this project, since the workflow could be more automated in the following aspects: the clipping mechanism, most of the manual steps and system control. Experiments of sample contamination buildup and its influence on imaging results should also be carried out in both old and new workflow in the future to compare the difference and quantify the improvements.

keywords: Cryo, Cryo sample transfer, cryogenics, vacuum, AutoGrids, FIB/SEM, TEM

Contents

1

Introduction

1.1. Introduction to Microscopy

Microscopy is the science of investigating structures and object of microscopic size using an instrument called microscope Microscopic is means that the object is invisible to the naked eye without any additional help.

From the earliest of human existence the usage of the glass as a magnifying glass was a first attempt to enter the realms of microscopy. In 1590 the first compound microscope was used in the spectacles making centers in the Netherlands [**?**].Galileo Galilei (also sometimes cited as compound microscope inventor) seems to have found after 1610 that he could close focus his telescope to view small objects and built his own improved version.

Since then the intrigue to view objects which cannot be viewed by the naked eye grew considerably and the demand to view even smaller object grew.This was supported by many discoveries and publications. Anton van Leeuwenhoek and Robert Hook were a huge contributor in increasing the demand.

This created several new improvements in microscopes over the years, by the 20th century light was replaced by electrons to view even more smaller object.By 1931 Transmission electron microscope was discovered, . The transmission electron microscope works on similar principles to an optical microscope but uses electrons in the place of light and electromagnets in the place of glass lenses. Use of electrons, instead of light, allows for much higher resolution. Soon Scanning electron miscroscope (SEM) was also discovered and commercially both the TEM and SEM was available in the market by 1970's.The most recent developments in light microscope largely centre on the rise of fluorescence microscopy in biology. During the last decades of the 20th century, particularly in the post-genomic era, many techniques for fluorescent staining of cellular structures were developed.

During this time there was a new branch eveolved from the existing TEM microscopy called the cryo electron microscopy(cryo-EM).It was simply made to reduce the beam damage in the sample during TEM by experimenting on the sample in cryogenic conditions. While the development had begun in 1970's,recently in 2017, the Nobel Prize in Chemistry was awarded to Jacques Dubochet, Joachim Frank, and Richard Henderson "for developing cryo-electron microscopy for the high-resolution structure determination of biomolecules in solution."

1.1.1. Types of Microscope

optical microscope

Optical microscopy uses lens and visible light to maginify images and small objects. They are the oldest types of microscopes still in use, though modified and improved over time. They were invented in the 17th century. Optical microscopes have typically a combination of multiple lenses , including ocular and condenser lenses. By varying these light sources there can be 5 types of light microscopy

1. light microscopy

2. dark field
3. phase-contrast
4. differential intereference
5. flouroscence

SEM
Scanning electron microscopes(SEM) is a type of microscope which uses a focused beam of electron to image the surface of the sample.It forms images by scanning the sample with high intensity beam of electrons. During the interaction it produces secondary electrons, back scattered electrons and X-Rays.The signals are collecrted by detectors and the computers use image processing to produce a image The interaction of the elctrons with the sample depends on the sample size and the accelerating volatge of the electrons.

TEM
Transmission electron Microscope(TEM) is a type of microscope in which the image is formed by the electrons which have been transmitted through the sample.This creates a requirement that the specimen should be ultrathin so that the electrons can pass through it (in the range of 100nm).The image is formed by a screen or a scintillator.They are widely used in cancer research, virology,nanotechnology and semiconductor industry.

1.2. Cryo Electron Microscopy(Cryo EM)

In 2017 Nobel prize was awarded for" developing cryoelectron microscopy for the high-resolution structure determination of biomolecules in solution" to 3 scientists i.e Jacques Dubochet Joachim Frank and Richard Hendreson[14].

This is significantly ground breaking because until a few years ago it was a dream for a scientist to use an electron microscope to zoom in further into cells and organelles,just to uncover the detail structure of the biomoleculoes and observe their architechture and their function.This dream became reality recently when a series of critical developments made it possible to take full advantage of the pioneering discoveries and improvements made by Jacques Dubochet,Joachim Frank and Richard Henderson. These advances now allow structural determination of non-crystalline biomolecules in solution at high resolution, using single-particle1 cryo-electron microscopy (EM).

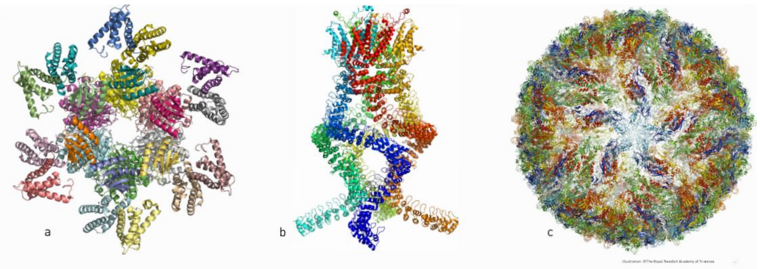


Illustration: ©The Royal Swedish Academy of Sciences

Figure 1.1

1.3. DELMIC

Delmic is a High Tech company based in Delft that produces integrated light and electron microscopy solutions. They aim to produce innovative products to offer superior performence and user expirience

Delmic was founded in 2011 by charged particles optics group of Delft and NWO institute . The flagship product was SECOM system and SPARC system.The SECOM was brought into the market by 2014 They are working their way into different segments of microscopy with products already in cathode Luminiscnece and also entering into the cryo-microscopy area which is in demand for biosciences .Delmic continues to collaborate with its founding institutions in Delft and Amsterdam and currently works on the development of new products. It has a multidisciplinary workforce from application specialists, physicist to mechanical and software engineers.

They currently focus on material science , lifesiences and geological improvemnts by introducing microscopes specific to improving imaging in these areas

2

Research Background

2.1. Sample preperation for Cryo EM

2.1.1. Trends in cryo sample preperation

Short after the experimental demonstration of an electron microscope by Ernst Ruska, for which he was honored with the Nobel Prize for Physics in 1986 (1), Ladislaus Marton published a paper (2) that commented on Ruska's discovery. In this short report, Marton noted that the new instrument unfortunately could not be used to study biological material without the "destruction of the organic cells by the intense electronic bombardment". Preventing such destruction would require a new sample-preparation technique. Marton proposed visionary solutions to the problem: cooling the biological material or the use of an approach similar to negative staining. Another major problem was how to preserve water in the biological sample in the vacuum maintained inside the electron microscope chamber. And there were even more challenges to face. To mention only the most basic ones, intact biological material has very low image contrast as most high-energy electrons pass straight through the specimen. At the same time, the electron dose must be kept low enough to prevent damage. The probability for multiple electron scattering events must be negligible at the electron energy used; i.e. samples must be thin, ideally comprising a single layer of the particles of interest. Furthermore, the studied objects often move both upon interacting with electrons and due to drifts in temperature; the movement reduces information content, especially when using film or slow detectors to record images. As a result, until recently the resolution was typically limited to a few nanometres for biological molecules.

As we can see above cooling was expected to solve the majority of the problems that were the limitations for electron microscopy for the study of biomolecules.The formation of crystalline ice could be overcome by cooling water into a vitrified state.Before the 1980's the theoretically required cooling rate for transforming the bulk water into into its vitrified state was practically unattainable.Hence the possibility was very controversial as the phenomenon has only been demonstrated for condensation of water at very cold metal surfaces.In the 19080's the controversy was finally resolved by demonstration proving that the rapid cooling of micrometer-sized droplets of bulk water.In 1981 Dubochet and Alasdair McDowell finally presented a method that allowed formation of a film of non-crystalline solid water in a specimen grid for EM.

The method consisted of numerous steps , first the water was sprayed on a carbon film mounted on a grid, after which the grid was rapidly immersed in liquid ethane or propane at -190°C with maintenance of cooling by liquid nitrogen.This formed this layer of vitrified water was shown to yield nearly uniform absorption of electrons in cryo-EM. The conversion temperature of amorphous to crystalline form was at a temperature about -140°C. It was also observed by Dubochet that the vitreous ice could be maintained for an extended period of time around the specimen if the temperature was kept below -160 °C.Dubochet further improved the sample preparation method further with aqueous solutions ,suspensions of bacteriophages and DNA at cryogenic temperature.

2.1.2. Technical Developments

With the improvements in workflow there have also been a continuous development in the microscope industry in terms of the technology available and the rapid integration to achieve better imaging resolution.

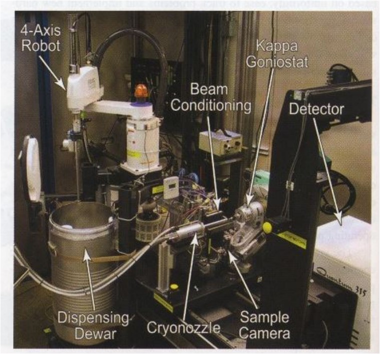


Figure 2.2

Electron detectors were a major development in the recent times. The detectors are constructed from monolithic active pixel sensors, based complementary metal oxide semiconductors, known as CMOS technology.These sensors were used in astronomy but are now used in Electron Microscopy as Direct electron detectors since 2012-2013. They have improved speed ,less noise and detection of high energy electrons.

Volta phase plate also solves problems such as volt correction, encountered when using defocusing to obtain phase contrast in the electron microscope.Recent developments in image processing and computer programs have also been essential for the current developments.New algorithms such as Maximum likelihood estimate was implemented to get better image quality with high contrast.

2.2. sample exchange systems

Sample exchange systems are an essential parts of many industries.It consists of many systems from pick and place mechanisms to micro-sample handling. This section deals with different types of sample handling systems which are used in the industry and their innovations

2.2.1. SSRL Automated Mounting (SAM) system

SAM is a fully integrated hardware and software system for mounting and dismounting pre-frozen protein crystals and judging samples for quality in a semi-automatic system. SAM is installed on all of SSRL macro molecular crystallography beam lines and is integrated into the beam line control and analysis software. The sequence of mounting the sample, loop centering in the x-ray beam, video and diffraction image acquisition at 0 and 90 degrees and dismounting takes less than three minute per sample.The images are analyzed on the fly.[?]

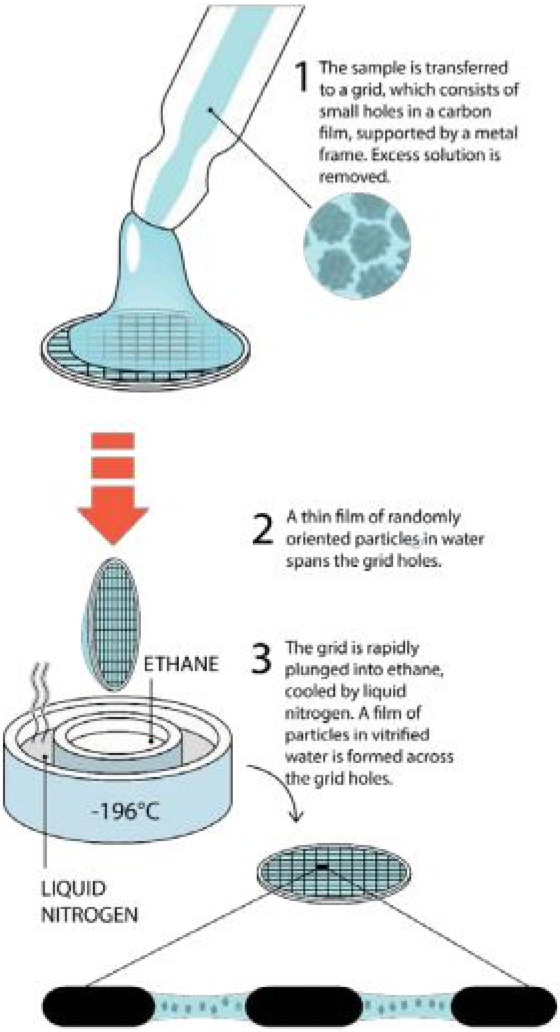


Figure 2.1

The storage of the samples are stored in specialized SSRL cassettes for use of SAM.There are two types of container for storage of the samples.

SAM has improved the quality of the diffraction data.Manual screening was also a tedious data.Using SAM scientist can easily screen all of their samples for a quality data collection

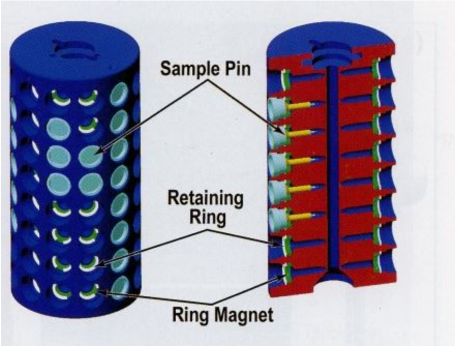


Figure 2.3

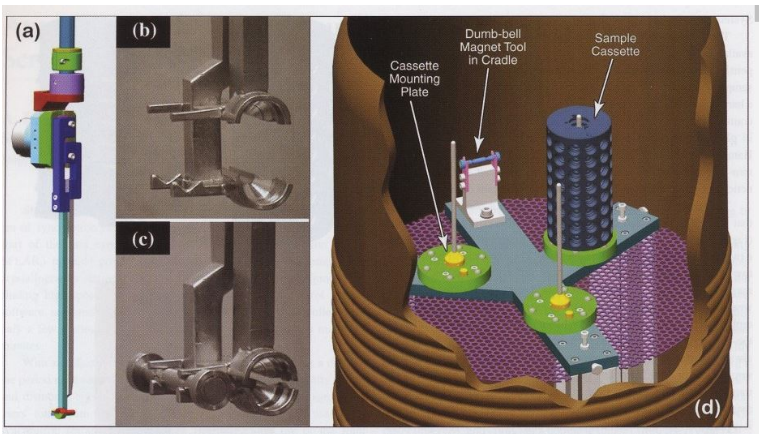


Figure 2.4

System Description
The complete system i based on the commercially available 4 axis robot (SCARA) and a Dewar of liquid nitrogen which hold the sample storage cassettes adjacent to the sample goniomete.The SSRL cassette is a aluminum cylinder with 96 sample ports,each sample has a ring magnet which holds the ring sample in place inside the cylinder(Ref fig 2.3)

The translation of the robot is achieved by the pneumatic actuator that is used to open and close multi functional crystal transport tongs. One side of the tongs has a small finger that is used to grip a two sided sum bell shaped magnet tool.The magnetic strength of both the ends are different as the stronger one is used to remove the sample pin from the cassette storage while the weaker side cannot perform the extraction. The weaker side is used to replace the sample in the the cassettes.Whenever the magnet dumbbell is not in use it is kept submerged in the liquid nitrogen. For safe transport of the samples out of the liquid nitrogen . This side has a standard cavity similar to that found on the standard manual cryo tongs.The cavity surrounds the sample pin and keeps the crystal protected at cryogenic temperaturesduring transfer to and from the beamline gonoimeter.[13]

2.2.2. Photon factory robot PAM-HC

Automated sample exchange robots are indispensable for the operation of beamlines at synchrotron, neutron and other facilities which enables automated ,efficient and remote experiments.This particular robot is used in the structural biology research center in the Photon Factory(PF) called the PAM(PF Automated mounting systems) and operated them in the macromolecular crystallography beamlines BL-5A and AR-NW12A since 2006 .[5] The beamline, BL-1A, was designed for low energy experiments: for this purpose, a helium path was implemented between the sample and detector in order to decrease the absorption of the diffraction signal by air during the experiments. To increase the effectiveness of the helium path, we enclosed the entire diffractometer in a helium chamber. In addition, we developed a new, specialized sample exchange robot, PAM-HC (Helium Chamber), in parallel with development of the helium chamber, designed to minimize the

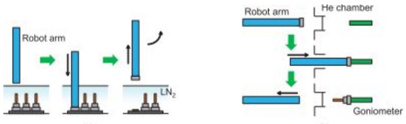


Figure 2.5

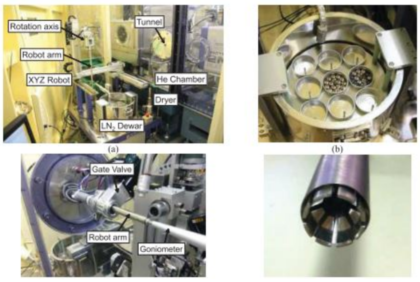


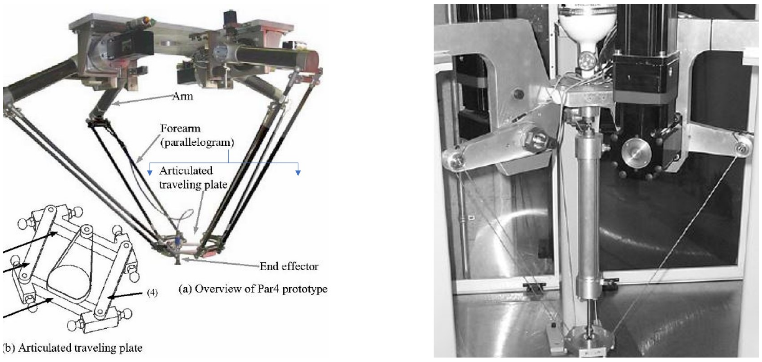
Figure 2.6

leakage of helium gas. The PAM-HC arm is fixed on a rotation axis and an XYZ robot and is equipped with a pneumatic collect at the tip of the robot arm, shown in Fig. 2 (d), in order to grasp and release the cryo pins. The gate valve is used to keep the concentration of helium gas at nearly 100

2.2.3. Par4: High speed parallel pick-and-place robot

The mechanism proposed by Nabat and Rodriguez is a four DoF parallel manipulator that has an architecture particularly suited for high dynamics[9]. High accelerations of 13g have been reached with a cycle time of 0.28s. A prototype of this mechanism is shown in Fig. 2.7(a). The end-effector has 4 degrees of freedom. It can translate in all three axes and rotate about the vertical axis. It has four parallel kinematic chains granting it homogeneous behavior in all directions and a good stiffness within the workspace. A disadvantage with these type of legged-mechanisms is the presence of singularities. In certain configurations, usually when the fore-arm and upper-arm linkages become collinear, the subsequent behavior of the mechanism cannot be predicted.

This type of mechanism could be a good option for our test rig but the acceleration offered by this particular set-up is insufficient. A different actuator may be used to obtain greater accelerations. The hinges can also be a source of error due to backlash and wear.



(a) (b)

Figure 2.7: (a) Prototype of Par4 Concept (b) Prototype of CableBot concept

2.3. Motion Planning

In a task orientation industrial robot. The system is expected to repeat a set amount of tasks. The tasks can be grasping, movement and placements etc. These generalise tasked can be subdivided into goals.When each goal is performed by a robot, it has numerous ways to execute that task while the end product remains the same.For example, If a robot has to move from Point A to a point B in the coordinate system . It can take numerous ways the system can take going from A to B.There are lot of dependencies which dictate how the velocities and path planning should take place . It depends on factors such as environmental constraints , maximum torque and force provided by the actuators.Hence, Motion planning is the process of selecting the motion and its corresponding torque and forces while satisfying the external constraints imposed on them via the environment

Robot planning employes 3 different spaces for selection of the motion. The task space, joint space and the actuator space. The actuator is the source of all the energy and the powerhouse of the system. The actuator space supplies is dynamically coupled to the joint space and the joint space provides a kinematic coupling to the the space.The diagram depicts the complete dependencies with the spaces. The obstacles in a robot motion creates additional factors to be taken into considerations. The additional considerations are usually represented in a configuration space. The configuration space(C-Space) defines all the paths which are in direct conflict with the obstacle , motion path which graze the surface of the obstacle and finally all the possible motion paths which are completely avoiding the obstacle.The motion planning has types of algorithms which are classified into 2 kinds

- implicit
- explicit

Implicit algorithms are algorithms which plans a strategy for controlling the robot in the presence of obstacles in the environment . The strategy is never per-computed and always decided by a function which dictates the movement according to certain potential function. The potential function dictates how it reacts to sensory information and environment interaction.They are usually closed loop and are dependent on sensory information.

Explicit methods focus on the problem of finding a set of discrete configurationsThey find the basic motion system which is finding a configuration for a set of start an send goals , which is basically a feedforward way of selecting a motion.They dont take any feedback information. They are further divided into discrete, continous and underactuated motion planning algorithms.The motion planning is an important part of the system altogether but it is also decided mostly in experimentation with the whole system as the positions of the items and obstacles are not completely decided when the whole system is not completely designed

2.4. cryocoolers

Cryocoolers are essential in cryo-EM. They are used for keeping the sample at cryogenic temperature. Cryocooling can be achieved in many ways i.e

1. Mechanical pumps
2. using combination of chemicals such as liquid nitrogen baths

This section deals with different types of cryocoolers available in the industry and their properties. The focus is on mini controllers which can be easily transportedThe development of small coolers is of importance for coo- ling electronics to cryogenic temperatures. Cooling can improve the signal to noise ratio and the system bandwidth and it reduces aging

2.4.1. Linde-Hampson cooler

This type of a cooler is a combination of liquid nitrogen flow and glass tube heat exchanger.This cooler works on principle of Linde-Hampstead (LH) cycle as one of the major advantage of this cycle is the moving parts in the cold stage. This cold stage is a combination of counterflow heat exchanger(CFHX) and a joule thomson(JT) valve.

The cycle works in the following way.The high- pressure gas, at 10 MPa in Fig. 2.8, enters the CFHX in state A.It is subsequently cooled to state B by heat transfer to the low-pressure return fluid, in Figure 1 at pressure 0.1 MPa, that warms from state D to state E. The high- pressure fluid in state B expands isenthalpically to state C in the liquid–vapour envelope. Part of the fluid liquefies and part is vaporised in state D. Cooling is obtained via the liquid fraction that can take up heat from the environ- ment and also vaporize into state D. The corresponding cooling power is equal to the mass flow rate times the dif- ference in specific enthalpy between the states D and C.

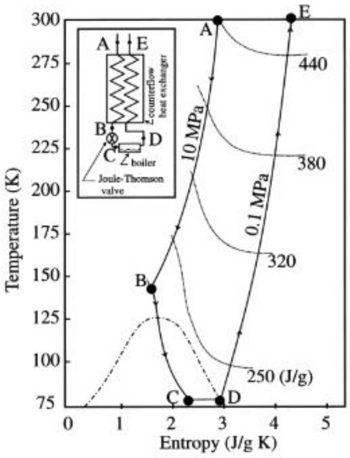


Figure 2.8

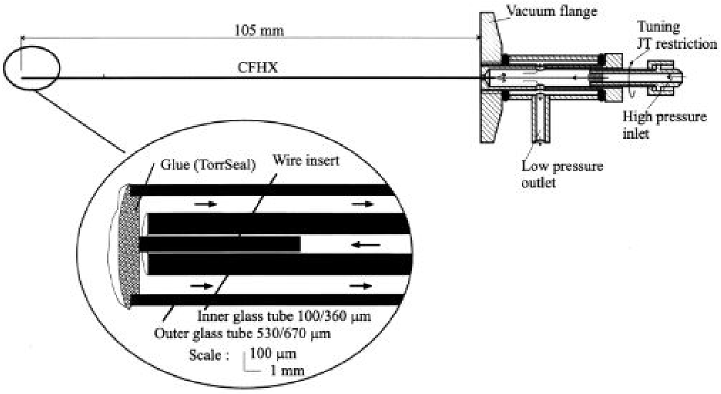


Figure 2.9

The smallest cooler they presented measured15 x 2 x 0.5 mm3 and could reach 88 K with zero load or could supply a cooling power of 25 mW at 101 K, with circulation of 3.1 x 10^{-6} kg/s nitrogen gas at a pressure of 16.5 MPa.Tip of the outer tube is closed by a small plug of seal(Torrseal) .The JT valve is formed at the tip by the inner tube which is 0.08mm in diameter and 15mm in length , it is made of NiCr wire.The outlet of a metal outlet tube and a rigid high-pressure connector is connected by a glass tube CFHX as shown in Fig. 5.9the flow impedence of the JT valve can be tuned by this. All glue connections are made with TorrSeal. Because of the thin- walled glass tubes the cooler is rather flexible (minimum radius of curvature roughly 15 cm).

The research paper [**?**] stated that the Linde-Hampson cooler can be made in a surprisingly simple way out of glass tubes. The 270 mm cooler is efficient enough to reach the boiling temperature of nitro- gen even at a supply pressure of only 7 MPa. The shorter cooler (105 mm) can also reach the boiling temperature, but only in a restricted flow range of 1.0–2.3 × 10^{-6}kg/s.Advantages are that the CFHX made out of small glass tubes is cheap, flexible and the mass is less then 0.2 g. There are disadvantage because of the flexibility of the tubes this is difficult and only possible by means of a spacer between the inner and outer tubes.

2.4.2. Supercooling of peltier cooler using current pulse

Peltier cooling can be a very effective way of achieving cryocooling as the pelitier coolers have no moving parts and are easy to manufacture.A Peltier cooler uses the thermoelectric effect to transport heat with the application of an electric current.The cooling coefficient of performance and maxi- mum temperature drop depends on the properties of the ther- moelectric materials used through the figure of merit$Z = \frac{\alpha}{\rho\kappa}$, where α is the seedback coefficient ,ρ is the electrical resistivity and κ is the thermal conductivity.This is very important as the heat removed due to the peltier cooling is propotional to the Current I, is counteracted by the joules heating proportional to I^2R. Since joule heating is proportional to the 2nd power of current. There has to be a maximum current that produces the best temperature difference between he terminals.

Peltier cooling occurs at the junction at the cold end of the thermoelectric elements. Joule heating, however, occurs uniformly throughout the thermoelectric elements. Thus when current is applied, the cooling at the cold junction occurs before the Joule heat reaches the cold end. In this way, an applied current pulse Imax can be used to temporarily produce a difference in temperature greater than Tmax .

Such a cooler could be useful for a device such as a mid-IR laser gas sensor, or any other semiconductor device that needs to be cold for a few milliseconds.Experiments were carried out by the researchers at JPL(Jet propulsion laboratory at Caltech, Pasadena).[12]

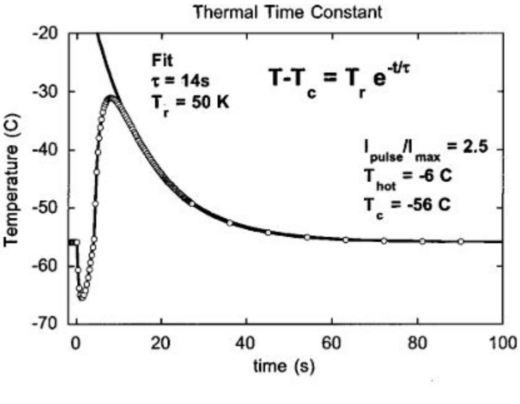


Figure 2.10

The conclusion was that the time to reach minimum temperature and the time below a specific temperature can be predicted with a simple equation, derived from simplifications to the heat equation. Both times decrease as the current pulse is increased. After pulse cooling, the sample will overheat by an amount that can be predicted by a simple empirical relationship. The re- turn to steady-state temperature follows simple exponential decay

2.5. sensors

Sensing by mechanical terms is the ability of a machine to detect an required object or a change in environment.A sensor is always accompanied with relevant electronics which is mostly used to convert the detected signals into readable values. The sensors required for the system for the SEM is mostly due to the positioning sensing of the robot and collision detection during transfer. It is important the system ensures a successful extraction of the grid.To summaries the basic assumption to detect certain objects in the way is important

1. The system should be ble to detect the grids
2. The system should be able to detect the cassette position
3. The system should be able to detect the stage position
4. Th

There have been lot of research on the sensor systems for robotic hand,and three types of sensing systems have been tested

- Non-contact
  - Vision sensors
- Proximity
  - proximity sensors
- Contact
  - stick-slip sensors
  - tactile sensors

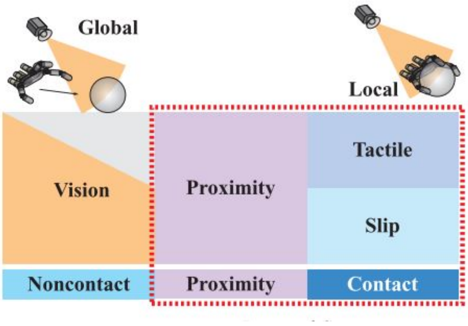


Figure 2.11

For our current system we can discard tactile system as it is difficult to maintain crygonic temperature when initiating touching and also during movement from A to B we have to ensure collision less travel..We can look more into proximity and vision sensors for a deeper idea.

2.5.1. vision sensors

Vision sensors are typically used a a global positioning devices rather than an precision positioning. The use of vision sensors as a means of feedback and moment is called visual serving as the motors have an included feedback mechanisms to change the pose of the robotic hand.Visual servoing (VS) has been divided into the [2]

1. Eye to hand- the visual system is on a fix frame outside the moving robot
2. eye in hand - the visual system is on the moving robot controlling its movement dynamically

In eye in hand motion control the system is a closed loop control , where the camera is observing the relative motion of the target and the robot.While in eye to hand visual servoing the system is an open loop control , the camera is fixed and observing both the robot motion and te target location. The aim of a vision based

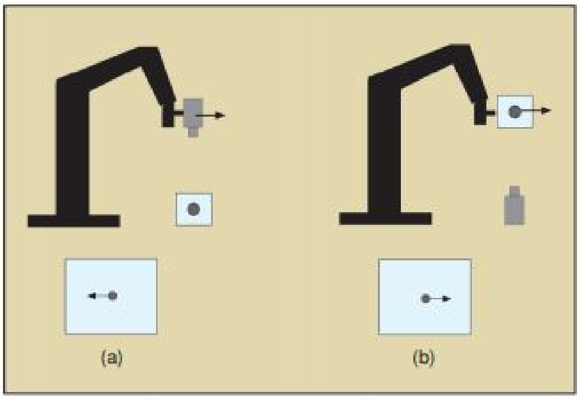


Figure 2.12

control system defined by[3]

$$e(t) = s(m(t)) - s*$$

where the objective is minimize the error$e(t)$.the vector $s*$ is the desired value or feature. While the s vector is the current value or feature. $m(t)$ is the image measurements and a is the additional knowledge about the system.There are 2 servoing schemes in liteature.

- image based visual servoing(IBVS)
- pose based visual servoing(PBVS)

In IVBS the vector s consists of a set of features available through the image while in PBVS , which consist of a pose which is estimated from an image measurement and a 3-D model of the object observed to be known.After the s is selected the control scheme is very straight forward for a velocity controller.

2.5.2. proximity sensors

Proximity sensors are able to detect the presence of objects using electromagnetic fields, light and sound. There are lot of subdivisions of the proximity sensors which are used depending upon the environment. The broad classification includes :

- inductive sensors
- capacititaive sensors
- photoelectric sensors
- ultrasonic sensors

A brief overview into the whole working of a proximity sensors.

inductive sensors

These non-contact proximity sensors detect metallic(especially ferrous) targets, suitable for mild steel with greater than 1mm thickness,. Inductive proximity sensors consists of four components usually: a ferrite core with coils, an oscillator, a Schmitt trigger, and an output amplifier. The oscillator is responsible for creating an oscillating magnetic field from the ferrite core at the sensing face. When a ferrous target enters the magnetic field , it induces an edy current on the target object. This causes a change in the natural frequency of the magnetic field, which in turn reduces the the amplitude of the oscillations. As more metal enters the sensing field the oscillation amplitude shrinks to collapse.This phenomena is called the Eddy current Killed oscillator(ECKO).The schmidt trigger is responsible for generating a response for the amplitude reduction.Inversely when the target moves oyt of the sensor range the amplitude increases and schmidt trigger returns the sensor to its previous state.

nductive sensors are typically rated by frequency, or on/off cycles per second. Their speeds range from 10 to 20 Hz in ac, or 500 Hz to 5 kHz in dc. Because of magnetic field limitations, inductive sensors have a relatively narrow sensing range — from fractions of millimeters to 60 mm on average — though longer-range specialty products are available.

To accommodate close ranges in the tight confines of industrial machinery, geometric and mounting styles available include shielded (flush), unshielded (non-flush), tubular, and rectangular “flat-pack”. Tubular sensors, by far the most popular, are available with diameters from 3 to 40 mm.

capacitive sensors
Capactive proximity sensors can be used to sense ferrous and non materials like powder, granulate, liquid and solid form.They are mostly used for glass monitoring,tank level detection,hopper powder level.

these sensors are made up of two conduction plates which are at different potentials at the sensing head and positioned to operate like an open capacitor . Air acts as an insulator in between . Similar to inductance sensors, the platyes are linked to electronics like the schmidt trigger and an output amplifier. As the target enters the sensing zone the capacitance is changed due to change in geometry of the capacitor. This causes amplitude change in oscillator.As the p[lates have to be charged , it is somewhat slower than the inductive sensing, ranging from 10 to 50Hz, with sensing range from upto 12 to 60mm.There is also a lot of false triggering in these sensors as it reacts to lot of materials and hence have to be used in environment where it should not get triggered by other elements.

photoelectric sensors
photoelectric sensors are very versatile sensing devices.They can easily detect targets less than 1 mm in diameter, or from 60 m away.Classifications depends on how the light is emitted and received However, all photoelectric sensors consist of a few of basic components: each has an emitter light source (Light Emitting Diode, laser diode), a photo diode or phototransistor receiver to detect emitted light, and supporting electronics designed to amplify the receiver signal. The emitter, sometimes called the sender, transmits a beam of either visible or infrared light to the detecting receiver.

ultrasonic sensors
Ultrasonic proximity sensors are used in many automated production processes. They employ sound waves to detect objects, so color and transparency do not affect them (though extreme textures might). This makes them ideal for a variety of applications, including the longrange detection of clear glass and plastic, distance measurement, continuous fluid and granulate level control, and paper, sheet metal, and wood stacking.

3

System design

3.1. improved workflow

The desired reault of the overall project is to create a simplified workflow process for the sample preperartion of the cryo-microscopy lemela preperation. The existing workflow is continued since its discovery in the 20th century. The conventional workflow model is provided below

Figure 3.1

We can see that the biological samples goes through 22 different steps to be finally be imaged on a TEM. It is very important to understand the sample is biological cells which have to be kept at a certain minimum tempertaure to be viable for imaging. The samples are prone to contamination and heating during the all 22 steps which cause majority of the samples to be destroyed even before reaching the TEM.

1. The sample is grown on the TEM Grid
2. The grid is plunge frozen into a liquid nitrogen bath
3. The grid is extracted to a holder
4. C clips and a copper ring is attached to the grid to imrpve its mechanical rigidity
5. The grid is transffered to a carrier

6. the carrier is placed on a cryo transfer
7. The grid is taken to a Floroscence microscope
8. The carrier is unloaded
9. Transfer to light microscope
10. Imaging in light Microscope
11. The LM is used to map the ROI's. (Region of interest)
12. Take the sample ou tof the LM
13. Place it back in the carrier
14. The carrier is placed on the
15. Take it to FIB/SEM
16. load the sample into the FIB/SEM
17. Map the ROI on the sample
18. FIB lamella cutting the sample to smaller size suitable for TEM
19. Unload from FIB/SEM
20. Place it in the cryo transfer
21. Transfer it to the autoloader
22. Take the casette to the TEM

The objectoive of delmic is to improve the workflow of the system to enable more efficient imaging of the biological samples. Hence its primary focus is on integration and automation of the workflow.This has been partially achieved by Delmic by designing a SEM which also includes a optical microscope. Hence the improved workflow can be visualised in a 14 step procedure given below

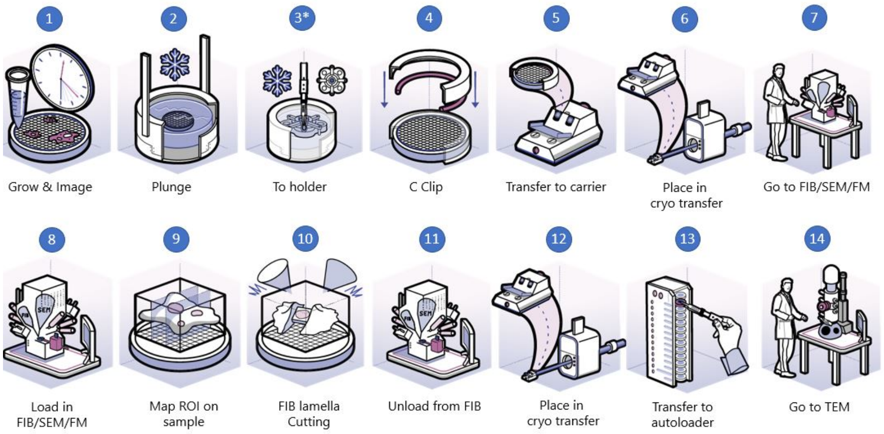


Figure 3.2

However we can still se some places where the sample has to be taken out of a microscope and kept on a carrier and moved further to the next station. There are several deficiencies in the above workflow which is explained by the pictures below The red boxes are the points of transfer which also cause significant human interaction which induces contamination, jerks and damaging movements which should be improved. The final expected workflow model is shown below Here the new transfer system which is to be designed should be:

- actively cooled

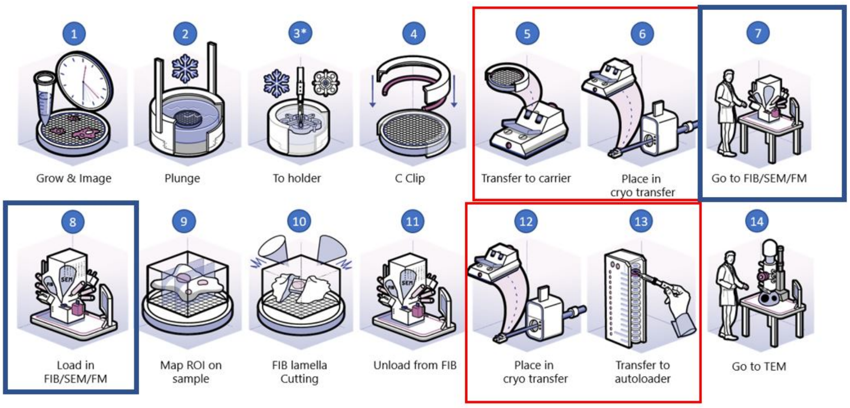


Figure 3.3

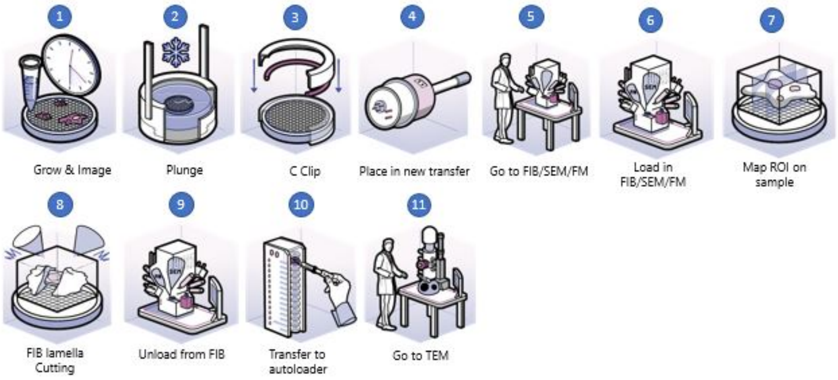


Figure 3.4

- easy to use(user friendly)
- always kept in vacuum
- automated and monitored

The above requirements are essentially customer requirements for the system as it directly entails the solution the industry feels should be able to provide. In the section of the system requirements these requirements will be further expanded and explored

To achieve this requirements through the whole process ,the whole project is divided into 3 areas of focus

- TEM Grid plunge freezing system
- contamination analysis during the process
- automation of the sample extraction and placing into the microscope(SEM)

My focus is on the automation of the pick and placing of the sample inside the microscope.

The total problem can be divided into 4 sections

3.2. V model

The evaluation,verification and validation of the model is an essential part of the systems engineering method.It is very important that there is verification and validation to improve system architecture. V model presents a method of designing systems. It is a improved model over the traditional waterfall model. The traditional waterfall model is a sequence of steps which in total constitute of a single system development.The waterfall method is a flexible approach rather than an iterative approach. it has a unjidirectional flow through initatiation, analysis to testing deployment and maintainence.

The V method is a simple variant of the waterfall method method with emphasis on verification and validation for each step of its process. The V method has 2 branches the ideation and the validation branch and both the braches have to verified with each other.

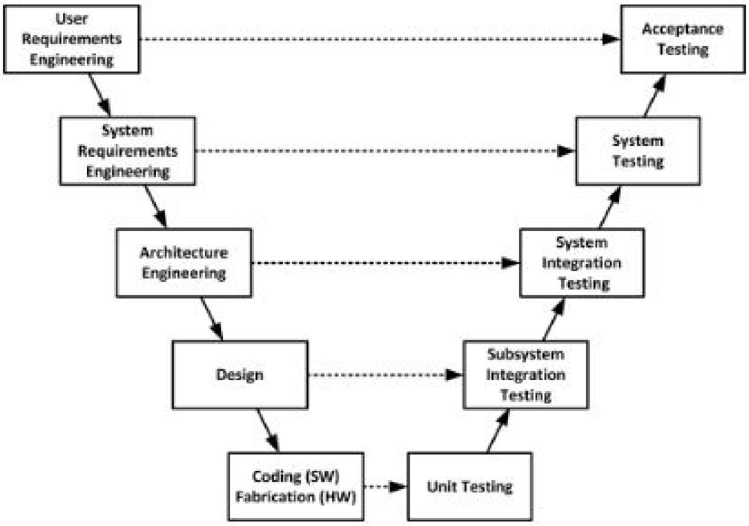


Figure 3.5: V- Model

For the project the objective is to complete till the unit testing.

3.3. customer requirements

The customer requirement for this product is very limited because the iteraction with the customer is minimal. The system is developed based on the requirement that there should be minimum human interaction possible.The only contraint is that the system should be compatible with the cassette which is a fixed design constraint for the entire process

From that we can see that the customer requirement is below:

The system should be compatible with the current FEI Cassette. The cassette can be inserted into the chamber and extracted from the chamber after experimentation on the FIB-SEM.

There can be some derived user requirements, which has been summarized below

- The system detects the grids on the cassette
- The system gives a readout when the grid is placed inside the stage
- A readout when the cassette is ready to be taken out from experiment
- Jamming readout when the system is unable to calibrate

3.4. system requirements

This table describes the customer requiremests of the system

3.5. risk assesment

The possible and expected risks are analysed and prioritised in a list below:

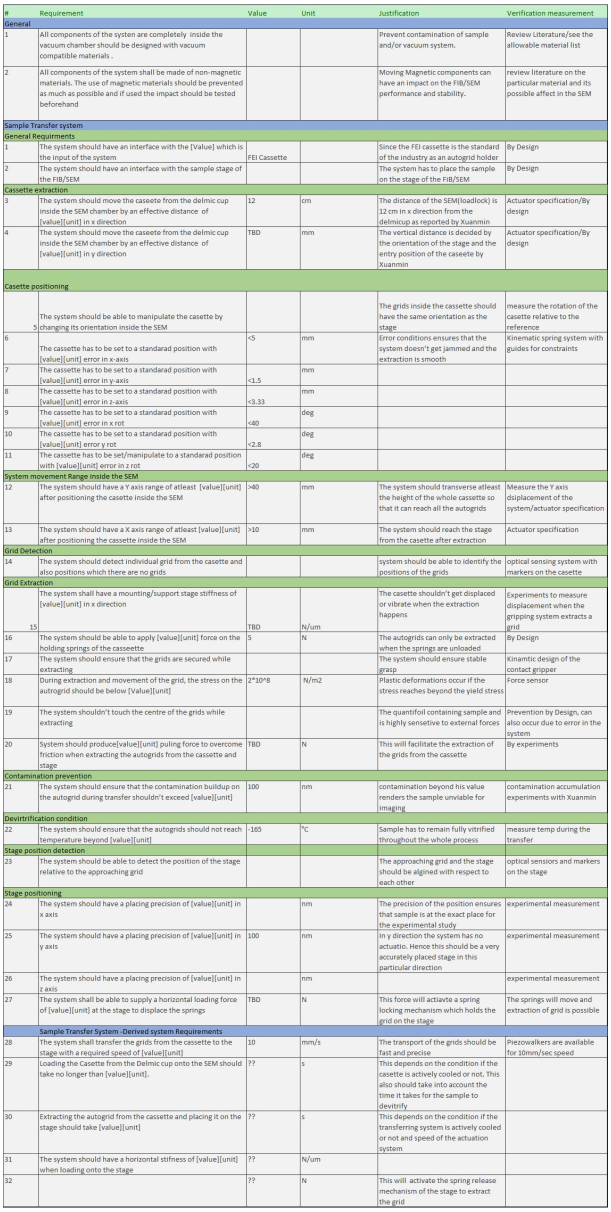
3.6. conclusion

After System Design we can see that the whole problem can be divided into the following design problems:

- Gripper design
- sensing the movement inside the microscope
- control system design which governs the complete system movement
- actuation of the system and ensuring that the precision is maintained during actuation of the system

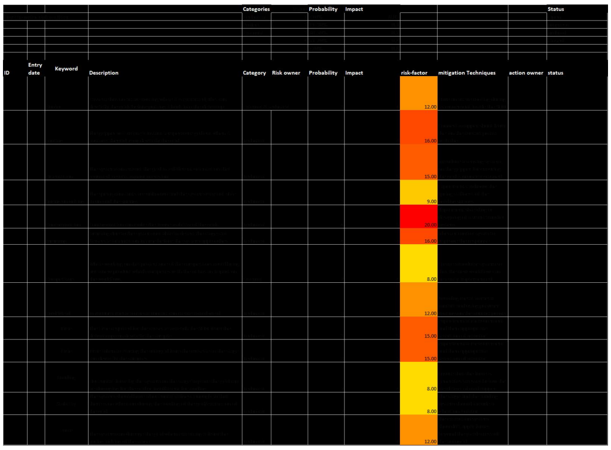
From the above subclassification of the problems, we can see that solving the gripping subproblem will enable us to esure the further design of the system. The gripper system will define the interaction between the grid and the environment.Hence it is very important that we design that the system first before proceeding in to the sensing and the actuator design. We need a gripping system as

- Gripper ensures a position certainty of the grid(grid is always with the gripper) during transfer
- Contamination is avoided and devitrification is controlled
- Future modifications in the workflow is easy to integrate with the gripper
- The automation system makes the system flexible in reaching various other places in the microscope in the future for placing e.g. having 2 cassette to sort out the bad and good samples



#	Requirement	Value	Unit	Justification	Verification measurement
General					
1	All components of the systen are completely inside the vacuum chamber should be designed with vacuum compatible materials .			Prevent contamination of sample and/or vacuum system.	Review Literature/see the allowable material list
2	All components of the system shall be made of non-magnetic materials. The use of magnetic materials should be prevented as much as possible and if used the impact should be tested beforehand			Moving Magnetic components can have an impact on the FIB/SEM performance and stability.	review literature on the particular material and its possible affect in the SEM
Sample Transfer system					
General Requirments					
1	The system should have an interface with the [Value] which is the input of the system	FEI Cassette		Since the FEI cassette is the standard of the industry as an autogrid holder	By Design
2	The system should have an interface with the sample stage of the FIB/SEM			The system has to place the sample on the stage of the FiB/SEM	By Design
Cassette extraction					
3	The system should move the caseete from the delmic cup inside the SEM chamber by an effective distance of [value][unit] in x direction	12	cm	The distance of the SEM(loadlock) is 12 cm in x direction from the delmicup as reported by Xuanmin	Actuator specification/By design
4	The system should move the caseete from the delmic cup inside the SEM chamber by an effective distance of [value][unit] in y direction	TBD	mm	The vertical distance is decided by the orientation of the stage and the entry position of the caseete by Xuanmin	Actuator specification/By design
Casette positioning					
5	The system should be able to manipulate the casette by changing its orientation inside the SEM			The grids inside the cassette should have the same orientation as the stage	measure the rotation of the casette relative to the reference
6	The cassette has to be set to a standarad position with [value][unit] error in x-axis	<5	mm	Error conditions ensures that the system doesn't get jammed and the extraction is smooth	Kinematic spring system with guides for constraints
7	The cassette has to be set to a standarad position with [value][unit] error in y-axis	<1.5	mm		
8	The cassette has to be set to a standarad position with [value][unit] error in z-axis	<3.33	mm		
9	The cassette has to be set to a standarad position with [value][unit] error in x rot	<40	deg		
10	The cassette has to be set to a standarad position with [value][unit] error y rot	<2.8	deg		
11	The cassette has to be set/manipulate to a standarad position with [value][unit] error in z rot	<20	deg		
System movement Range inside the SEM					
12	The system should have a Y axis range of atleast [value][unit] after positioning the casette inside the SEM	>40	mm	The system should transverse atleast the height of the whole cassette so that it can reach all the autogrids	Measure the Y axis dsiplacement of the system/actuator specification
13	The system should have a X axis range of atleast [value][unit] after positioning the cassette inside the SEM	>10	mm	The system should reach the stage from the casette after extraction	Actuator specification
Grid Detection					
14	The system should detect individual grid from the casette and also positions which there are no grids			system should be able to identify the positions of the grids	optical sensing system with markers on the casette
Grid Extraction					
15	The system shall have a mounting/support stage stiffness of [value][unit] in x direction	TBD	N/um	The casette shouldn't get displaced or vibrate when the extraction happens	Experiments to measure displacement when the gripping system extracts a grid
16	The system should be able to apply [value][unit] force on the holding springs of the casseette	5	N	The autogrids can only be extracted when the springs are unloaded	By Design
17	The system should ensure that the grids are secured while extracting			The system should ensure stable grasp	Kinamtic design of the contact gripper
18	During extraction and movement of the grid, the stress on the autrogrid should be below [Value][unit]	2*10^8	N/m2	Plastic deformations occur if the stress reaches beyond the yield stress	Force sensor
19	The system shouldn't touch the centre of the grids while extracting			The quantifoil containing sample and is highly sensetive to external forces	Prevention by Design, can also occur due to error in the system
20	System should produce[value][unit] puling force to overcome friction when extracting the autogrids from the cassette and stage	TBD	N	This will facilitate the extraction of the grids from the cassette	By experiments
Contamination prevention					
21	The system should ensure that the contamination buildup on the autogrid during transfer shouldn't exceed [value][unit]	100	nm	contamination beyond his value renders the sample unviable for imaging	contamination accumulation experiments with Xuanmin
Devirtrification condition					
22	The system should ensure that the autogrids should not reach temperature beyond [value][unit]	-165	°C	Sample has to remain fully vitrified throughout the whole process	measure temp during the transfer
Stage position detection					
23	The system should be able to detect the position of the stage relative to the approaching grid			The approaching grid and the stage should be algined with respect to each other	optical sensiors and markers on the stage
Stage positioning					
24	The system should have a placing precision of [value][unit] in x axis		nm	The precision of the position ensures that sample is at the exact place for the experimental study	experimental measurement
25	The system should have a placing precision of [value][unit] in y axis	100	nm	In y direction the system has no actuatio. Hence this should be a very accurately placed stage in this particular direction	experimental measurement
26	The system should have a placing precision of [value][unit] in z axis		nm		experimental measurement
27	The system shall be able to supply a horizontal loading force of [value][unit] at the stage to displace the springs	TBD	N	This force will actiavte a spring locking mechanism which holds the grid on the stage	The springs will move and extraction of grid is possible
	Sample Transfer System -Derived system Requirements				
28	The system shall transfer the grids from the cassette to the stage with a required speed of [value][unit]	10	mm/s	The transport of the grids should be fast and precise	Piezowalkers are available for 10mm/sec speed
29	Loading the Casette from the Delmic cup onto the SEM should take no longer than [value][unit].	??	s	This depends on the condition if the casette is actively cooled or not. This also should take into account the time it takes for the sample to devitrify	
30	Extracting the autogrid from the cassette and placing it on the stage should take [value][unit]	??	s	This depends on the condition if the transferring system is actively cooled or not and speed of the actuation system	
31	The system should have a horizontal stifness of [value][unit] when loading onto the stage	??	N/um		
32		??	N	This will activate the spring release mechanism of the stage to extract the grid	

Figure 3.6



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[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	

ID	Entry date	Keyword	Description	Category	Risk owner	Probability	Impact	risk-factor	mitigation Techniques	action owner	status
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		[illegible]	[illegible]	[illegible]				16.00	[illegible]		
		[illegible]	[illegible]	[illegible]				15.00	[illegible]		
		[illegible]	[illegible]	[illegible]				9.00	[illegible]		
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		[illegible]	[illegible]	[illegible]				8.00	[illegible]		
		[illegible]	[illegible]	[illegible]				12.00	[illegible]		

Figure 3.7

4

Research question and problem statement

4.1. Problem statement

The use of cryo-Microscopy in the life sciences areas is increasing at a very fast rate.Cryo-Microscopy is used in lot of material science , biology and semiconductor industry.The most useful and chellenging part of it is to see the structure of the protein cells of virusees and biological cells to make a advancements in the microbiological research and disease prevention.According to Delmic 70%of the samples are destroyed before even reaching the microscope. The procedure for preparing the sample is very complicated. A sample has to complete atleast 22 steps till it reaches the TEM Microscope while maintaning a particular temperature throughout the whole provcess and preferably in vacuum condition in the whole time..The sample is biological cells which have to be imaged and are hence very delicate to handle.Each step in the sample preperation process makes the sample prone to become contaminated or affected by temperature shocks or completely destroyd by the mishandelling. Delmic is interested in improving the sample viability by improving the current sample preperation workflow.There is a group inside delmic which is working on developing integrated cryomicroscopes for further simplyfying the workflow process. But there is also need to improve the sample handling as improving the microscope is of no consequence if the sample is destroyed before even reaching the microscope. The objective is to improve the current sample handling. The problem points in the whole process was identified by the cryo group in delmic and three students were chosen to solve each particular problem. The problem points are given below

- sample handling during vitrification
- sample handling will it reaches thw microscope
- sample handling inside the microscope

I was assigned to solve the sample handling inside the microscope

4.2. Research question

The Rearch objective is to improve a sample handling system inside the microscope which is able to monitor the sample temepratrue and ensure that the sample is kept in a UHV(Ultra hig Vacuum) condition.The current system uses a 12 sample casette which is a standardised cassette used in lot of microscopes in the world. Hence we also take this casette and design a system which is able to extract sample inside to place it on the microscope sample stage and vice-versa while keeping the sample image -viable for the entire travel. The accuracy and repeatability of the sample extraction is highly important due to the small size of the sample and the casette and the fragility of the biological sample. The improved design is supposed to adress many ofthe current problem .

The research question posed is that

How can we design a mini gripper which is able to extract millimeter sized sample from a space without using any sensors and ensuring certain imposed requirements on it.

5

gripper Design

This chapter focuses on the contact interface between the robot and objects as well as on contacts among objects and between objects and constraints in the environment.The focus is on the manipulation rather than the manipulator.Manipulation includes grasping,pulling , rolling , throwing,catching and tapping.For this this point of view we want to focus on grasping as it is the required interaction. This chapter explores the existing technologies in grasping then explores the theories of grasping, the required constraints in the system. Then finally some concept designs will be provided and finally a favorable design will be selected.

5.1. Research background

In respect to gripper research , the content is vast in the literature. There have been lot of grippers in development . The one of most earliest research into gripper hands is the MIT hand reported in 1984 . They had two important research objective, first was to develop and test different control system methods and manipulation techniques and the second objective was to do develop tactile sensing hands which can mimic the human nature[6].They concluded with a experimental hand with 25 degrees of freedom and it responded well to high and low manipulation.It was designed for a long term research use and was designed such that it can be easily reconfigured.The improved deterity was also a research topic in robotics in the Stanford labs and they together collaboarted with JPL(Jet propulsion lab) to create a Stanford handFig. 5.1b.Their research mostly connected to hysteresis due to friction,dynamic modelling and system identification of the system. They concluded succesful testing but insisted that having many fingers hindered the coordiantion in grasping as the computational power was limited and suggested better motion control labs in the future.[8].

The standford arm inspired by the sailsbury hand [11], they were looking into a end effectors with only 6 degrees of freedom with simeple graspinng and improving the precision in small displacements of the hand and the ability to improve the variable object handling.They experimented with several areas such as mobility, force application, inaacuracies and singularity and noise propagation. Inspired from them various hands were developed. A few examples include the okada hand[10],Upenn hand[15],GASPAR hand [4] and DLR -2Fig. 5.1a hand[]

These mechanical hands have several degrees of freedom,which leads to high dexterity. They are mostly inspired by the human hands, whose motion involves 35 muscles and 47 articulations. According to the latter reference, a total of 19 bones, 17 articulations and 19 muscles are located in the human hand, in addition to many tendons, ligaments and sensing elements. Therfore they were trying to accomadate many types of systems with lots of actuators, complex control systems to manage all the sensors feedbacks. From these studies a very important aspect of gripping was developed called the underactuation.

In Recent types there have been lot of classification of gripper. They are mostly based on the type of actuation used to grip the object.

5.1.1. underactuated Mechanical Gripper

Underactuation is achieved by using kinematic design such that the amount of actuators are less than the number of degrees of freedom. The un-actuated degrees of freedom are activated by kinematically.Underactuation


(a) DLR Hand-2

(b) Stanford Hand

Figure 5.1: Dexterous Hands by Research Groups

allows the use of $n - m$ actuators to control n degrees of freedom, where m passive elements replace actuators. underactuation is highly used in manufacturing the bigger hands which wants to reduce the bulkiness of the hands and ensure minimum actuator load with maximum degrees of motion.

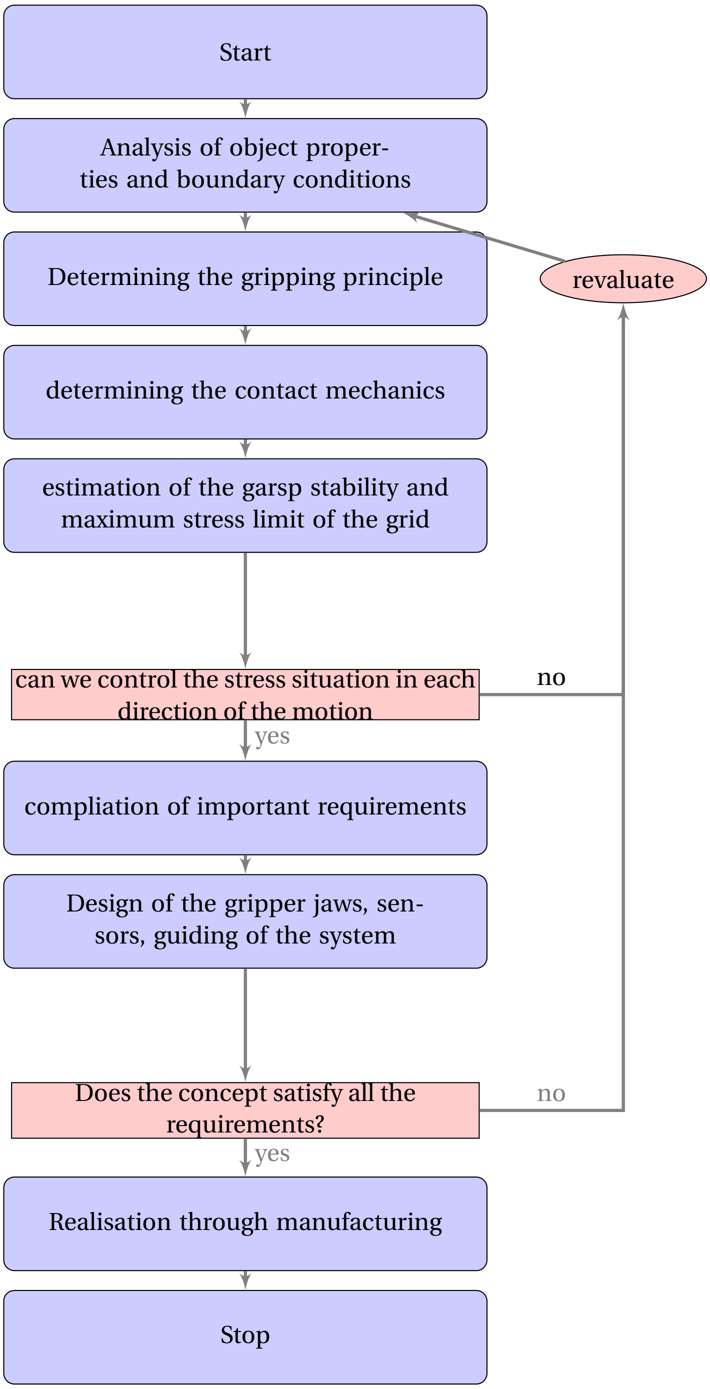
5.1.2. Mems Gripper

The grippes developed on the otherr side of the size spectrum are the MEM's based grippers. These grippers are mainly used to pick up very small particles in the range of nanometers.The most common ways of gripping in the micro scale is either thermal stresses or electrostatic forces. Thermal and electrostatic forces are very predominant in the nanoscale and their influence can be used for actuation with very small strokes.

There is lack of literature in the area of grippers which are used in the size between mimilimeter and centimeter sizes. To design a gripping mechanism in the milimeter range, it was decided to use the existing technologies and adapt it to our design.There are 2 options, that is to mininaturize the large grippers or enlarge the MEM's grippers. It was chosen that miniaturizing the existing grippers would be suitable since we can do protyping on a bigger scale to study the Mechanics and understand the motion system of the gripper. The existing designs were inspired from he Gareth Monkman Book on grippers.

5.2. Design Flowchart

The design flowchart is inspired from the Robot grippers book by Gareth Monkman.



5.3. Problem restrictions

There are numerous design restrictions imposed on the system which is to be taken into account before designing the system. Each component will be explained in detail.

5.3.1. The autogrid

The autogrid is the object which needs to be manipulated by the system. The autogrid consists of a TEM Grid which is mounted by a copper ring and a autogrid is mounted on top of the grid. This is all done to give structural rigidity to the very fragile TEM grid. The whole structure is made up of brushed copper. They are commercially manufactured and made by casting and machine finishing for getting the desired accuracy. The middle area is used for growing the biological sample which is hence the most sensitive part.The image below shows the exact components of an autogrid. Twelve of these auto-grids reside inside the cassette from which it has to be picked. The dimensions of auto grid is 3.5mm diameter and a width of 0.5mm.

Figure 5.2

5.3.2. The cassette

The cassette is an important part of the design analysis because it defines a lot of design parameters for the extraction. The most important part is the current dimensions and design of the cassette. The casette is manufactued by FEI systems which is currently the GATAN systems.The casette has springs which is used to hold the grid in place. It can be seen in the second figureThe image below shows the image of the cassette. The acess to the cassette is only available from one side. The other side cannot be used to acess the grids.The dimensions of the cassette is 9.58x18.5x47.64 mm .

5.3.3. relative grid positioning inside the grid

The one of the most critically important restriction posed by human error is the relative positioning uncertainty with respect to the grid space.Since the scientist insert the grids inside the cassette when they have grown the sample on the TEM Grid it is done manually.The sample can be completely inside the casette touching the wall or completely in the front depends on the scientist and his approach . The relative positioning of the grid inside the cassette can be in 2 axis's in the plane.The available position in a rectangle in which the grids can reside.

The length of the whole gris is 9mm. The grid has a total play of 6mm in y axis and 1.5 mm in x axis. These are some important criteria to take into consideration while designing the gripper.The most important is the condition when the grid is touching the end of the wall which makes the complete area of the grid is Unaccesible to the gripper

There is also a requirement that there is minimal positioning error during placement of the grid. The gripper should have an internal position mechanism such that the grid can be placed at an exact point with 10 micrometer accuracy.

5.3.4. De-vitrification

The samples on the grid are already in a vitrified state. Vitrification is very important as it is very critical for imaging purposes.By vitryfying the samples , we are able to produce amorphous ice on the biological sample. Amorphous ice is very important for imaging purposes in microscoe as it doesnt deflect the light. The amorphous ice is very sensetive to tempertaure change. According to []the ice changes from amorphous to crystalline at a critical temperatrue of 113K. Below this critical temperature the ice is maintained in amorphous state and any temperature shocks which makes the temperature go beyond 113K makes the ice change its condition to crystalline making the sample destroyed. It also important to notice that once the ice reches

(a) Side view of the cassette

(b) Stanford Hand

Figure 5.3: Internal view of the cassette

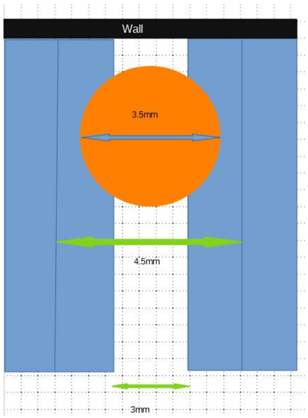


Figure 5.4

its crystalline state, it cannot be changed back to its amorphous state. Hence it is very important to keep the sample vitrified. The sample inside the casette is already kept well below its vitrified state. The requirement that the grid has to be kepyt below 113K imposes a condition on the gripper to ensure sufficient cooling during the transfer of the grid to the stage.

The cryo coolers researched in the literature review will be integrated with the gripper in the future. Hence the gripper acts as a heat sink . It is important to realise that the contact between the gripper and the sample has be very good. The larger area the gripper has with the sample, the cooling effect is increased. The gripper needs to have maximum amount of contact with the grid.

5.3.5. Contamination

The sample mainly conssists of biological cells for inspection.The cells are in a very cold condition stored in the cassette. The enviornment around the microscope is UHV(Ultra high vacuum). However there is considerable amount of particles in the sealed enviornment due to the leakage of pumps and particles left from experiments. The sample being very cold acts like a magnet in which the particles start attacking and settling on the sample. This destroys the sample as the particles get settled on the top of thensample. Hence the grippe shouldr give proper shielding to the cells in the sample to reduce contamination of the grid.

5.3.6. Springs

There are spring attached inside the cassette is mainly used to hold the grids inside the cassette. The springs are usually in contact with the outer ring of the cassette. The purpose of the springs is to provide thermal contact for the grids. Hence the gripper needs to take into consideration of the spring and the space it occupies on the grid.

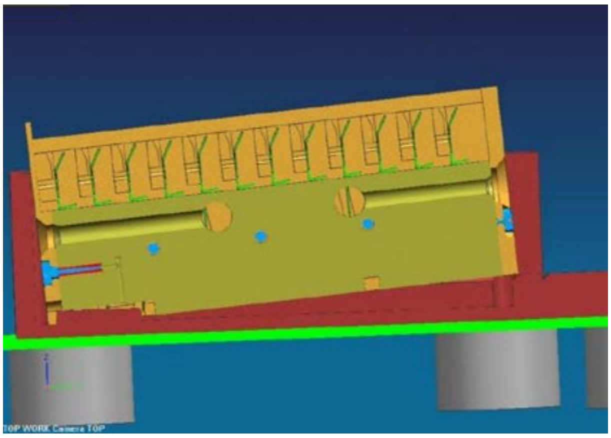


Figure 5.5

5.3.7. stage

The stage of the system is the final destination of the grid where it has to be kept.The stage is yet to be designed for this system but the current design of the stage of the current model is made up of 2 pararell plates on which the grid is kept stable. In the current system the leica system extends forward and exposes the grid shuttle. The grid shuttle attaches itself to the stage. The grid is secured inside the stage by a screw from the top. The function of the screw is to provide a good position accuracy of the grid and a thermal contact during the experiments. The drawing with the dimensions are provided below.

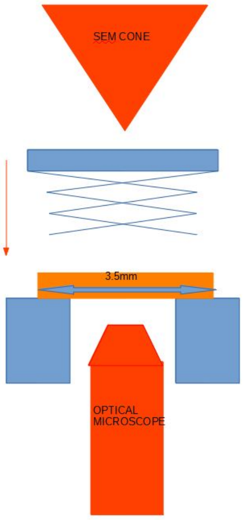


Figure 5.6

5.3.8. Fragility of the sample

The autogrid is a very fragile sample holder for the microscope. It is very sensetive to temperature shock and contamination. It is important to realise that the while handling the grid with a gripper , we need to understand that the grid can be protected from containation and cooled but it should also be considered that the forces during the grasping of the grid should not deform the grid . The deformation in shape will cause problems in placing the grids on the stage. The subsequesnt picking up and placement in the stage can be also become differnt as the dimensions has changed unexpectedly.

5.3.9. Vacuum

The enviornment inside the microscope is completely vacuum(UHV). Ultra- high vacuum environment creates a material choice restriction. The material to be used should have a very low outgassing rate. When pumping down a chamber below a particular atmospheric pressure and working under UHV(ultra high vacuum) conditions. The materials inside a vacuum chamber should be considered very carefully.The whole system experiences gas load when in UHV condition. There are many sources of Gas loads which includes leaks,migration and outgassing as some of the reasons for a gas load.Of these outgassing is claimed one of the hardest to estimate and a very important contribution to the overall gas load. Outgassing rates differ from material to material by 9 orders of magnitude.Generally metals and glass have significantly lower outgassing rate than polymers.

5.3.10. Space Restriction

The space restriction while gripping is dominated by the size of the cassette. The dimensions of the internal organization of the cassette is given belowFig. 5.7

5.4. Gripper principles

The grippers seen from above can be varied for size difference from mimicking the actual hand to having MEMS devices which can be used for grippers. In Literature the most used classification is based on the actuation principle.They are classified according to :

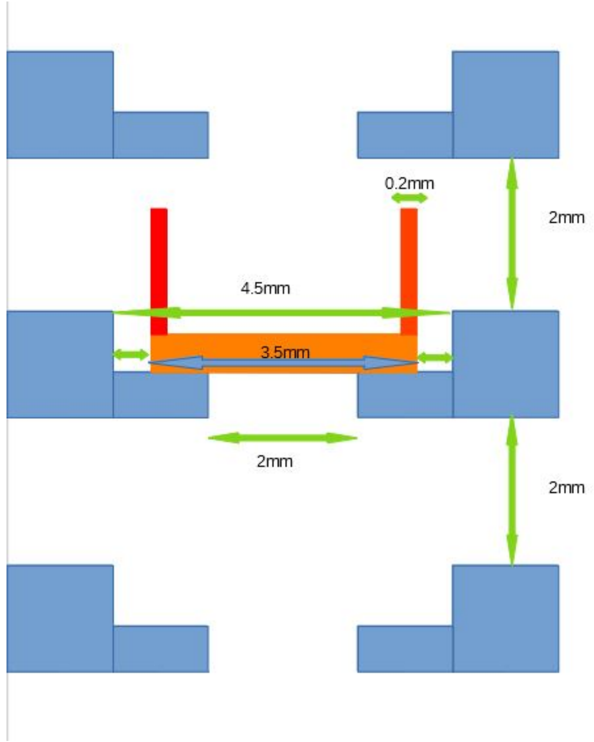


Figure 5.7

- Impactive-clamping jaws, pincers
- Ingressive- hooks and brushes
- Astrictive- electrostatic adhesion,vacuum suction
- Contigutive-Thermal adhesion,surface tension force

According to the required restriction usage of magnetic grippers are not preffered since it can affect the use of electrons beam during imaging and creating a heat sink creates too much complication. The use of vacuum gripper is not possible as there is no air to create pressure difference in a UHV chamber. Hence Impactive grippers were chosen as it was expected to be easily miniaturized for the actual application from prototying and also the impactive contact provided by the grippers can be used as a heat sink.

Classified based on the grasp movement

- Top grasp
- Side grasp

The top and side grasp is a important decision. The side grasp has very limited space inside the gripper. The distance between 2 grids is 2mm in actual system and 0.25 mm in the sides. The top grasp also provided a way to cover the grid by modifying the finger which is one of our important design restrictions.This also gives more area of contact with the grid.

5.4.1. contact mechanics

gripping can be described into 4 processes consisting of object prehension and retention

- preparation of contact
- Prehension by establishing contact between object and gripping surfaces
- Retention of the object during its manipulation
- Release of the object

5.5. Grasp Stability

In literature the contact mechanics of the grasping is broadly categorized into

- Form Closure
- Force Closure

From [1] we can get a basic definition of form closure;

Definition 5.5.1. Form Closure A grasp is said to be form-close if, and only if, for every motion of the object, at least one contact constraint is violated

contact constraint refered above is the fact that relative motion of 2 bodies are contarined by the condition of non-impenetrability.There is 2 types of form closure detailed in the literature: 1st order and 2nd order. The Image below explains the different grasps. There are three types of combinations shown.The contact points prevent the object from translating.in the figure below, the contact points prevent the object from rotating in (a) but not in (b) and (c). The object can rotate a very small amount after it is again constrainted by the same. However in the (c) , the object can rotate and escape completely. Grasp (a) is 1st order form closed whereas (b) is 2nd order form closed.[7]

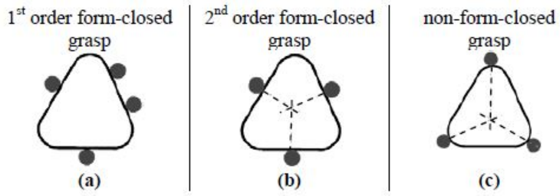


Figure 5.8

Theorem 1. constraint conditionThe minimum number of contacts necessary to form-restrain an object with respect to an m-dimensional subspace is m + 1.

However the form restraint here defines a 1nd order form constraint. For the second order form constraint can be achieved by lesser amount of constraints than the first order. But it is important to position the constraints such that the object has not translation movement. The shapes of the object also depends on condition if the form closure can be achieved or not. The form closure for a disc is not possible as it has infinite number of axes on which it can move , hence only 2nd order form closure can be achieved for a disk object.

By this choice we need at least 3 points of contact on a plane if we consider the object 2 Dimensional

5.6. Design analysis for requirements

For coming up with design concepts for the gripper.

The motion expected by the whole system can be simplified into a very specific schematic focusing on only the extraction and placement of the grid can be divided into a very basic to and fro motion given below

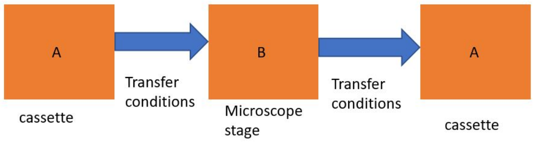


Figure 5.9

The transfer conditions can be summarized below:

1. The sample should not be de-vitrified
2. The sample should be shielded properly

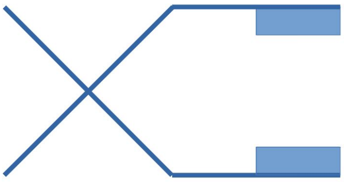


Figure 5.10

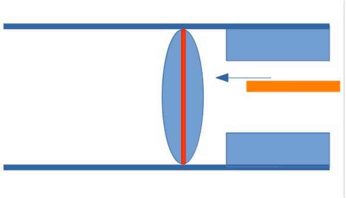


Figure 5.11

3. The structural integrity of the grid remains intact
4. Placing the grid on stage
5. The springs should be taken into consideration

For satisfying the above conditions , we need a way to cover the grid as well as provide a big area contact point. If we look at the grid from bottom we can see that there is ample contact area below if we can introduce a contact there

For satisfying the conditions of springs, the top finger should be modified accordingly so that as it approaches to grip , it automatically unlocks the spring. Since we are unaware of the spring stiffness. The width of the top finger should be equal to the distance between the two springs + width of the springs

5.7. concept Designs

The concept design was thought about seeking the requirements of the gripper. There were several concepts thought about.The established decisions were that the gripper should have a top grasp and should be able to cover the grid from the top and should provide maximum contact as well as hold the grid.

There were lot of concepts though about for the gripper. Here are some of the concepts explained. Initially a basic "X" Transmission was selected to be used a way to transfer motion. The X transmission was used particularly more for the gripper to position the grid when it touches the intersection. The jaws were designed to have a kinematic coupling with the grid. However it was determined that the positioning would be very inaccurate as the grid if already displaced will cause uncertainty in its placement. Furthermore, It is unsure where the location of the grid inside the cassette, hence the closing of the gripper can cause it to touch the biological sample or grip it in a very inaccurate position.Fig. 5.10

There were further some improvements made in the gripper design concept, the intersection of the x mechanism was replaced with a compliant Mechanism which was bi-stable. As the grid would arrive and touch the bi stable mechanism the bi-stable mechanism would snap to its 2nd state and activate the fingers. This seems to advantageous that the gripper activated when the grid was located, the problem with this system was that when the gripper releases the grid, the bi-stable mechanism will have a snap back mechanism which will create a impulsive force on the grid and the grid would have a velocity during placement which is bad since the positioning accuracy is severely compromise.Fig. 5.11

The next iteration of the idea was to introduce a method in which the system will automatically center the grid while the gripper was in process of extracting the grid by creating a concept of mid block between the two fingers. The concept presented here is that the midblock has the same structure as the grid(i.e a half ring) of slightly bigger diameter. This will make the grid position according to the midblock while the gripper

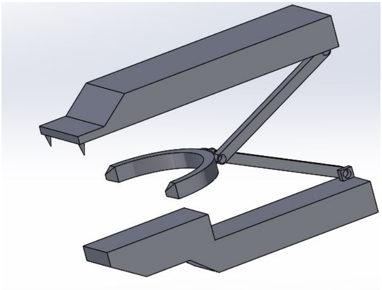


Figure 5.12

moves into the rails.The closing of the gripper will occur after it has traveled till the end of the rails(which is 9mm). The closing will make the grasp very accurate as the grid is already positioned in the correct way. The advantage with this concept is that the when releasing the grid, the mechanism doesn't exert any impulsive forces to the grid. However the drawbacks for this mechanism is that the the midblock actuation is very hard to achieve to do in millimeter scale.The top finger also hits the wall of the cassette which causes some unaccounted forces on the cassette. The next improvement was to remove the mechanism and attach the midblock with lower-finger. The attachment would be around 11mm from the front .This will benefit the overall mechanism as there is significant less moving parts. The shape of midblock was changed to a V shaped notch like structure shown in the diagram. This would be much more better and would improve the positional accuracy of the grid. Then there were some pins added on top finger which would make the grid support on the V notch and these pins.The pins would have to positioned such a way that the pins exactly hit the empty spaces on side of the gripper. The drawback with this model is that the grid is in over constrained with 6 points of contact.

Hence to release a little bit of over constraint , the V notch was modified into a shape which would allow the Grid to have only 1 point of contact with the V groove.This was the finally proposed concept for the design.

5.8. Design of the jaws

The jaws are an important part of the gripper. The jaw design can be divided into 3 parts:

- Top Finger
- Bottom Finger
- Middle Block

5.8.1. Top finger

The responsibility of the to finger is to provide contamination protection and also for self alignment of the gripper with the basic feature of providing the basic force needed for gripping with the bottom finger. The dimension restriction of the top finger is mainly decided by the locking springs, if they engage the springs or not. If the top finger doesn't engage the springs. The width of the top finger is 2.6mm .If we look at the figureFig. 5.7, we can see that the diameter of the grid is 3.5mm and if we don't want to engage the springs, we remove the 0.4mm from both sides. Hence the available space for the top finger is 3.1mm. 0.5mm was assumed as a manufacturing tolerance. If it engages the spring then the width becomes 3.5 mm mimumum.The pins on the gripper is 0.1 mm diameter. The pin is important for centering the grid inside the gripper with the midblock. The height of the top finger maximum can be 4mm .The solidworks model of the object is shown here. Fig. 5.13

There is a concern that the manufacturability of the pins are poor. Then we have to make the upper finger compliant by adding flexures or making the end plate of lower stiffness so that it becomes flexible. The different iterations of the top fingers are discussed in the experimental validation section.

5.8.2. Bottom Finger

The bottom finger is used for mostly for the grid to sit on it. The bottom finger has a with of 1.7mm. This is because the width of the free space for the gripper to take out the sample from the bottom is 2mm. We

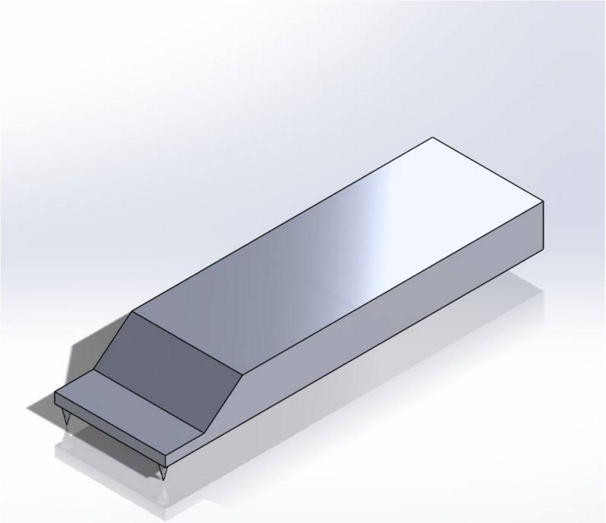


Figure 5.13

take .3mm as the manufacturing tolerance. The middle block is attached to the lower block with a 0.5mm separation from the bottom.Fig. 5.14

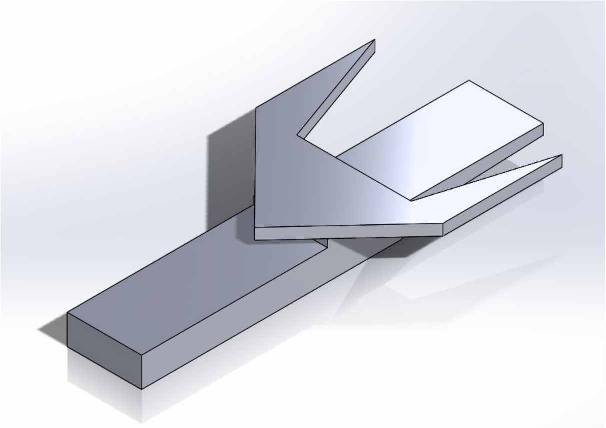


Figure 5.14

5.8.3. Midblock

The midblock is essentially used for centering the grid. Midblock consists of 2 flanges which are at a distance of 4mm apart. This is the distance of the gap of the block.As explained in the concept design it is used for positioning the grid inside the gripper. The design of the midblock was made according to the grid size. It assumed that the grid will be held in between the jaws. Hence the scenario that both the jaws will be touching the grid is the maximum condition which can be assumed.

5.9. Gripping motion

The overall motion gripping motion consists of the following steps

- Robot positions the lower finger of the gripper in front of the required Grid.Fig. 5.15
- Robot pushes the lower finger into the rails of the grid and grips the gridFig. 5.16
- Robot pushes it in by 9mm till the end and with the help of midblock it automatically positions the grid into a defined locationFig. 5.17
- The upper finger is actuated and the gripper is closed

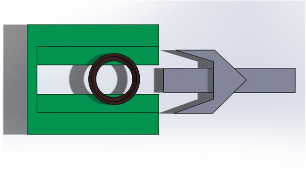


Figure 5.15: Lower gripper being aligned with the lower rails

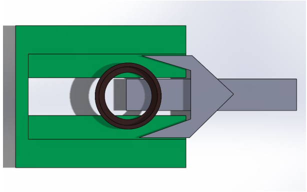


Figure 5.16: Lower finger is pushed into the rails

5.10. Precision requirement

The gripper is designed for gripping millimeter sized objects. In this section we will detail out some accuracy conditions necessary for handling the gripper and extraction and placement of the grids.

Alignment has one of the most important precision requirement for extraction of the grid.It is absolutely essential for the robot which is attached to the gripper to have precise alignment with the cassette rails for perfect grasp. The design of the gripper imposes some precision requirements on the robot.

Looking at figureFig. 5.18, The distance between the lower finger and the midblock is 0.16mm. This distance if of essence as a slight miscalculation of minimum of 0.1mm in y axis will cause either the middle finger to hot the grid damaging the grid or the whole mid block is going to crash into the rails. This will destroy the gripper and to the grid.

Looking at the figure from the top Fig. 5.19, We can see the midblock and the rail has a tolerance a total 0.16mm or if we take the center of the rails as reference for the lower finger. The extreme sides of the midblock has a clearance of 0.08mm on each side. It is however important to notice that the even if the midblock is inserted by touching one extreme side of the rails. it still does a successful centering as the gri will always settle in between the Mid block. However if the precision is off by more than 0.08mm, then the mid block will not be able to do a grasping as it will clash with the rails instead.

5.11. conclusion

In this chapter the gripper design was discussed and steps taken to finalize a design according to the requirements were done.The validation of the design is done in the next chapter.

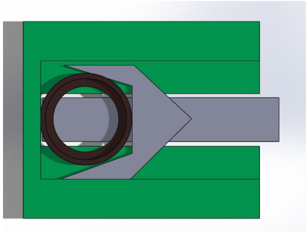


Figure 5.17: The lower finger finally pushes the grid into position

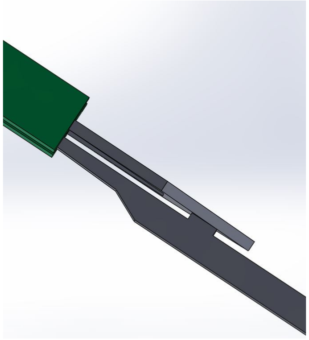


Figure 5.18: alignment with cassette in y

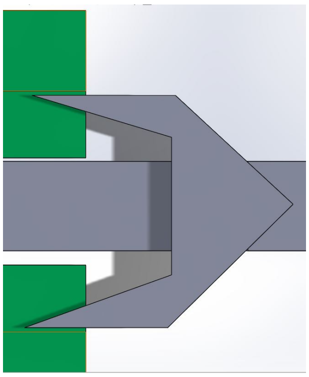


Figure 5.19: alignment with cassette in x

6

experimental verification

The main goal of this chapter is to document the test setup for the experimental testing of the designed gripper in the previous chapter. The chapter is divided into the objective ,components and finally the test setup for the whole system.

6.1. experiment objective

The objective of the experiment is to test the accuracy and repeatability of the designed gripper. The accuracy is the ability of the gripper to successfully grasp the grid from the cassette. repeatability of the gripper is defined as the ability of the gripper to put it back on a given position. The grippers ability of detach the springs from the grid is also tested by creating a similar environment with the leaf springs.

the overall motion required is given in steps below:

- Robot positions the gripper in front of the required Grid.
- Robot pushes the gripper into the rails of the grid and grips the grid
- Robot takes the gripper out and moves to wards the stage
- Robot positions itself on the stage
- Gripper is actuated to release the grid on the stage
- after experimentation Robot positions the gripper in front of the grid
- Gripper is actuated to get the grid
- robot positions itself in front of the cassette
- Robot pushes the grid and actuated the gripper

6.2. components for experiments

The building of the test setup had many components listed below

- 6 axis robot
- Gripper actuator
- cassette
- auto grid

6.2.1. 6 axis robot

The main actuation and positioning system used for positioning the gripper is the 6 axis robot provided by delmic. Meca500 (R3) is a Ultracompact six-axis robot arm. It has the controller embedded inside the base of

technnical specification	value
Repeatbility	0.005mm
Max. (TCP) linear velocity in cartesian mode	500mm/s
maximum payload	max 1kg

the system which makes it more compact and fast. It weighs 4.5 kgs with a reach of 260 mm.

6.2.2. euler angles

Euler angles are a way of describing orientation of a mobile frame of reference with respect to a fixed reference. The 6 axis robot used by mecademic employs this principle to orient the gripper axis with the fixed world axis.It is based on the eulers rotation theorem which states that

Theorem 2. eulers rotation theoremIn 3 dimensional space any displacement of a rigid body in such a way that a point on the rigid body remains fixed is equivalent to a single rotation about an axis that passes through a fixed point.This rotation can be represented by 3 independent parameters: two for describing the axis and one for the rotation angle.

In a 3D space a rotation of a frame F and F* can be described by a rotation matrix. This matrix is always 3x3.However , it is not a very useful and unique way of describing rotation.

Figure 6.1: 6 axis robot

Some other important technical specifications are included in the table below

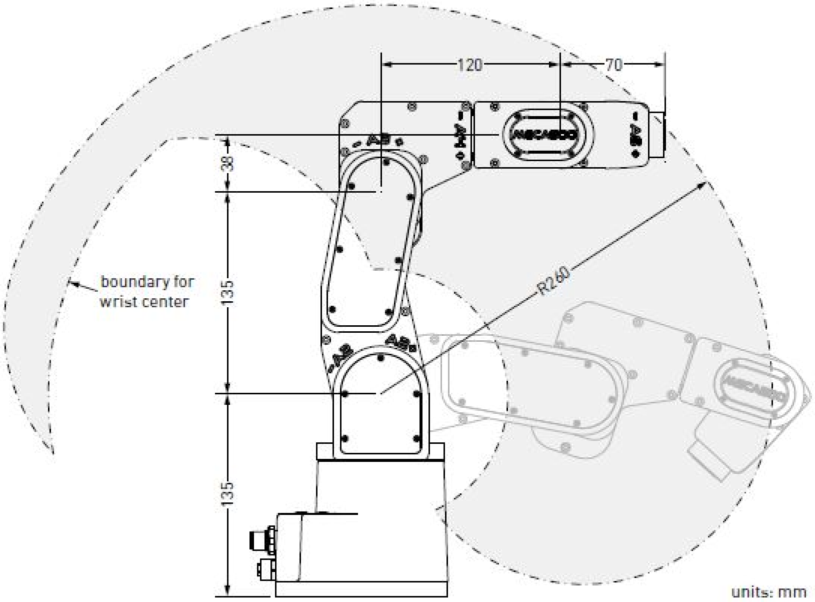


Figure 6.2: 6 axis robot range

6.2.3. Gripper actuator

The gripper actuator is a electric motor manufactured as an add on interface to the already avialable 6 axis robots.

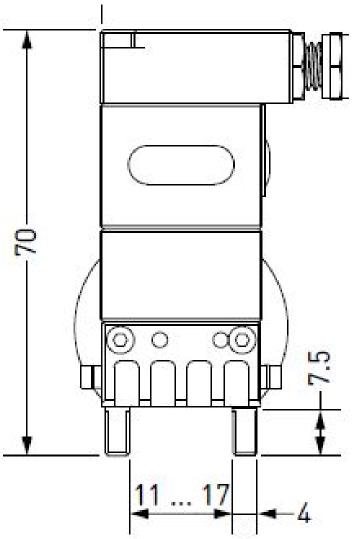


Figure 6.3: actuator

Some important specifications of the electrical actuators are given below

6.2.4. casette

The casette was manufactured by 3D Printing. The prototype is manufactured was 3:1 ratio to the actual caseette. This was done as it was easier to do gripping experiments with an enlarged prototype which can is compatible with the 6-axis robot.The image of the enlarged cassette is shown below. The spring is not attached to the cassette as we don't understand how the spring affects the locking of the grid.The current

technical specification	value
Maximum gripping force	40N
repeatability	0.02mm
stroke per jaw	4mm

cassette is a basic understanding of the original cassette as the real cassette is a patented product and really hard to acquire.

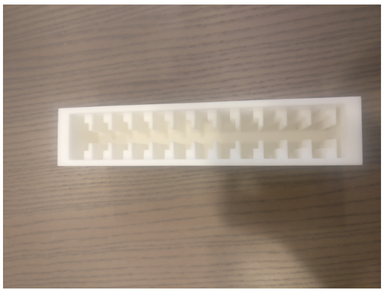


Figure 6.4: actuator

6.2.5. autogrid

The autogrid was also enlarged to a 3:1 prototype.However manufacturing these autogrids by 3D printing proved to be a huge challenge as the material used for the cassette PA-12 was very flexible and not stiff enough for the gripper. Metal printing was suggested as an alternative solution for improved stiffness for the gripper. However the manufacturing with metal printing is not very accurate and some shapes cannot be produced. The problemwas that the curvature of the grid could not be achieved with metal printing.The image below shows the problems with the metal printing is that the width of the grid has to be modified due to limitation of metal printing.There was a slight modification of the geometry of the manufactured grid. Also in metal printing they add 2mm of material on the bottom of the part because they use a bend saw to remove the part from the build plate. The accuracy of the bend saw is 0.3mm . Hence the final height of the sample can vary between the 1.5mm to 2mm. Hence it was decided to remove the details from inside of the grid.This doesnt affect the overall experiment as the gripper has to avoid the inside of the grid anyways. The height of the grid was between 1.5-2mm but not consistent overall.

(a) original autogrid

(b) modified autogrid

Figure 6.5: Modification of the Autogrids for manufacturing

6.2.6. Gripper finger modification

The gripper finger developed in the previous section was modified according to the flanges on the actuator.A extension of the arms have o be added to include the screwing location. The distance between flanges during the open position of the actuator is 2cm. While the stroke of the gripper is 2mm. Hence a sloping curve ws attached to realize when the actuator moves the gripper moves by 2mm. The stroke of the actuator is 6mm . Hence we need program it to perform a smaller stroke for this specific purpose. The full drawing of the gripper wrth actuator was shown in figure below.

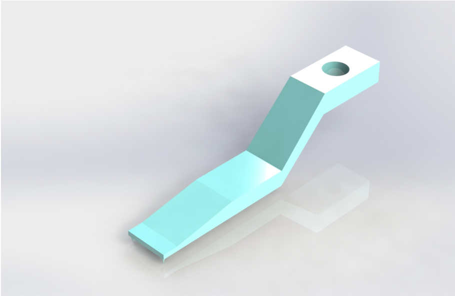


Figure 6.6: modified upper finger

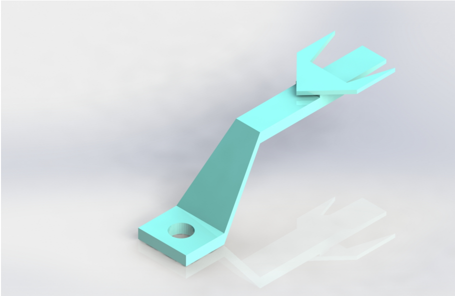


Figure 6.7: modified lower finger

6.3. Programming

The robot comes with its own operating system. The robot and the computer communicate through the Ethernet port and is plug and play. There are certain limitations with the given operating system that it doest allow to modify some properties of the robot. This includes the gripping force , the gripping stroke and the speed of the movement of its joints. This causes certain hindrance in our project as we want to be able to change the gripping force and gripping stroke. This called for a change in a way in which we can control the Machine.

Philip Winkler,software engineer at Delmic suggested to use the ROS(Robot operating system), which he had worked on before for another project with the same robot. This middle ware is able to use the basic drivers of the robot to control its gripper force, speed and stroke. ROS was a complex system to understand but it is mostly used for controlling multiple robots in a production environment or multiple sensor readout in Research project. I was help a lot by a ROS programming MOOC by the Cognitive robotics section of the 3ME(TU Delft)

The programming language used to make the robot work was a middleware called Robot operating system(ROS).It is a middleware and not a software as it doesnt have a complete operating systems to its name but just a set of packages with integration with python and C++ to create communication with various packages inside it. ROS based processes are represented in a graph nodes which recieve , post and multiplex , control state, planning and actuator data. A GUI was created with the software and used to control the actuation and the movement of the robot.The main motivation for using ROS as a language is that it can be complied with lot of languages like the python node and C++.It has simulation tools and a open source application which makes it compatible.

More information about the programming language can be found out in the Appendix A

6.4. test setup

The test setup is shown below.

6.5. Experiments

(a) gripper moving inside cassette

(b) gripper centering the grid

Figure 6.8: Experiment during gripping

6.6. Problems

The major problem encountered during the experimentation is that the internal stresses during manufacturing was not making the gripper close.Hence extraction was not very successful. This can be shown by the following pictures

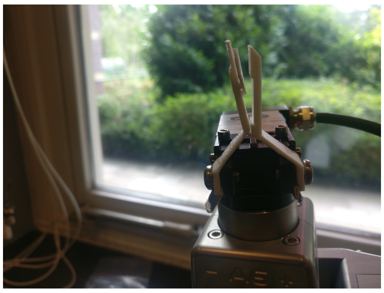


Figure 6.9: Grippers not closing

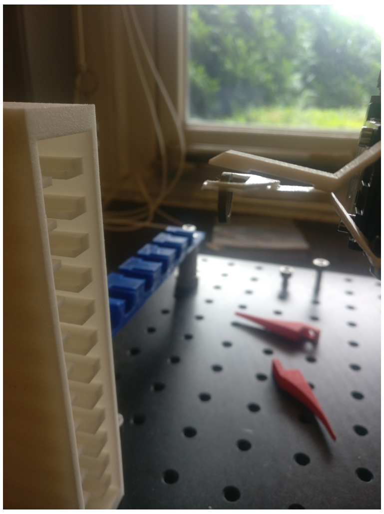


Figure 6.10: problems

7

Conclusion and Discussion

The project consisted of finding a solution of a wider problem which is to simplify the sample preparation for the cryo-microscopy. The cryo-microsopy currently suffers with poor quality of samples reaching the TEM. To prepare the samples , 22 distinct steps have to be performed including moving the biological cells, growing it on ice, experiencing temperature shocks etc. Tu delft with Delmic BV wanted to improve the sample viability by creating a new sample processing method. The whole 22 steps was divided into 3 distinct processes.I was assigned the phase where the sample reaches the SEM microscope. The objective was to analyze the system design of a automated sample transfer system which would take the samples for a defined cassette and put it onto the stage. The system was analyzed and divided into subproblems. From the subproblems the system interaction with the sample was chosen as the crucial problem and a solution for that sub problem was a gripper which was designed with the required conditions.

The gripper design was concluded with iterations on the design. Design Engineering is a type of engineering in which the focus is more on functionality , performance and fit for purpose.

The gripper designed was according to the conditions derived from the required functions. Required functions are imposed due to the environment, mechanical contacts and the safety of the sample. These conditions are compounded more because samples handled are biological cells which are live and extremely sensitive to these conditions. Hence it was important to ensure that the all conditions are satisfied.The proposed design solves these problems considering these conditions. Overall system design imposes many more restrictions on the system but the design of the gripper gives an important starting point as it defines the machine-sample interaction. Using this interaction we can further formulate actuation and the sensing system requirements. The overall system design is always iterative and for a optimal system design there has to be certain trade-offs in requirements, costs and performance.

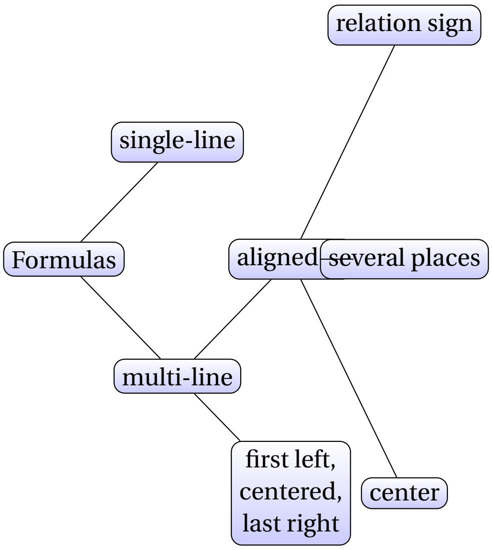
The gripper is completely in feed-forward control that is there are no sensors included in the whole gripping mechanism as the sensors create delay and are not suitable to be carried around due to the size of the gripper. The gripper relies on the positional accuracy of the connected robot for positioning it on the rails.

The gripper is a miniature of a impactive parallel gripper. The parallel impactive grippers are used a lot in the industry for pick and place operations in production lines.

The gripper's midblock is unsymmetrical for positioning and jamming purposes. The intention was to use the midblock as a guiding mechanism but not as a gripping mechanism. Hence it only guides the grid to a certain positioning before gripping

The gripping actuation is 2mm. That is the top finger and bottom finger move by 2mm to secure the grip.

Below are the conditions and the proposed Decision tree for each of the solution for most of the decisions taken.


relation sign
single-line
Formulas
aligned
several places
multi-line
first left, centered, last right
center

8

future scope

Already listed in the the system Design. There are further subproblems which is needed to be discussed for future. The overall system needs to be

8.1. Devitrification

It is already established in the gripper design that lower finger acts as a heat sink for the extracted grid.This can be achieved by by either a active mechanism or a passive mechanism. In active mechanism a mini-Sterling cooler is installed inside the microscope with a copper shunt connecting the cooler and the gripper. In passive cooling a liquid nitrogen pipe can be introduced inside the microscope and when the gripper is idle, the gripper can grip the pipe so that the fingers are cooled. However the decision will depend on cooling rate of the sample. For these experiments have to be done in the actual sizes of the gripper.

8.2. motion controller

Currently the system runs completely in a feed forward control. The feed-forward control is very precise and accurate if the we know the system behavior completely or the system identification is accurate. However if there is some error inside the system , it is unable to correct the error. The system also has to transport the grids from the cassette to the stage. The system has to identify the location of the stage, The stage is also moving during the experiment. Hence the system has to identify the location of the stage for positioning accuracy.

8.3. Collision avoidance

The gripper is used a sample manipulating system inside the SEM, there is an expectation that the system can also be able to operate with 2 different cassettes at a time. Hence it needs to navigate its way around the microscope.Delmic makes microscopes tuned according to the customer and their needs. It should not damage the modules added inside the microscope.

8.4. Micro-robots

The whole system should fit inside the microscope chamber.The system should be small and accurate to ensure that the gripper is able to ensure that the system is able to grasp the grid completely and place it on the stage. Actuation techniques from literature research is found out to be piezoelectric actuators.The piezoelectric actuators are vacuum compatible and suitable for accurate movements.

8.5. Cassette Placement

The interface with Xuanmin's project is essential for a better sample transfer system. The new system developed by Xuanmin's uses Delmicup. The cassette has be extracted from the delmic cup into the microscope.

8.6. cassette acquisition

On July 5th, The actual cassette was acquired by Delmic for experimental purposes. The cassette was the most recent version of the cassette.There are some interesting observations looking inside the cassette. The new cassette has a slanted opening so that the gripper can be automatically align itself while placing the object.

List of Figures

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