KAUNAS UNIVERSITY OF TECHNOLOGY
MECHANICAL ENGINEERING AND DESIGN FACULTY

Akash Sheshappa

Design and Analysis of Suction Cups Activated by Piezoelectric Actuators

Master's Degree Final Project

Supervisor
Assoc. Prof. Dr. Rūta Rimašauskienė

KAUNAS, 2018

KAUNAS UNIVERSITY OF TECHNOLOGY
MECHANICAL ENGINEERING AND DESIGN FACULTY

Design and Analysis of Suction Cups Activated by Piezoelectric Actuators

Master's Degree Final Project
Mechatronics (621H73001)

Supervisor
(signature) Assoc. prof. Dr. Rūta Rimašauskienė
(date)
Reviewer
(signature) Dr. Marius Gudauskis
(date)

Project made by
(signature) Akash Sheshappa
(date)

KAUNAS, 2018

KAUNAS UNIVERSITY OF TECHNOLOGY

Faculty of Mechanical Engineering and Design

(Faculty)

Akash Sheshappa

(Student's name, surname)

Mechatronics (621H73001)

(Title and code of study programme)

" Design and Analysis of Suction Cups Activated by Piezoelectric Actuators"

DECLARATION OF ACADEMIC INTEGRITY

5 January 2018

Kaunas

I confirm that the final project of mine, **Akash Sheshappa**, on the subject “Design and Analysis of Suction Cups Activated by Piezoelectric Actuators” is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarized from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this thesis.

I fully and completely understand that any discovery of any manifestations/case/facts of dishonesty inevitably results in me incurring a penalty according to the procedure(s) effective at Kaunas University of Technology.

(name and surname filled in by hand) *(signature)*

Akash, Sheshappa. Design and Analysis of Suction Cups Activated by Piezoelectric Actuators. Master's Final Project / supervisor Assoc. Prof. Dr. Rūta Rimašauskienė; Faculty of Mechanical engineering and design, Kaunas University of Technology.

Research field and area: Production Engineering, Technological Sciences.

Keywords: *Piezoelectric, suction cup, smart material.*

Kaunas, 2018. 51 p.

SUMMARY

The aim of the project is to design and analyze suction cup activated by piezoelectric actuator, suction cups play an important role in industries, especially packing, food industries etc., which involve moving objects from one place to another. Commercial suction cups use pneumatics for its working, which are heavy, take a lot of space, sometimes dangerous, very noisy etc. This project aims to introduce a novel suction cup which uses smart materials to activate the cup. A piezoelectric material is attached to a membrane, when electric current is applied the piezoelectric material deforms, causing the membrane to deform as well. Using this phenomenon to create a small pressure difference inside the cup, which can be used to adhere it to the workpiece. This gives lot of flexibility to the suction cup, since piezoelectric materials can be activated at a very high frequency, and it just needs a DC source and a control panel to be controlled, which is portable and easy to control and can be programmed. In this project a design for a suction cup is done, and is modeled using simulating software and compared with the experimental data to find membrane material that gives the best results.

Akash, Sheshappa. Vakuuminių siurbtukų su pjezoelektriniais vykdikliais kūrimas ir analizė. Magistro baigiamasis projektas / vadovas doc. Dr. Rūta Rimašauskienė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Mokslo kryptis ir sritis: gamybos inžinerija, technologijos mokslai.

Reikšminiai žodžiai: *pjezoelektra, vakuuminiai siurbtukai, sumanios medžiagos.*

Kaunas, 2018. 51 p.

SANTRAUKA

Šio magistrinio darbo tikslas vakuuminių siurbtukų su pjezoelektriniais vykdikliais kūrimas ir analizė. Vakuuminiai siurbtukai yra svarbi pramonės, susijusios su objektų pakavimu, transportavimu bei manipuliavimu, dalis. Komerciniais tikslais dažniausiai naudojami pneumatiniai siurbtukai, kurie yra pakankamai sunkūs, užima daug erdvės, kartais pavojingi sveikatai bei triukšmingi. Šio projekto tikslas buvo sukurti naujo tipo vakuuminį siurbtuką naudojant sumanias medžiagas. Šiame įrenginyje naudojamos membranos gali būti pagamintos iš skirtingų medžiagų, prie jų tvirtinamas pjezoelektrinis vykdiklis. Veikiant įtampa, vykdiklis deformuojasi kartu deformuodamas metalinę membraną bei sukuria vakuuminį slėgį įrenginyje. Sukurtas siurbtukas gali būti patogiai ir lengvai naudojamas pramonėje, nes jam valdyti reikalingas tik nuolatinės įtampos šaltinis bei valdymo pultas. Jis lengvai valdomas bei gali būti programuojamas. Šiame darbe buvo sukurtas vakuuminis siurbtuko modelis, naudojantis kompiuterinių modeliavimo programų nustatyti ir parinkti geriausiai įrenginiui tinkantys elementai bei jų charakteristikos . Rezultatai patikrinti eksperimentiškai.

KAUNAS UN IVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
Head of Production engineering Department

____
(Signature, date)

Kazimieras Juzėnas
(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHATRONICS

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Design and Analysis of Suction Cups Activated by Piezoelectric Actuators

Approved by the Dean Order No. V25-11-12, 11 December 2017

2. Aim of the project

To design and analyze a suction cup activated by piezoelectric actuator and find the most suitable material for the application.

3. Structure of the project

Introduction, Aim, Task, Literature review on suction cups, Design of suction cup, Simulation of suction cup, Suction force calculation, Experimental analysis of brass membrane actuated by PZT, Applications of suction cup, Conclusion, Reference.

4. Requirements and conditions

Designing piezoelectric material with radius 7.5mm and thickness of 0.1mm. Simulating the displacement of the piezoelectric material and comparing the results with experimental data. Calculating the lifting force produced by the suction cup and finding the one with best results.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 21 December 2017

Student ____ Akash Sheshappa____ _____________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor _Assoc. Prof. Rūta Rimašauskienė_ _____________________
(*Position, Name, Surname*) (*Signature, date*)

Table of Contents

1 Introduction 11

2 Literature review of suction cup 12

3 Designing of suction cup 22

3.1 Dimensions of suction cup 22

3.2 Piezoelectric material 23

3.3 Membrane selection for the suction cup 25

3.4 Cup Selection and its specification 26

3.5 Modeling the suction cup 26

3.6 The Working Mechanism of the Suction Cup 28

4 Simulation of suction cup 29

4.1 Simulation Results 30

5 Suction force calculation for suction cup 38

6 Experimental analysis of brass membrane actuated by PZT 44

7 Applications of suction cup 46

Conclusion 48

Reference 49

Table of Figures

Figure 1: The sealed air cavity in the elastic material: a) before activation; b) after activation [9]. 14
Figure 2: Cross section of suction cup: a) cross sectonal view; b) top view [12] 15
Figure 3: Schematic of self-healing cup : a) top view; b) cross sectonal view [13]......................... 16
Figure 4: The three-fingered gripper : a) Representation of the three-fingered gripper ; b) experimental setup [13] 16
Figure 5: Structure and operation of EAP actuator [14].. 16
Figure 6: Analysis of air in flow a) initial status of suction cup attached to the surface (b)changing status of suction cup inner pressure [15] 17
Figure 7: CAD model of piezo actuator based micro manipulation system. [16] 18
Figure 8: Schematic of the robot model and the locomotion mechanism [17]................................ 19
Figure 9: Schematic structure :a) conducting polymer actuator; b) representation of the bending principle; c)gripper handling a spherical object [18].. 19
Figure 10: CAD model of the sucker: a) cross sectional view; b) 3D printed ; c) bottom view [19] 20
Figure 11: Suction cup working mechanism [20] 20
Figure 12: A vibration cycle of the suction and the conical figure of the cup [21].......................... 21
Figure 13:Working phases: a) initial phase; b) pushing phase; c) attached phase; d) detached phase [22] 21
Figure 14: a) commercially available suction cup; b) cross sectional view of a suction cup [22].... 21
Figure 15: Piezoceramics disc, industrial standards [24] 22
Figure 16:AUTOCAD model of the suction cup: a) a 2D cross sectional; b) bottom view; c) top view; d) 3D view 27
Figure 17: 2D representation of the suction cup with negative displacement.................................. 28
Figure 18: 2D representation of the suction cup with postive displacement.................................... 28
Figure 19: The displacement of Brass membrane actuated by PZT (10V) 30
Figure 20: The displacement of Brass membrane actuated by PZT (20V) 31
Figure 21: The displacement of Brass membrane actuated by PZT (30V) 31
Figure 22: The displacement of Brass membrane actuated by PZT (40V) 32
Figure 23: The displacement of Brass membrane actuated by PZT (50V) 32
Figure 24: The displacement of Brass membrane actuated by PZT (60V) 33
Figure 25: The displacement of Brass membrane actuated by PZT (70V) 33
Figure 26: The displacement of Brass membrane actuated by PZT (80V) 34

Figure 27: The displacement of Brass membrane actuated by PZT (90V) 34
Figure 28: The displacement of Brass membrane actuated by PZT (100V) 35
Figure 29: a) schematic of forces acting on vertical lifting; b) and c) direction of work material movement. 38
Figure 30: a) schematic of forces acting on horizontal lifting; b) directon of work material movement. 38
Figure 31:Experimental setup: 1) brass membrane with piezoelectric actuator; 2) liner amplifier P200 (FLC Electronics AB, Sweden), 3) 3D scanning vibrometer PSV-500-3D-HV (Polytec GmbH, Germany) 44
Figure 32: Brass membrane attached to PZT, fixed to platic frame 45
Figure 33: Modular vacuum gripper technology by COVAL [31] 47
Figure 34: Industrial applications of scution cup: a) array of suction cups used in food industry; b) packaging industry [32] 47

List of Tables

Table 1: Properties of PZT PIC 181 [27] 24
Table 2: Mechanical Properties: a) Aluminum; b) Copper; c) Silicon; d) Brass [28]. 25
Table 3: Specification of the silicon suction cup [28] 26
Table 4: Specifications of the suction cup used 27

List of Graphs

Graph 1: Relationship between the displacement and voltage for Brass membrane actuated by PZT 35
Graph 2: : Relationship between the displacement and voltage for Aluminum membrane actuated by PZT 36
Graph 3: Relationship between the displacement and voltage for Copper membrane actuated by PZT 37
Graph 4: Relationship between the displacement and voltage for Silicon membrane actuated by PZT 37
Graph 5: Dependency of lifting capacity with the applied voltage for Aluminum membrane actuated using PZT 42
Graph 6: Dependece of lifting capacity with the applied voltage for Copper membrane actuated using PZT 42
Graph 7:Dependency of lifting capacity with the applied voltage for Brass membrane actuated using PZT 43
Graph 8: Dependency of lifting capacity with the applied voltage for Silicon membrane actuated using PZT 44
Graph 9: Experimental data of brass membrane actuated using PZT 45
Graph 10: Experimental data v/s simulated data for brass membrane actuated by PZT 46

1 Introduction

This project presents a novel design for Robot gripper that uses adhering mechanism based on suction cup. Vacuum grippers have been used as robotic grippers to pick Non-Ferrous materials, it uses vacuum to pick materials. A negative pressure is developed in the suction cup through various methods like using a Vacuum generator or Mechanical means. This principle is used widely to lift various objects of various size and shapes and in other branches like locomotion assistance for a wall climbing robot to surgical process. This project aims to introduce a novel suction cup which uses smart materials to activate the cup. A piezoelectric material is attached to a membrane, when electric current is applied the piezoelectric material deforms, causing the membrane to deform as well. Using this phenomenon to create a small pressure difference inside the cup, which can be used to adhere it to the workpiece. This gives lot of flexibility to the suction cup, since piezoelectric materials can be activated at a very high frequency, and it just needs a DC source and a control panel to be controlled, which is portable and easy to control and can be programmed.

The scientific definition of Vacuum is "A state of emptiness". This refers to the space devoid of any matter. This cannot be practically achieved. Hence, vacuum is considered as a space with air pressure less than atmospheric pressure. Vacuum technology is a very important study subject, many chemical reactions, biological and physical phenomenon are studied in vacuum conditions. It plays a crucial role in industrial processes, for instance semiconductor manufactures or mass spectroscopy [1].

AIM

To design and analyze a suction cup activated by piezoelectric actuator and find the most suitable material for the application.

TASK

1. To design the suction cup activated using a piezoelectric material.
2. To model and study the performance of the suction cup using simulating software, analysing the data to find the most suitable membrane material. To select the suction cup design.
3. To perform experiments to study the performance of the membrane actuated using piezoelectric actuator, to compare the experimental data with the simulated data.
4. To perform mathematical force calculation usng the simulated data, to find the theroetical lifting force.

2 Literature review of suction cup

Vacuum technology

There are basically three types of achieving a vacuum: Positive displacement pumps, Momentum transfer pumps or molecular pumps, Entrapment pumps [2].

Has resulted in the development of new gripper technology in industry, i.e. lifting, holding, rotating and transporting of parts.Vacuum gripper is very commonly used in industries as an end effector of an industrial robot in Transporting, Feeding, Moving, Insertion, Reposition, Turing, Lifting, Loading, conveyance, Gripping, Machining, holding especially good at handling the objects with smooth, flat, and clean surfaces. The vacuum cups are commonly round shaped, these cups are made of soft and elastic materials like Silicon, rubber or plastics [3].

Removing air from a closed volume develops a pressure differential between the volume and atmosphere. If the closed volume is bound by a surface of vacuum cup and a workpiece, the resulting difference in the pressure outside and inside the cup causes the atmosphere to exert pressure on the cup and the material. In industries the difference in pressure is achieved by using a vacuum pump.

Suction cups are commonly made of soft materials like rubber, silicon or plastics, they have a concave part and a convex exterior part, the faces meet at the periphery of a suction cup, they form a thin edge and the body of the suction cup have a progressively increasing thickness from the edge part of the cup to the central part. To apply a suction cup on a plane of glass, paper or a pane, the cup is placed on the required material and a pressure is applied on the center part of the cup, this causes the cup to flatten out from the center and the air that was present in the cup is exhausted out at the periphery of the cup as the force is applied, after the air has been expelled out from in between the concave and convex face and the material, the middle part is slightly pulled up causing a negative pressure inside the cup, effectively creating a mild vacuum, this difference in pressure inside the cup and outside, causes the atmospheric pressure to exert force on the suction cup, in turn holding it or making the cup adhere to the material [4].

Smart Materials

Smart materials are special material which changes one of its properties when exposed to an external stimulus, for example stress, temperature, moisture, pH, electric or magnetic fields etc. [5]

There are many types of Smart Materials, a few of them are: Piezoelectric, Electroactive Polymer, Shape-memory alloys and shape-memory polymers, Magnetostrictive, Magnetic shape memory, pH-sensitive polymers, Temperature-responsive polymers, Halochromic, Chromogenic systems, Ferrofluid, Photomechanical materials, Polycaprolactone, Self-healing materials, Dielectric elastomers, Magnetocaloric materials, Thermoelectric materials [5].

Piezoelectric Materials

Piezoelectric materials produce electric current when they are exposed to stress or mechanical force. The phenomenon is also reversible, i.e. when the material is subjected to electric field they develop mechanical stress and hence deform. The word is derived from Greek, meaning pressure and electron. The piezoelectric effect has a linear relationship between the electromechanical state and its mechanical state of a crystal. For instance, when a Lead Zirconate Titanate crystal (PZT) generates a measurable electricity when it's deformed by about 0.1%, conversely the same crystal deforms by 0.1% when an electric charge is applied to it. It is used in the field of detection of sound, electronic frequency generation, ultrafine focusing of optical assemblies, Acoustics, generation of high voltages, microbalances and to drive an ultrasonic nozzle [6].

Principle of working

The principle of piezoelectric effect is based on the occurrence of electric dipole moments in solid materials. The crystals maybe induced with ions or crystal lattice has asymmetric charges. When a mechanical force is applied to the crystal it deforms the crystal, this causes the ions to displace and orient differently in the crystal lattice, resulting in a difference in charge and this causes electric current. The reverse of this phenomenon, when an electric field is applied to the crystal the ions in the lattice are repelled and this causes the crystal to deform [7].

Applications

High Voltage and power sources, Sensors, Actuators, Frequency standard [8].

Bio-inspired Miniature Suction Cups Actuated by Shape Memory Alloy by Hu Bing-shan, Wang Li-wen, Fu Zhuang and Zhao Yan-zheng is a study of a suction cup, bio inspired miniature suction cups actuated by shape memory alloy. It serves as a gripper for wall climbing robot using negative pressure inside a suction cup, the cup is actuated using a memory shape alloy. This design was inspired by the suction mechanism in biological organism. The suction cup is lighter and makes zero noise in comparison to a pneumatic air pump based suction cups. This phenomenon can be used to adhere a miniature robot to the wall, using this the robot can conveniently climb a wall. Two designs were modeled, and two prototypes were made seen in Figure 1.

The first prototype is made from two-way shape memory effect extension TiNi spring. The second prototype is made using a single way shape memory alloy. Experimental analysis was done to test the suction properties and simulation of the second design was made using Matlab and Simulink [9]. The biggest obstacle to the design unit was the actuator that can mimic the action of a muscle. The actuators should be strong enough to generate a negative pressure, and easy to actuate. On comparing

IPMC, EAP and SMA. It was deducted that IPMC can generate a lifting power of about 0.1-4.0g depending on the thickness of the actuator (Kim, B., 2003), EAP needss a very high voltage for actuation (Walker, I.D., 2005) [10].

Hence, IPMC and EAP are not feasible. SMA forms a suitable choice to use as an actuator for the suction cup. SMA actuators are commonly in the form of wires and springs. The SMA spring has a bigger displacement, hence spring form of SMA is used for actuator. SMA is of two types, one-way and two-way SMA depending on the capacity of SMA to restore its shape after heating as seen in Figure 1 [9].

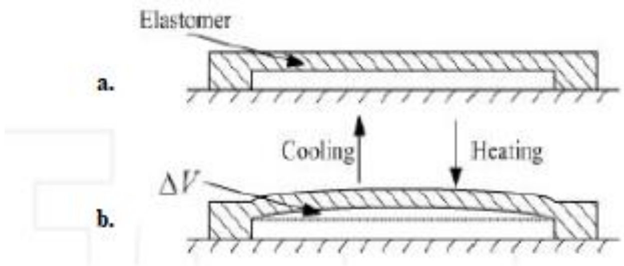


Figure 1: The sealed air cavity in the elastic material: a) before activation; b) after activation [9]

It was found that prototype 1 with a TWSME spring actuator which acts like a piston gave the best result, t created a lifting power of about 200g, the first design was not successful in canceling the negative pressure because of its smaller dimensions. Simulations and analytical model of the second prototype was performed and it was expected to be of 200g [9].

Soft robotics Biological inspiration, state of the art, and future research by Deepak Trivedi, a Christopher D. Rahn, A William M. Kierb and Ian D. Walkerc paper is an extensive research in the field of soft robotics. Inspired by biological features found among animals, it has the potential to be the future of robotics. It tries to bridge the gap between the nature and robotics. Conventionally robots are made of rigid and is not efficient when it comes to interacting with the physical world. In the animal kingdom there are many examples for an efficient interface with the physical world, like tentacles of an octopus or trunk of an elephant. These are made of connective tissue giving the organism the flexibility, dexterity, and delicacy. Hence, inspiring an ideal design to build an end effector to a robot.

A variety of suggestions are made in the paper towards the soft robotics inspired by biological specimen. Using EAP [Electro active polymer]. Robots made from EAP are light, fracture tolerance, pliability and relatively large actuation strain that is a desirable quality in the field of robotics. EAPs are classified as (dielectric elastomers, electrostrictive graft elastomers, electrostrictive paper, electroviscoelastic polymers ferroelectric polymers and liquid crystal elastomers) and ionic EAPs (Meijer et al. 2003). It was found that ionic EAPs operate at low voltage and require constant hydration and produce very low stress, while electronic EAPs have been found to produce large strain [11].

In Design, Fabrication, and Implementation of Self-sealing Suction Cup Arrays for Grasping Chad C. Kessens, Joppa. Suction cups have a vary varied application in the industries, to grip and manipulate objects. They provide us with a dynamic control of grasp, heightened handling ability. The paper introduces a self-healing suction cup; the cup only exerts a suction force when in contact with the material there by reducing wastage of energy. Since the grasping is achieved by only passive means it is cost effective. The design uses a central vacuum pump, thereby maximizing the suction force. The design of a suction cup which self opens using passive reaction forces when the cup lip contacts an object, and self-seals in the absence of contact with an object as seen in Figure 2 [12].

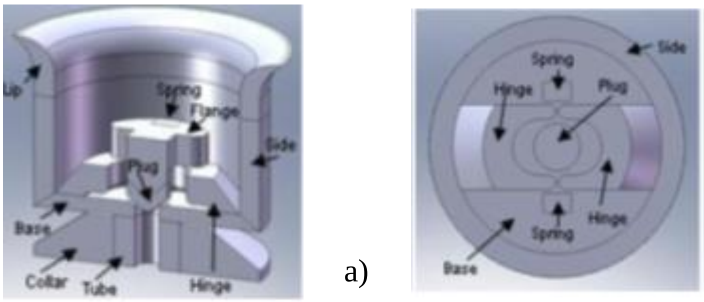
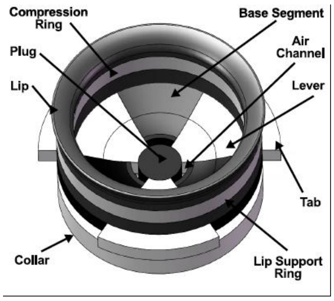
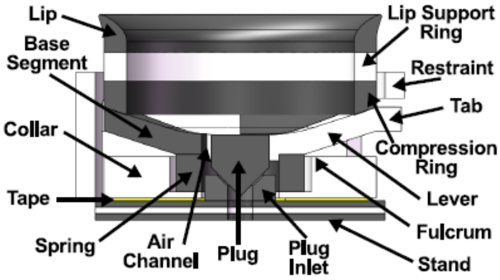


Figure 2: Cross section of suction cup: a) cross sectonal view; b) top view [12]

The Versatile Passive Grasping for Manipulation by Chad C. Kessens, Member, IEEE RAS, and Jaydev P. Desai, Senior Member, IEEE. Robots have been increasingly integrated in all fields of applications, hence there is a great need for a gripper which can be used for any applications. Hence, the need to a create a versatile gripper that can be used on any material of any shape and size. This following paper a proposes a self-healing suction cup technology to expand on the common grasping technology. In the paper a miniature design is proposed. Various characteristics like life cycle performance, self-seal quality, normal force-displacement response, leak rate, object seal and re-seal quality, and shear force responses are studied. Figure 3 shows the parts of the self healing suction cup. Figure 4 shows the schamatic represetaion of the the three-fingered gripper and the experimental setup [13].

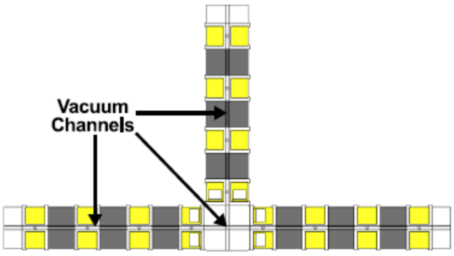


a)

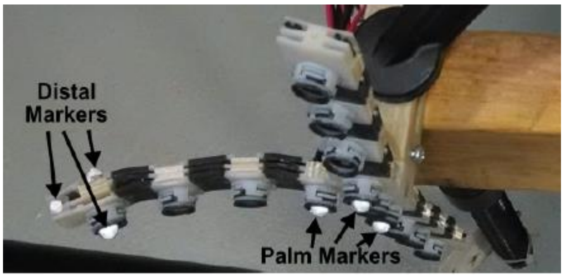


b)

Figure 3: Schematic of self-healing cup : a) top view; b) cross sectonal view [13]



a)



b)

Figure 4: The three-fingered gripper : a) representation of the three-fingered gripper ; b) experimental setup [13]

In Electroactive Polymers as Soft Robotic Actuators: Electromechanical Modeling and Identification by Rahim Mutlu, Gursel Alici and Weihua Li a proposal is made in this paper for EAP's application in the field of robot's actuator. EAP is also commonly known as artificial muscles, as its characteristics are close to the biological muscles. They have characteristics like as low consumption, compliance, bio-compatibility and ability to be miniaturized. This paper provides an analysis of dynamic behavior of EAP and reports the electromechanical modeling. A three-layer EAP actuator is used as an actuator, it consists many links connected with revolute joints. The study and analysis in the paper concludes EAP is a good material for soft robotics [14]. Figure 5 shows the structure and operation of EAP actuators and   shows the working of suction cup.

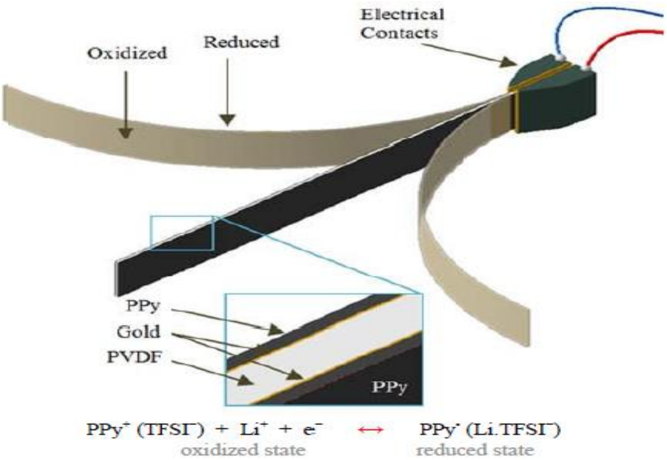


Figure 5: Structure and operation of EAP actuator [14]

The Study on Air Inflow of a Passive Suction Cup Takahiro Matsuno, Dingxin Ge, Shugen Ma and Atsushi Kakogawa paper presents a method to calculate the air flow in the vacuum suction cup, which is analyzed by a pressure sensor. The factors that affect the air flow speed are found by experimenting. The study is done to see the effects of material used, size of the cup and the displacement height of the suction cup.

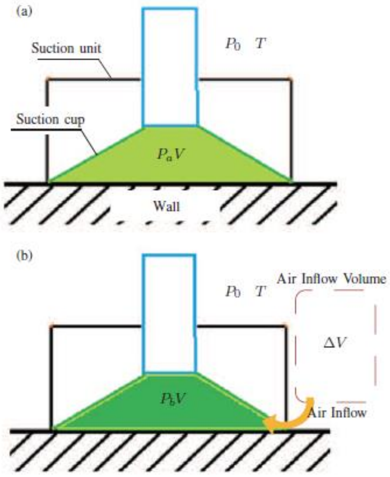


Figure 6: Analysis of air in flow a) initial status of suction cup attached to the surface (b)changing status of suction cup inner pressure [15]

From ideal gas law, the inner air amount of substance of the suction cup na, nb as seen in 2.1, can be calculated as;
na and nb = inner air amount of substance of suction cup.
Pa = pressure inside the cup; R = Gas constant; T= Temperature; V = Volume.

$$\mathrm{n_a} = \frac{\mathrm{P_a V}}{\mathrm{RT}} \qquad (2.1)$$

the air inflow is related with volume because the air inflow is generally expressed by volume in a specific pressure. The variation of air inflow volume in atmosphere pressure is ΔV derived by as seen in 2.2.

$$\Delta \mathrm{V} = \frac{\Delta \mathrm{n\ RT}}{P_o} \qquad (2.2)$$

$$\Delta \mathrm{n} = n_b - n_a \qquad (2.3)$$

Estimation of Air Inflow Speed

$$v = \frac{\Delta \mathrm{n\ RT}}{\Delta \mathrm{t}\ P_o} \qquad (2.4)$$

v and Δt and are air inflow speed and sampling time respectively as seen in 2.4.

The Development of Piezoelectric Actuator Based Compliant Micro Gripper for Robotic Peg-in-hole Assembly by Ravi K. Jain, Surajit Saha and Somajoyti Majumder is about a Piezoelectric material can be used in miniature gripper for handling of materials in micro scale or assembling or performing many activities at a micro scale as seen in the Figure 7. The paper discuses a micro gripper made using bimorph piezoelectric actuators along with 3 degrees of freedom. The examinations of piezoelectric based miniaturized scale gripper and smaller scale control framework are done which can give the exact position of article amid robotic small-scale assembly operations for moving it starting with one then onto the next hole in an expansive work space (100 mm X 100 mm). By building up a model, it is exhibited that piezoelectric actuator based consistent miniaturized scale gripper is fit for taking care of various pegs and it can perform the mechanical peg-in-gap get together in a vast work space [16].

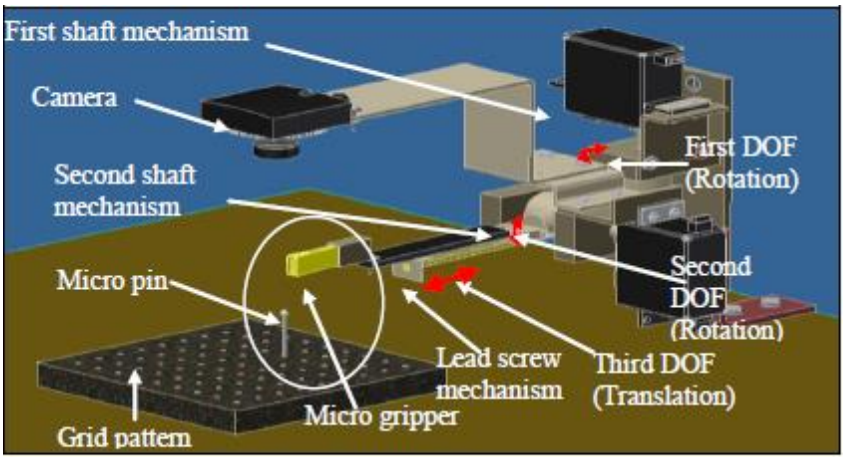


Figure 7: CAD model of piezo actuator based micro manipulation system. [16]

Development of a Small Legged Wall Climbing Robot with Passive Suction Cups by Soichiro KAWASAKI and Koki KIKUCHI the author discusses the development of a wall climbing robot with a suction cup, proposes a six-legged robot with suction cups to climb walls. The cup adheres to the wall using the negative pressure that is created, causing the difference in pressure outside the cup and inside, combined with the friction coefficient of the cup material with the material of contact. This mechanism has many advantages over pneumatic based cup, it makes almost zero noise and light weight. A prototype wall climbing was built, with dimensions 12 cm length and 34g of weight and a single degree of freedom linkage leg being the only driving mechanism [17].

The mechanism of its work are as follows:

(1) The leg that swings touches the wall, the required adhering force is not yet created.

(2) The swinging leg now, pushes against the wall, creating an effective vacuum by removing air inside the cup.

(3) Now the cup is adhered to the wall cause of the force created by the suction cup as seen in Figure 8**.**

The proposed suction cup is f smaller dimension and lighter and needs no external energy like vacuum pump, making it a simplistic system, it was found to move at a speed of 2 cm/s [17].

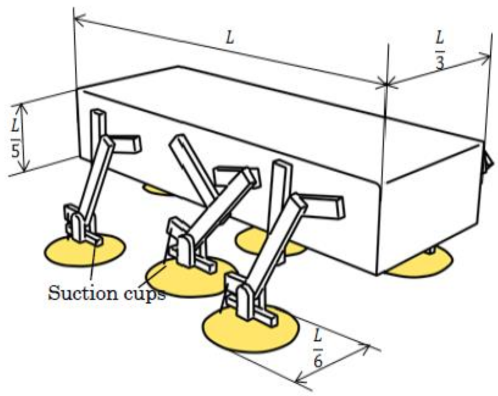


Figure 8: Schematic of the robot model and the locomotion mechanism [17]

In Performance Quantification of Conducting Polymer Actuators for Real Applications: A Microgripping System by Gursel Alici and Nam N. Huynh a polymer based actuator is modeled, characters and its performance are studied in this paper. The polymer actuator is created in the form of fingers like gripper, with two digits, called micro-gripping system. The actuator is made of five layers of three compounds, operates in a non-aqueous medium. The bending displacement and force outputs of a single digit is first experimentally determined, along with other characteristics like hysteresis and creep effects. The paper concludes that the creep devoted is substantial, and needs to be considered while the hysteresis is small enough to be ignored. Two digits are used to form a micro gripper; its payload is experimentally determined. The gripper is found to support a load up to 50 times its own weight when supplied with 1.5V. The results obtained can be used to design a micro robot as seen in Figure 9 [18].

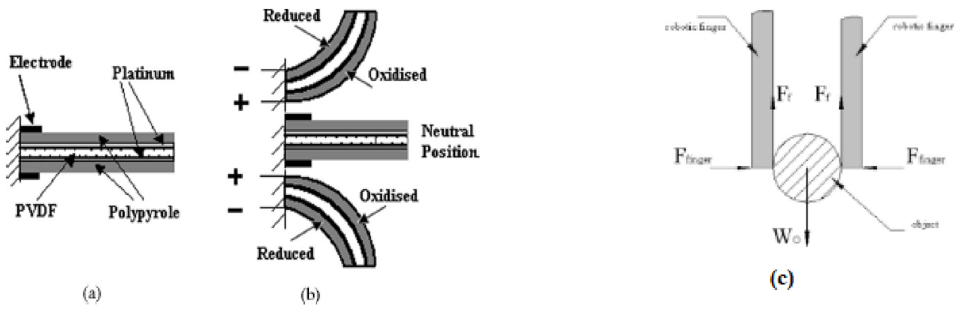


Figure 9: Schematic structure :a) conducting polymer actuator; b) representation of the bending principle; c)gripper handling a spherical object [18]

In the Artificial Adhesion Mechanisms Inspired by Octopus Suckers by Francesca Tramacere, Lucia Beccai, Member, Ieee, Fabio Mattioli, Edoardo Sinibaldi, Barbara Mazzolai, Member, Ieee the suction cup discussed was inspired by the octopus suckers. The octopus suckers are one of the most efficient naturally found suckers that works even under water. The working mechanism are very impressive and has been an intriguing subject to scientists. The paper discusses a suction cup designed inspired by the octopus suckers. The octopus tentacle was scanned under MRI and then a model is recreated using CAD precisely, as seen in Figure 10 so to be a copy of the real one and the suction cup is fabricated, and experiments are performed and study its characteristics [19].

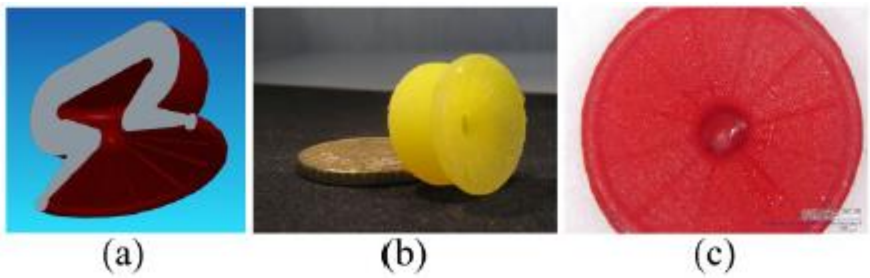


Figure 10: CAD model of the sucker: a) cross sectional view; b) 3D printed ; c) bottom view [19]

The A Wall-Climbing Robot without any Active Suction Mechanisms by Yu Yoshida and Shugen Ma proposes a wall climbing robot that adheres to the wall using passive suction cups. It uses single motor to move on the wall, it automatically attaches and detaches to the wall as seen in the Figure 11. The suction cups do not use additional energy to maintain adhesion. Hence, the robot can perform the feat with relatively low energy [20].

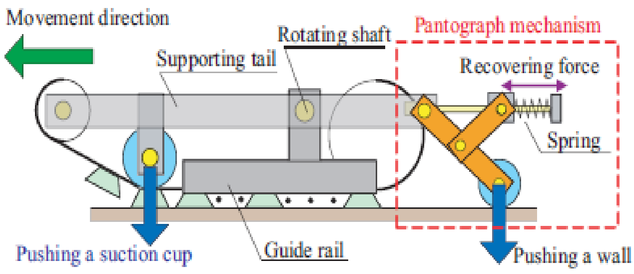


Figure 11: Suction cup working mechanism [20]

In the Principle and Application of Vibrating Suction Method Tao Zhu Rong Liu, Xu D. Wang, Kun Wang a suction cup that uses high frequency as a mechanism to adhere is explained in this following paper. Mathematical model of the system is obtained using a few assumptions. The model shows the relationship between the pressure inside the cup with the frequency and the amplitude of the vibration applied, as seen in Figure 12.

A prototype of the suggested model is fabricated based on the results obtained and experiments are performed on the robot [21].

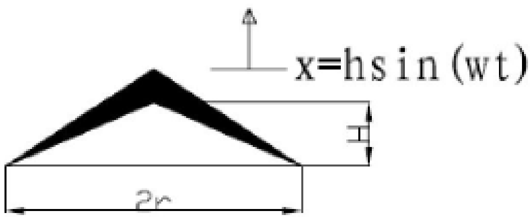


Figure 12: A vibration cycle of the suction and the conical figure of the cup [21]

The Quantitative study on the attachment and detachment of a passive suction cup by Dingxin Gea, Takahiro Matsunoa, Yi Suna, Chao Rena, Yongchen Tanga, Shugen Ma presents a comprehensive study on parameters necessary for the attachment and detachment of a suction cup on a wall. Study of the forces that influence and the suitable characteristics for industrial uses. The complete mechanism of the process of attachment and detachments are presented, as seen in Figure 14. A test platform has been constructed to study the optimal suction force needed to attach and to study the vacuum created on the contact surface and internal elastic forces, deformation of the cup is studied, as seen in Figure 13. The method proposed in the paper can be adopted to study other suction cups give a valuable insight to the design a suction cup [22].

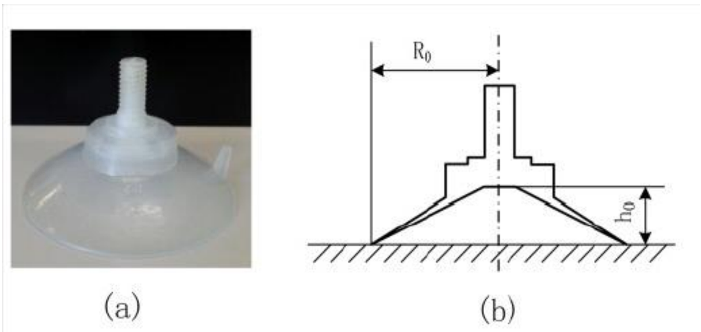


Figure 14: Sucion cup a) commercially available; b) cross sectional view [22]

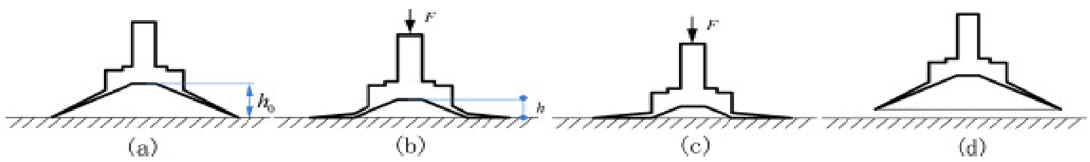


Figure 13:Working phases: a) initial phase; b) pushing phase; c) attached phase; d) detached phase [22]

3 Designing of suction cup

In this project we explore a novel design proposal of a suction cup that can be activated using a smart material, mainly piezoelectric material. The analysis is done to simulate and experiment the best material for membrane and the best piezoelectric material, the combination of which gives the best result, namely the lifting force in this context. The design has been inspired by a combination of sources available in the industrial world and scientific project on vacuum cups. The suction cups have been inspired by some of the examples found in the biological world i.e. octopus.

In the designing process many considerations were made, one of important considerations in the process was to make the idea commercially viable and hence the availability of the materials used was of prime importance. Hence, commercial availability of the materials used in the research of this project was cross referenced with some of the commercial retailors near Lithuania or the ones that can deliver the product.

3.1 Dimensions of suction cup

Dimension consideration was also made by cross referencing the availability of materials with the local retailor store and the dimension was selected.

PI ceramics (Physik Instrumente) is a global industry which was established 40 years ago. The company has been certified by and maintain the standards established by the ISO. They have productions in many countries in Asia, Europe and America. They produce a variety of piezoelectric products examples Piezoelectric Rods, discs and cylinders, plates and blocks, rings, tubes, sphere and hemispheres, piezoceramics actuators Linear, blenders, stack actuators, shear actuators, transducers, crystals, tube actuators, piezo controllers and drivers [23].

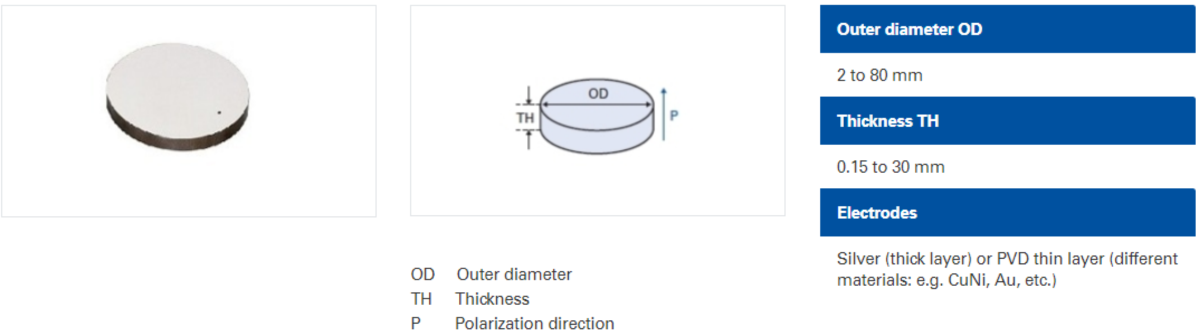


Figure 15: Piezoceramics disc, industrial standards [24]

Looking at the profile of the retailor and the products they have in stocks, refereeing their product profile for reference in this research is a good choice. Hence, their product catalogue on the disc shade piezoelectric material was explored as you can see in Figure 15.As seen in the Figure 15, the store provides a variety of options when it comes to disc size, all the way from 2mm to 80mm of outer diameter. Since, I am using piezoelectric material, which are known to give displacement in the level of micro scale, I decided to make start from the smallest size.

As a part of analysis, I wanted to find the best fit or the best combination of piezoelectric material that would give the best result, hence a very efficient method to determine the combination of piezoelectric and membrane was created. To cross refer the simulation results with the experiment result, dimensions that would match the product used for experiment was used. That was a disc of radius 7.5mm, and membrane of 10mm radius was used as the dimensions for analysis [24].

After looking at the commercially available dimensions.

Radius: 7.5 mm

Thickness: 0.15mm

were decided to be the dimensions of the piezoelectric in this project.

3.2 Piezoelectric material

Lead Zirconate titanate (PZT)

PZT is a metallic inorganic compound with chemical formula Pb[ZrxTi1-x] O3, it is made from a perovskite material that has a very significant piezoelectric effect, which means they change their shape when an electric field is applied. It has a very wide application from ultrasonic transducer and actuators [24].

Electroceramics properties

A piezoelectric, PZT creates voltage across its surface when its subjected to mechanical stress, also the reverse is true when a voltage difference is applied the crystal will undergo a deformation. PZT can be used as a heat sensor. PZT is a ferroelectric material, which gives rise to spontaneous electric polarization (electric dipole) that can be reversed as well. When the material features an extremely large dielectric constant at a morphotropic phase boundary near x = 0.52. Some formulations are ohmic until at least 250 kV/cm, after this point the current grows exponentially with field strength before reaching avalanche breakdown; but PZT exhibits time-dependent dielectric breakdown may occur under constant-voltage stress after minutes to hours, depending on voltage and temperature, so its dielectric strength depends on the time scale over which it is measured. Other formulations have dielectric strengths measured in the 8–16 MV/m range [25].

Table 1: Properties of PZT PIC 181 [27]

Parameters		Unit	PIC 181
Physical and dielectric properties			
Density	ρ	g/ cm^3	7.8
Curie temperature	T_c	Celsius	330
Permittivity	ε_{33} T/ε_0		1200
	ε_{11} T/ε_0		1500
Dielectric loss factor	tan δ	10^{-3}	3
Electromechanical properties			
Coupling factors	k_p		0.56
	k_t		0.46
	k_{31}		0.32
	k_{33}		0.66
	k_{15}		0.63
Piezoelectric charge coefficient	d_{31}		-120
	d_{33}	10^{-12}C/N	265
	d_{15}		475
Piezoelectric Voltage coefficient	g_{13}	10^{-3} Vm /N	-11.2
	g_{33}		25
Acoustic-mechanical properties			
Frequency coefficients	N_p		2270
	N_1	Hz ·m	1640
	N_3		2010
	N_t		2110
Elastic compliance coefficient	S_{11E}	10^{-12} m2 /N	11.8
	S_{33E}		14.2
Elastic stiffness coefficient	C_{33D}	10^{10} N /m2	16.2
Mechanical quality factor	Q_m		2000
Temperature stability			
Temperature coefficient of εT 33 (in the range -20 °C to +125 °C)	TK ε_{33}	10^{-3} /K	3
Time stability			
Relative permittivity	C_ε		/
Coupling factor	C_k		/

Applications of the PZT

PZT materials are used in components of ultrasound transducers and ceramic capacitors, STM/AFM actuators (tubes). They are used to make ultrasound transducers and sensors and actuators, and ceramic capacitors and FRAM chips. They are used in ceramic resonators in electronic circuit. It is used seldom in it’s pure form but rather doped for a commercial use. When doped it creates an oxygen (anion) vacancies or donors create metal (cation) vacancies. There are two types of PZT based on the doping, Hard and Soft PZT. When they are doped as acceptor it creates hard PZT and if doped as Donor it creates a soft PZT[26].

Varieties of PZTs

Commonly PZT chemical composition is PbZr0.52Ti0.48O3. we can increase the poling efficiency near x=0.52 is due to the increased number of domain states at the MPB. There are 6 possible domain states from the tetragonal phase <100> and 8 possible domain states from rhombohedral phase <111> are equally favorable energetically, thereby allowing a maximum 14 possible domain state [26].

The properties of piezoelectric materials

The properties of piezoelectric materials used are needed for studying them using simulation software, the properties of these materials also are also studied the same way the dimensions of the cup were decided. The properties of the materials are obtained from the company that are commonly used in for industries [27].

Properties of Lead Zirconate titanate (PZT)

The industrially preferred properties of PZT were obtained from the PI ceramics company, among many modified versions of PIC181 was chosen because of its Extremely high mechanical quality factor, good temperature, and time stability of its dielectric and elasticity constant properties. The properties are as seen in table 1 [27].

3.3 Membrane selection for the suction cup

a. Aluminum	
Young’s modulus	70.3 GPa
Poison's ratios	0.345
Density	2690

b. Copper	
Young’s modulus	120 GPa
Poison's ratios	0.33
Density	8960

c. Brass	
Young's Modulus	100 GPa
Poison's Ratio	0.31
Density	8400

d. Silicon	
Young’s modulus	130 GPa
Poison's ratios	0.064
Density	2300

Table 2: Mechanical Properties: a) Aluminum; b) Copper; c) Brass; d) Silicon [28].

In the field of Microelectromechanical systems (MEMS) metals, polymers are most widely used material. Membrane is important because when it is activated by a piezoelectric material they are displaced, metals due to their malleability, give a very good displacement. For the selection of material, the properties that are generally used and their mechanical properties are fed to the simulation software for the study. The properties are as seen in table 2 [27].

3.4 Cup Selection and its specification

The cup for the suction cup the material was also done the same way as the dimensions and piezoelectric materials were done. For the product to be commercially feasible, the current suction cup market was explored, cup specificatons are as seen in Table 3.

Specification	
Curve radius	45 mm
Movement, vertical max.	4 mm
Application	Mark Free, Dry sheet metal
Material	Silicon
Suction cup shape	Flat Concave
Volume	3 cm^3
Weight	3 g
Dimension	
Height	11 mm
Outer diameter	28.5 mm

Table 3: Specification of the silicon suction cup [28]

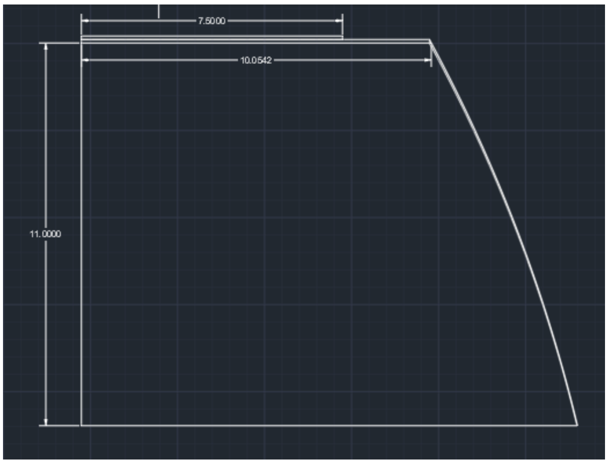
And the available size and varieties of the suction cups are studied, and a suction cup from the company Piab utilizes COAX. Silicon material is preferred as they are highly flexible and elastic and give the most displacement and are also commercially readily available. In the Table 3, the specification of the silicon cup is given.

3.5 Modeling the suction cup

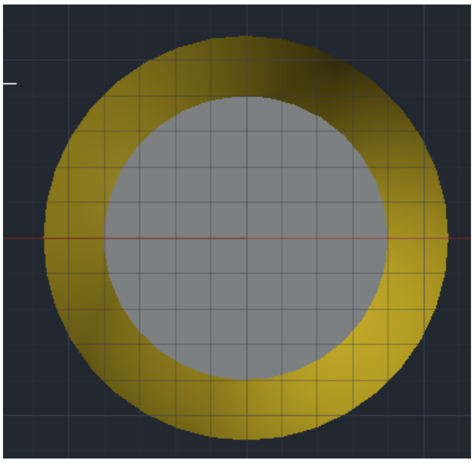
The designing of the cup is done using AUTOCAD, after going through the process of dimension selection, Material selection, cup selection and membrane selection, it’s time to bring into fruition, the idea proposed, which is achieved by using the designing software AUTOCAD. The specification selected in the designing process are as seen in the Table 4.

Design specification	
Radius of Membrane	10mm
Thickness of Membrane	0.1mm
Radius of Piezoelectric material	7.5mm
Thickness of Piezoelectric material	0.1mm
Height of Cup	11mm
Curve radius	45mm
Radius of the Cup	14.25mm

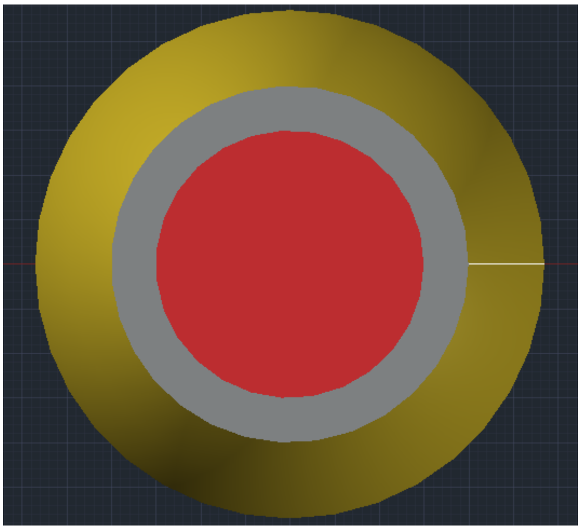
Table 4: Specifications of the suction cup used



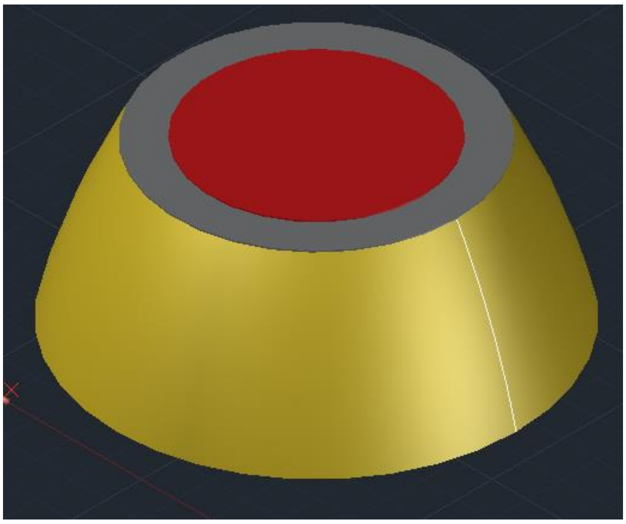
a)



b)



c)



d)

Figure 16:AUTOCAD model of the suction cup: a) 2D cross sectional; b) bottom view; c) top view; d) 3D view

As seen in the Figure 16 are the 2D and 3D diagram of the suction cup designed using AUTOCAD. The *RED* is Piezoelectric material, *GRAY* is the membrane and *YELLOW* is silicon cup.

The *RED* part that represents piezoelectric material is of 7.5 mm radius and thickness of 0.15mm. The membrane has a radius of 5mm and thickness of 0.15. The suction cup is made of silicon material, with outer radius of 28.5, and volume of 3 cm^3 and height of 11 mm.

3.6 The Working Mechanism of the Suction Cup

The Figure 17 shows the suction cup before it is placed on the work piece, the membrane is actuated to get a negative displacement, to reduce the volume in the suction cup. A piezoelectric material is used to deform the membrane as shown in the Figure 17. Before the actuation the cup is placed on the work piece to make contact. Then the piezoelectric material is actuated which deforms or develops stress when supplied with electricity. When the actuator deforms it forces the diaphragm to be deformed as well. This characteristic of the actuation, we can effectively control the deformation of the diaphragm.

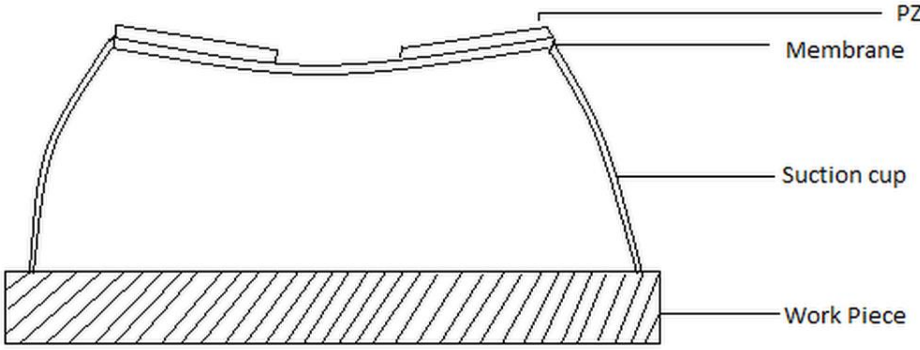


Figure 17: 2D representation of the suction cup with negative displacement

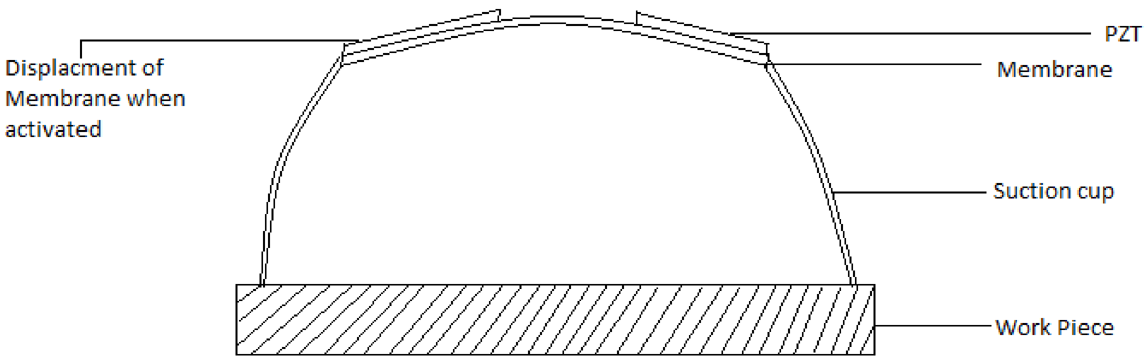


Figure 18: 2D representation of the suction cup with postive displacement

When the suction cup, which is in the state as shown in Figure 17 meets the work piece, the smart material is actuated, to achieve a budge, that protrudes out, as shown in Figure 18. The actuator is actuated using an electric field there by deforming it, and hence also changing the shape of the membrane. When the membrane is made to expand the effective volume of the suction cup increases, but as there is no opening for air to flow in, this causes a negative pressure to develop or vacuum to develop.

This results in a pressure difference between the outside of the suction cup and the inside. The difference in pressure causes the atmospheric pressure to exert force on the cup there by adhering it to the workpiece. Hence, theoretically the Adhering or gripping of a workpiece using suction cup actuated by Smart material is achieved.

4 Simulation of suction cup

After the dimensions, material of piezoelectric materials, membrane material was selected, now the simulation of the suction cup when it’s activated need to be studied. To study the effect of different metal membrane and its displacement effect when it is activated. So, to narrow down the best material to be used as membrane. To find the best material, shape, and material a method is devised, which is to study three different material i.e. Aluminum, Bass, Copper and Silicon. A disc shaped piezoelectric of outer radius 7.5mm is taken and then a study is done for different metal membranes.

Simulation steps

For simulating the displacement of piezoelectric material and its displacement when actuated can be studied using COMSOL software. In the COMSOL software we study the displacement of the membrane that is attached to the piezoelectric material after actuating, it is actuated when electric signal is applied

a) Choosing the space dimension to create the model to study.
b) To simulate piezoelectric materials and membrane. Go to study section > Structural Mechanics > Piezoelectric Devices.
c) The membrane and piezoelectric material is designed by using the geometry and using the dimensions that was decided in the section 3.
d) Selection of material is done, the membrane material i.e. Aluminum, Copper or silicon is selected. The piezoelectric material i.e. PZT.

e) The materials available in the COMSOL software come with predefined properties, they are edited to the specifications that were decided in the section 3.

f) Next step is to apply mechanical and electrical constraints, the end part of the membrane is mechanically fixed to mimic the actual world condition, when it comes to electronic constraints like grounds and terminals are applied. The upper piezoelectric material is applied with positive charge, and the ground is applied to the lower surface.

g) Now the model is simulated which gives the displacement for the voltage applied. Displacements for a range of voltage from 10 V to 100 V are computed.

4.1 Simulation Results

After completion of the steps in section 3 and feeding the specification that was decided in the section 3. into the simulating software COMSOL and computation is performed following the simulation steps results are obtained.

To find the best result among membrane materials copper, aluminum and silicon with the piezoelectric materials i.e. PZT. A method is devised in which PZT is chosen as the primary piezoelectric material and its performance is compared with all three-membrane material for varying voltage range from 10V to 100V. The displacements for each voltage ranges are computed and analyzed. Once the results are obtained, the largest displacement producing membrane is noted. Once, the results of all the studies are obtained, a comparison of their individual displacement is compared with each other.

Simulation results: Displacement for Brass membrane actuated by PZT when voltage is applied

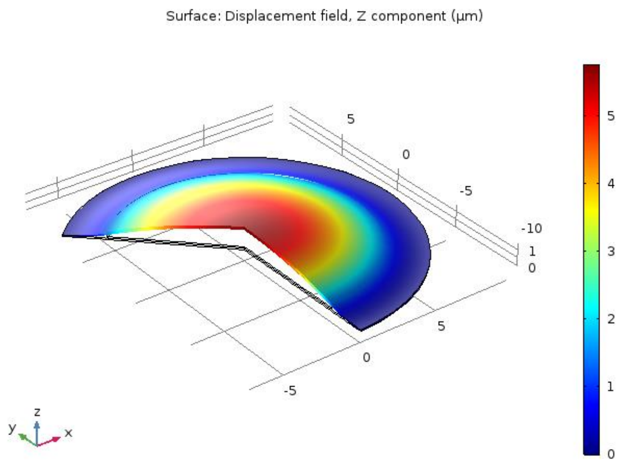


Figure 19: The displacement of brass membrane actuated by PZT (10V)

In the Figure 19 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 5.4 micro meters, and least at the circumference, when a voltage of 10V is applied.

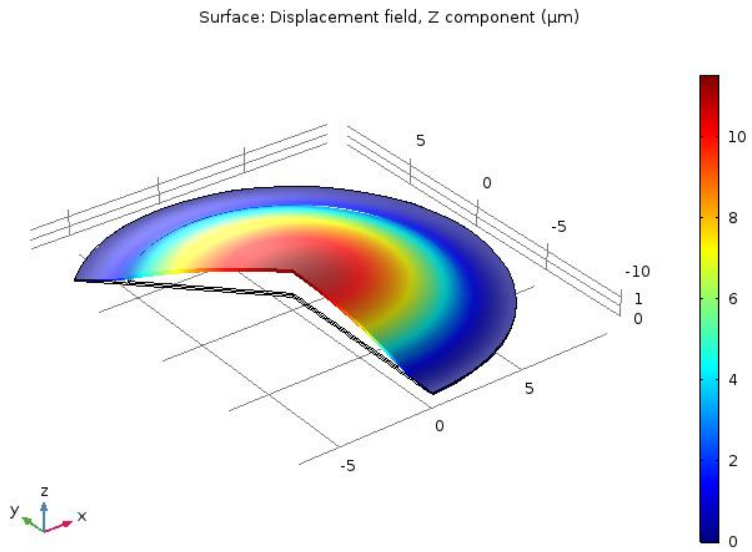


Figure 20: The displacement of brass membrane actuated by PZT (20V)

In the Figure 20 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 9 micro meters, and least at the circumference, when a voltage of 20V is applied.

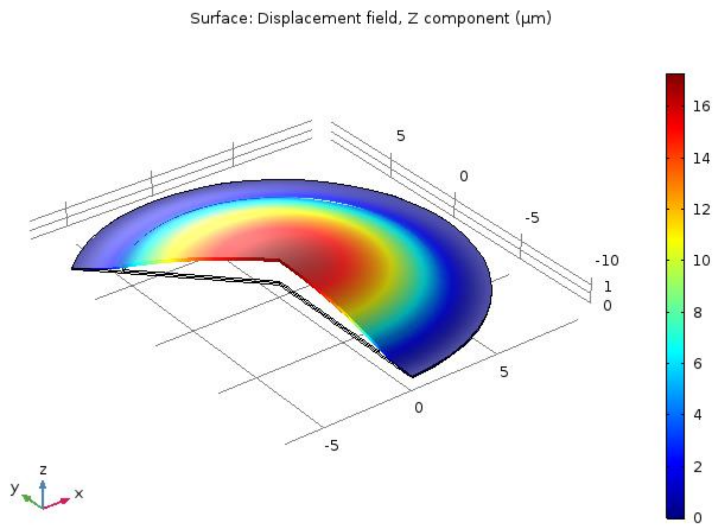


Figure 21: The displacement of brass membrane actuated by PZT (30V)

In the Figure 21 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 16.9 micro meters, and least at the circumference, when a voltage of 30V is applied.

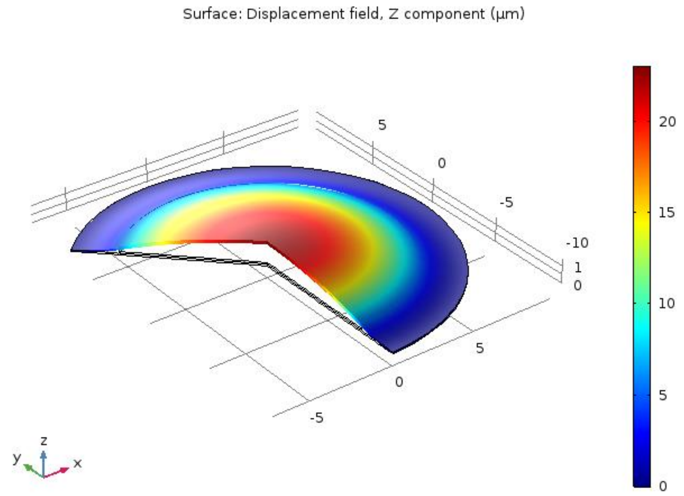


Figure 22: The displacement of brass membrane actuated by PZT (40V)

In the Figure 22 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 22 micro meters, and least at the circumference, when a voltage of 40V is applied.

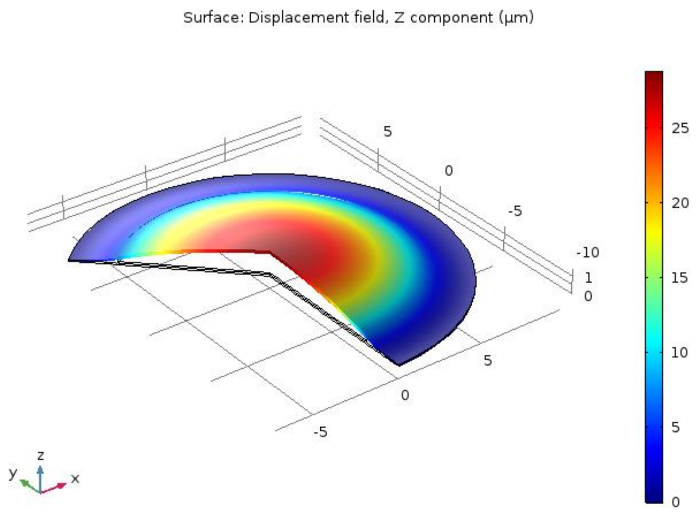


Figure 23: The displacement of brass membrane actuated by PZT (50V)

In the Figure 23 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 27 micro meters, and least at the circumference, when a voltage of 50V is applied.

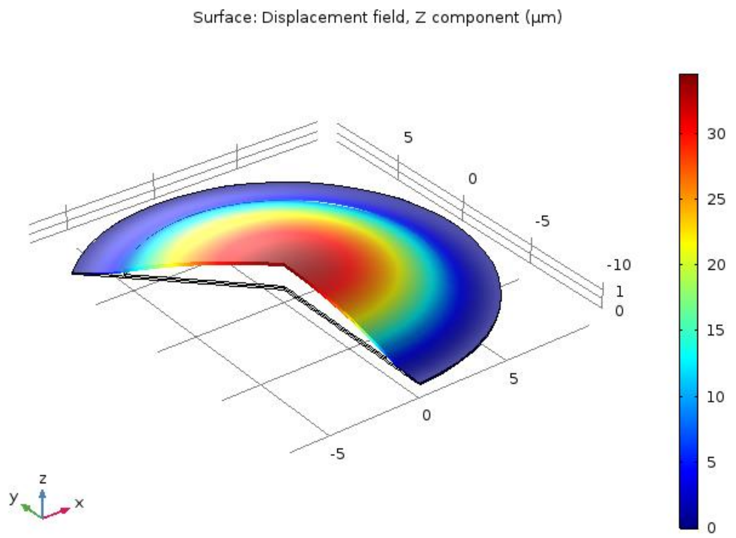


Figure 24: The displacement of brass membrane actuated by PZT (60V)

In the Figure 24 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 33 micro meters, and least at the circumference, when a voltage of 60V is applied.

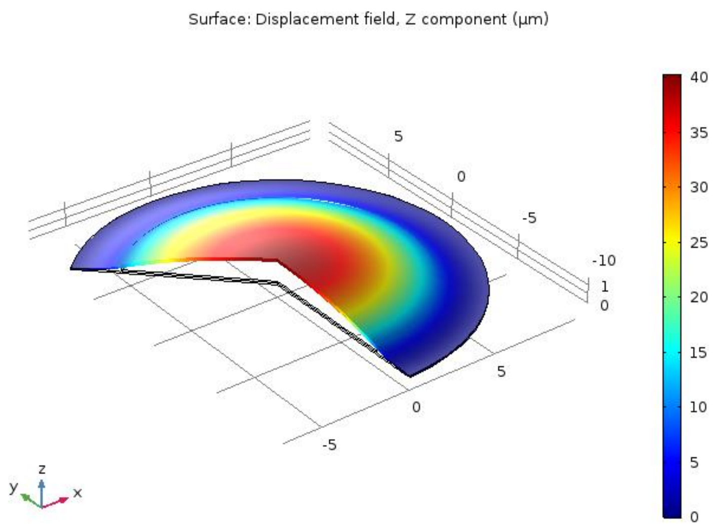


Figure 25: The displacement of brass membrane actuated by PZT (70V)

In the Figure 25 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 40 micro meters, and least at the circumference, when a voltage of 70V is applied.

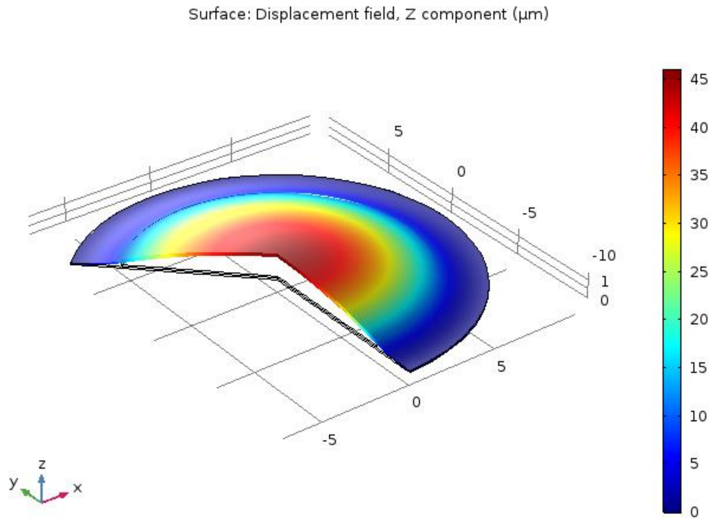


Figure 26: The displacement of brass membrane actuated by PZT (80V)

In the Figure 26 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 45.5 micro meters, and least at the circumference, when a voltage of 80V is applied

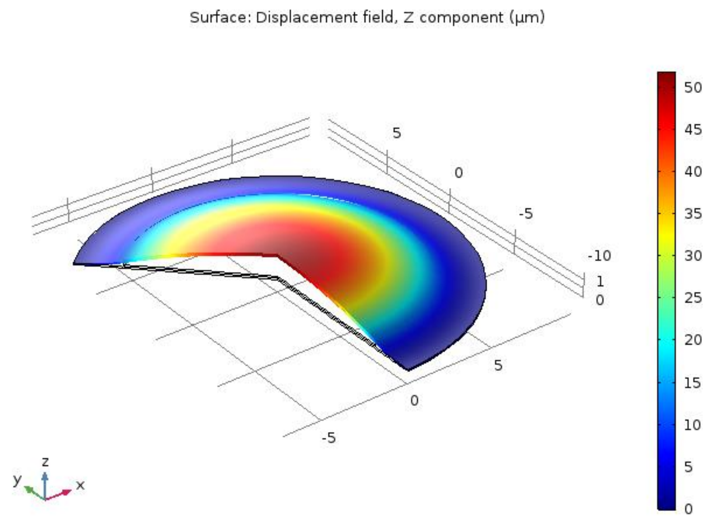


Figure 27: The displacement of brass membrane actuated by PZT (90V)

In the Figure 27 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 51 micro meters, and least at the circumference, when a voltage of 90V is applied.

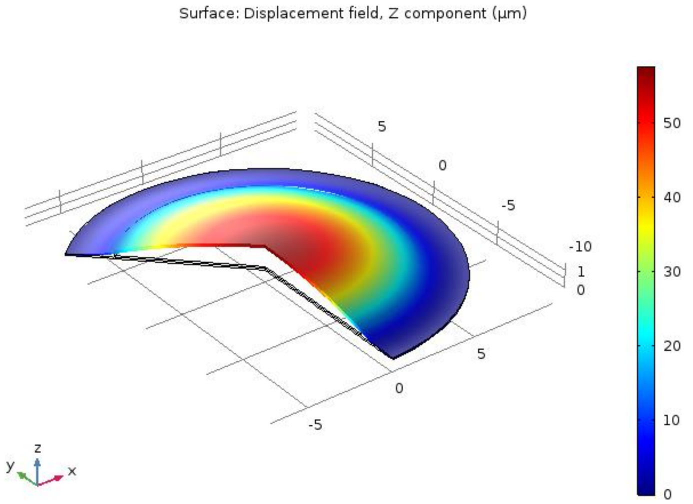
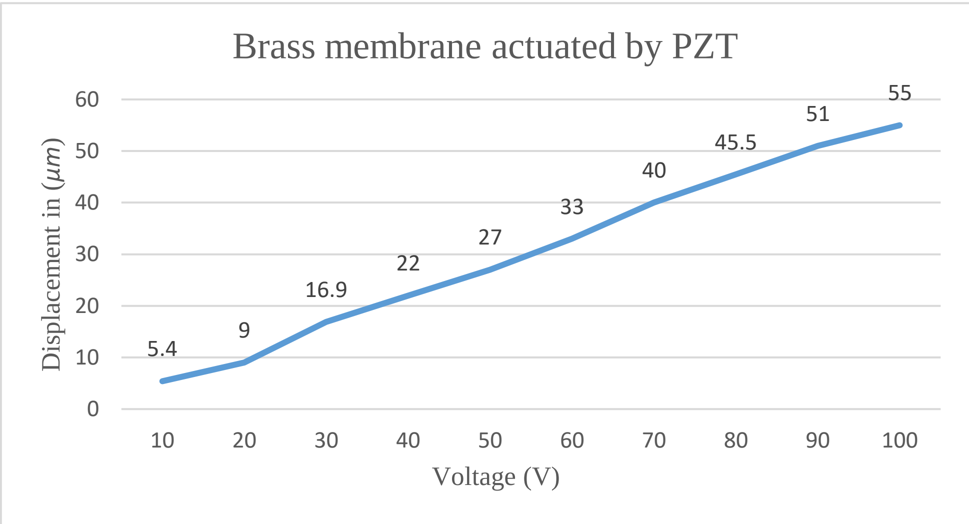


Figure 28: The displacement of brass membrane actuated by PZT (100V)

In the Figure 28 the displacement produced by the PZT actuator adhered to brass membrane of radius 10mm is found to be highest at the center with about 55 micro meters, and least at the circumference, when a voltage of 100V is applied. As expected the highest displacement due to the high voltage applied.

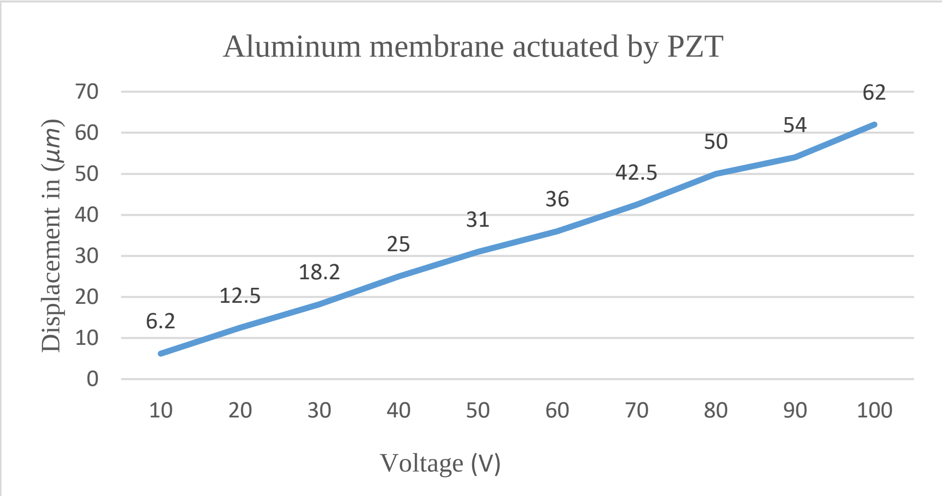
Studying the relationship between displacement of Brass membrane actuated by PZT to the voltage applied.



Graph 1: Relationship between the displacement and voltage for brass membrane actuated by PZT

In the Graph 1, relationship between the displacement of the membrane and actuator to the voltage applied is represented. The displacement of the Brass and PZT from the range 10V to 100V, as computed using the modeling software, are tabulated. As, expected as the voltage increases the displacement consequently increases. The highest displacement observed is, when 100 V is applied with, 55 µm of displacement at the center.

Studying the relationship between displacement of aluminum membrane actuated by PZT to the voltage applied.

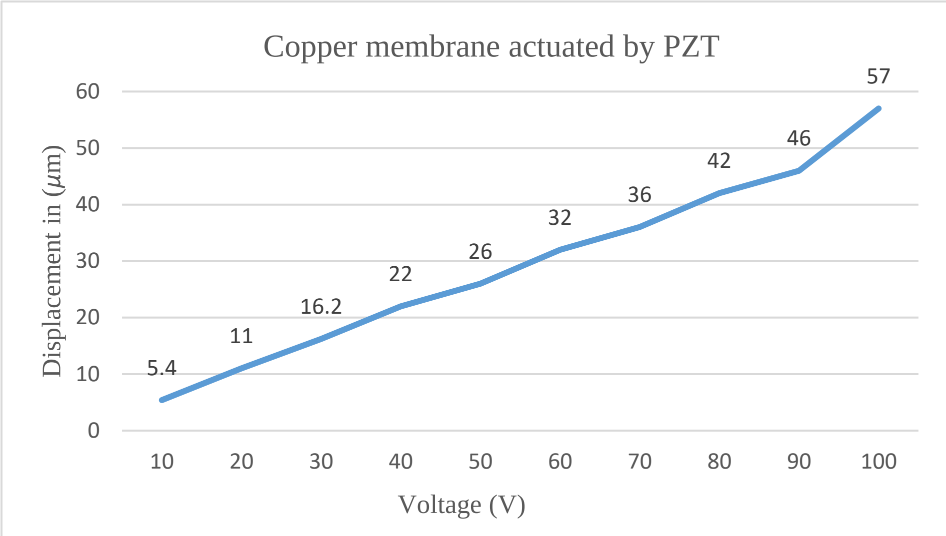


Graph 2: : Relationship between the displacement and voltage for aluminum membrane actuated by PZT

In the Graph 2, relationship between the displacement of the aluminum membrane and actuator to the voltage applied is represented. The displacement of the aluminum and PZT from the range 10V to 100V, as computed using the modeling software, are tabulated. As, expected as the voltage increases the displacement consequently increases. The highest displacement observed is, when 100 V is applied with, 62 µm of displacement at the center.

Studying the relationship between displacement of the actuator(PZT) and copper membrane to the voltage applied.

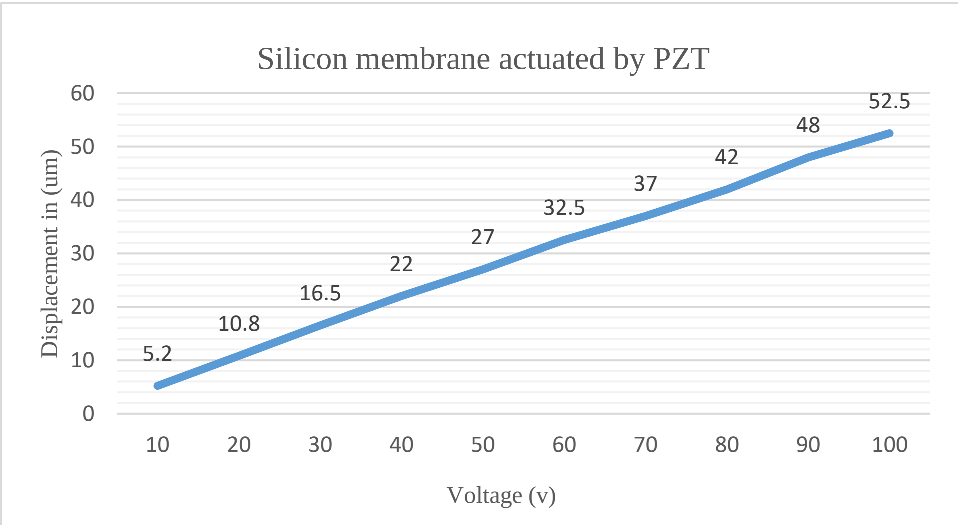
In the Graph 3, relationship between the displacement of the copper membrane and actuator to the voltage applied is represented. The displacement of the copper and PZT from the range 10V to 100V, as computed using the modeling software, are tabulated.



Graph 3: Relationship between the displacement and voltage for copper membrane actuated by PZT

As, expected as the voltage increases the displacement consequently increases. The highest displacement observed is, when 100 V is applied with, 57 µm of displacement at the center.

Studying the relationship between displacement of the actuator(PZT) and silicon membrane to the voltage applied.



Graph 4: Relationship between the displacement and voltage for silicon membrane actuated by PZT

In the Graph 4, relationship between the displacement of the silicon membrane and actuator to the voltage applied is represented. The displacement of the silicon and PZT from the range 10V to 100V, as computed using the modeling software, are tabulated. As, expected as the voltage increases the displacement consequently increases. The highest displacement observed is, when 100 V is applied with, 52.5 µm of displacement at the center.

5 Suction force calculation for suction cup

To calculate the pressure inside the cup after actuation Boyle's Law is used i.e. [29].

P_1V_1 = k = P_2V_2 (6.1)

Or

P_1V_1= P_2V_2 (6.2)

$P_1 = \frac{P_2V_2}{V_1}$ (6.3)

Using 8.3 to get the pressure that is acting on the cup.

$P_{cup} = P_1 - P_{atm}$ (6.4)

8.4 gives the theoretical suction force.

$F = P_{cup} \times A$ (6.5)

A = Area of the cup in contact with the workpiece. = 6.38×10^{-4}

To find the lifting weight capacity of the suction cup, one should consider friction coefficient of the work piece material and acceleration of the workpiece while lifting and the gravity [29].

F_{TH}= Theoretical holding force [N]

m = Weight [kg]

g = Gravity [9.81 m/s2]

a = 5 m/s2 (industrial standard) Acceleration [m/s2] of the industrial [29]

μ = Friction coefficient (0,5 for wood, metal, glass, stone, etc.)

S = Safety factor(SF); SF for horizontal directional lifting 1.5, SF for Vertical directional lifting is 2.

The meaning of Safety factor is a suction cup used to lift weight X should be producing a suction force equivalent to 2X or 1.5X [30].

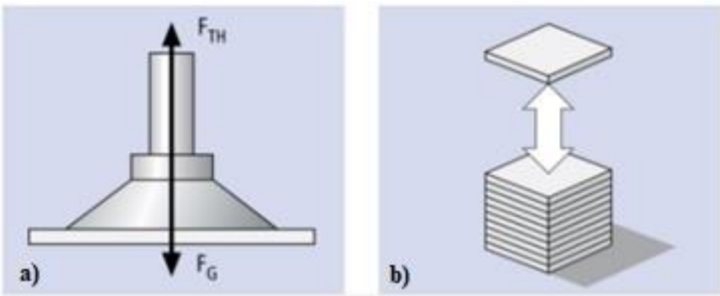


Figure 30: Schematic representation a) of forces acting on horizontal lifting; b) directon of work material movement.

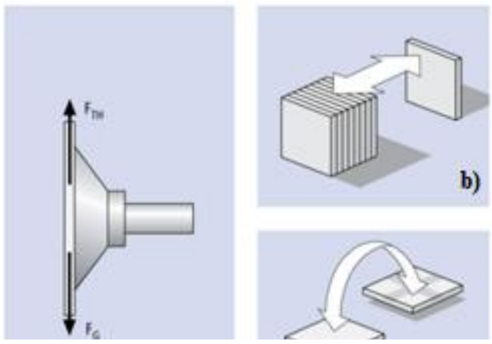


Figure 29: Schematic representation a) forces acting on vertical lifting; b) and c) direction of work material movement.

The mass lifting capacity is of the suction cup is found using 6.6 and 6.7.

$$\mathbf{F_{TH} = m \times (g + a) \times S} \qquad (6.6)$$

$$\mathbf{F_{TH} = m \times (g + a / \mu) \times S} \qquad (6.7)$$

Calculating suction force for Aluminum membrane actuated by PZT, when voltage of 50V is applied.

Volume of the cup in stationary condition

- Volume of the suction cup Vcup: **3000 mm3 (0.000003 m3)**
- Volume of cavity created by the membrane after actuation Va: **0 mm3 (0 m3)**
- Total volume of the cup after actuation: Vt = Vcup+ Va = **3000 mm3**

Volume of the cup when activated inward

- Volume of the suction cup Vcup: **3000 mm3 (0.000003 m3)**
- Displacement of the cup: **31 µm (inward)**
- Volume of cavity created by the membrane after actuation Va: **3.25 mm3 (3.25e-9 m3)**
- Total volume of the cup after actuation: Vt = Vcup - Va = **2996.75 mm3**

Volume of the cup when activated outward

- Volume of the suction cup Vcup: **3000 mm3 (0.000003 m3)**
- Displacement of the cup: **31 µm (Outward)**
- Volume of cavity created by the membrane after actuation Va: **3.25 mm3 (3.25e-9 m3)**
- Total volume of the cup after actuation: Vt = Vcup + Va = **3003.25 mm3**

$\boldsymbol{P_{atm}}$= Atmospheric pressure = **101325 Pa**; $\boldsymbol{V_{ina}}$ is Volume after inward actuation = **2996.75 mm3**
$\boldsymbol{P_{outa}}$= Pressure inside the Cup after outward activation =? $\boldsymbol{V_{out}}$ Volume after actuation = **3003.25 mm3**

Using the (6.3). We get the pressure to be **101105.700 Pa**.
Using (6.4) 101325- 101105.700 = **219.3 Pa**
From (6.5) the theoretical force is found to be F_TH = **0.13991 N**.
Using (6.6) and (6.7),
Horizontal directional mass capacity for Aluminum + PZT = ***6.29 X*** $\boldsymbol{10^{-3}}$ ***kg = 6.29 g.***
Vertical directional mass capacity Aluminum + PZT = ***2.36 X*** $\boldsymbol{10^{-3}}$ ***kg = 2.36 g.***

Using the Formula from the section 6, calculating the lifting capacity for Aluminum membrane and PZT actuator from voltage range 10 to 100 V.

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 10V.

- Horizontal directional mass capacity for Aluminum + PZT = ***0.001258653 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.000471995 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 20V.

- Horizontal directional mass capacity for Aluminum + PZT = ***0.002537048 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.000951393 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 30V

- Horizontal directional mass capacity for Aluminum + PZT = ***0.003693208 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.001384953 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 40V

- Horizontal directional mass capacity for Aluminum + PZT = ***0.005071886 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.001901957 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 50V

- Horizontal directional mass capacity for Aluminum + PZT = ***0.006287823 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.002357934 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 60V

- Horizontal directional mass capacity for Aluminum + PZT = ***0.007300716 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.002737769 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 70V

- Horizontal directional mass capacity for Aluminum + PZT = ***0.00861695 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.003231356 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 80V

- Horizontal directional mass capacity for Aluminum + PZT = ***0.01013494 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.003800602 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 90V

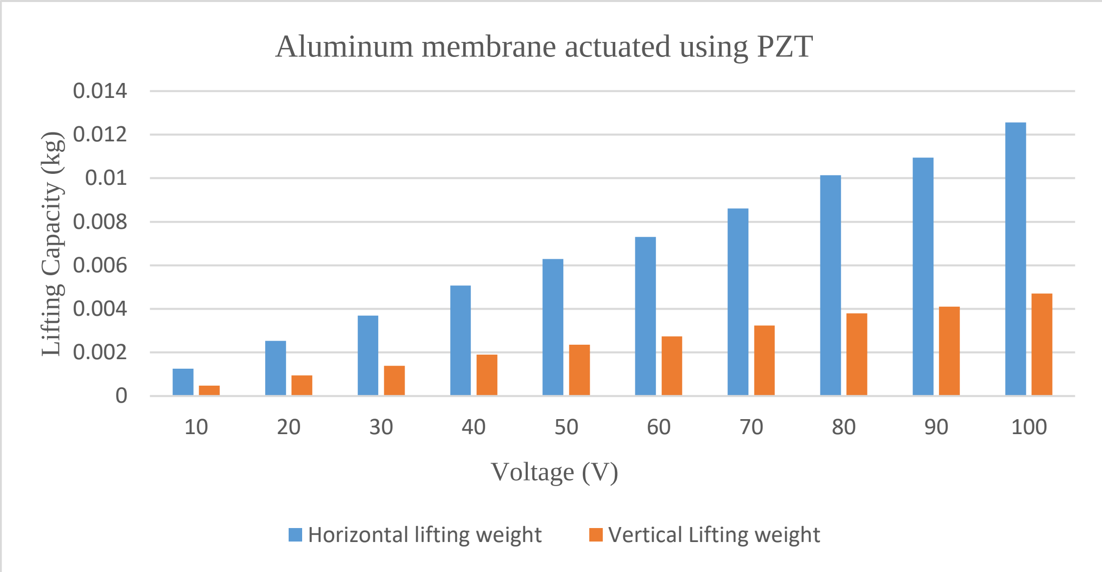
- Horizontal directional mass capacity for Aluminum + PZT = ***0.01094421 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.004104079 kg***

Using equation 8.6 and 8.7 the horizontal and vertical directional lifting capacity is calculated for 100V

- Horizontal directional mass capacity for Aluminum + PZT = ***0.012562075 kg***
- Vertical directional mass capacity Aluminum + PZT = ***0.004710778 kg***

From the calculation above we get the theoretical lifting capacity of the suction cup in vertical direction and horizontal direction. Using the calculation method shown in section, the lifting capacity for Aluminum membrane from voltage range 10V to 100V is plotted in Graph 5.

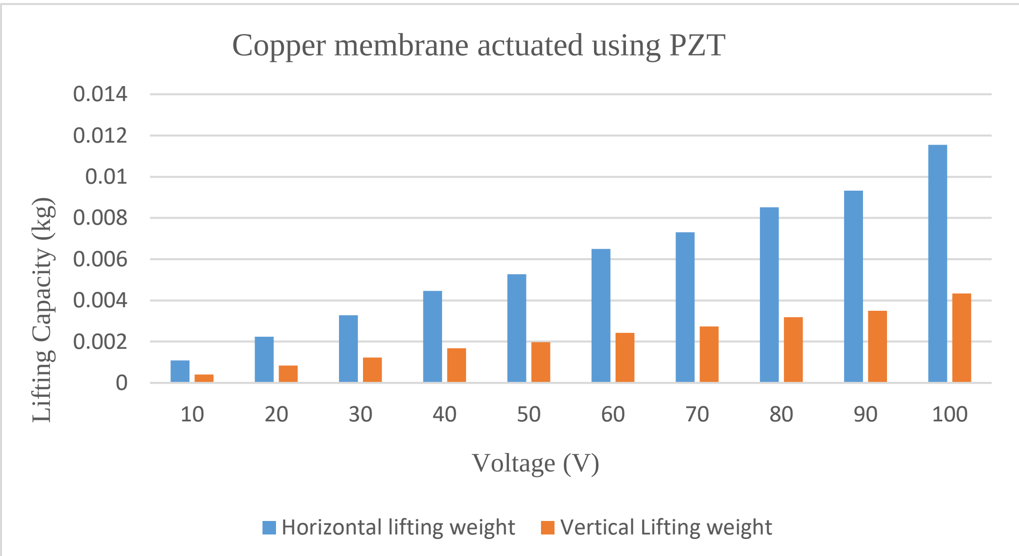
In the Graph 5 relationship between the voltage applied and the theoretical lifting capacity in the horizontal direction and vertical direction is tabulated.



Graph 5: Dependency of lifting capacity with the applied voltage for aluminum membrane actuated using PZT

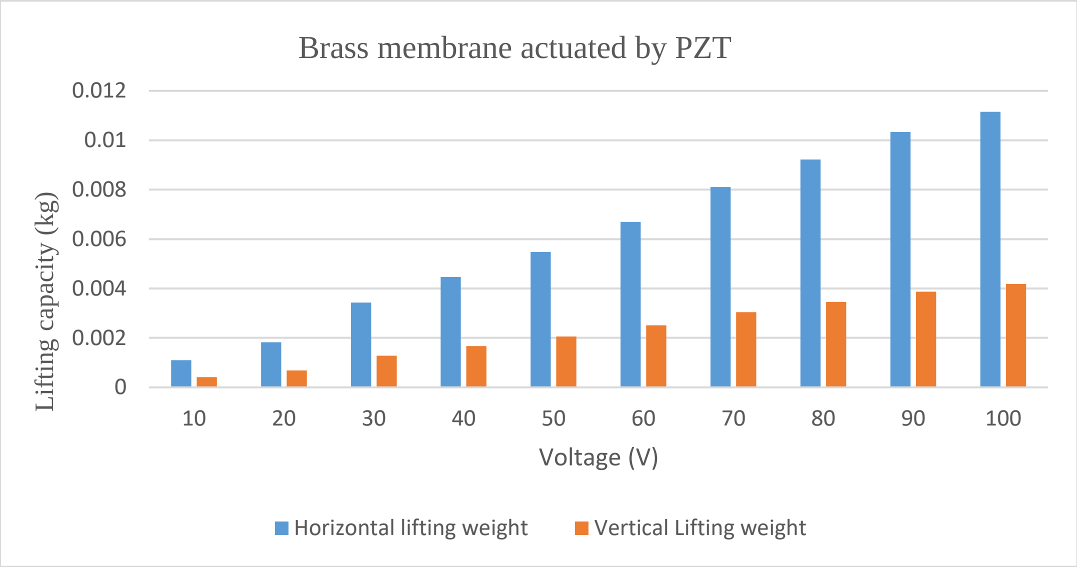
As seen, the horizontal lifting capacity is more than the vertical lifting capacity, as vertical direction lifting requires a safety factor of 2 and takes in to consideration the friction coefficient between the workpiece and the suction cup. While in the horizontal directional lifting the safety, factor is 1.5 and frictional coefficient is assumed zero.

Using the calculation method seen in section 8, the horizontal and vertical directional lifting capacity for Copper, Brass, Silicon for the range of 10V to 100V is calculated.



Graph 6: Dependece of lifting capacity with the applied voltage for copper membrane actuated using PZT

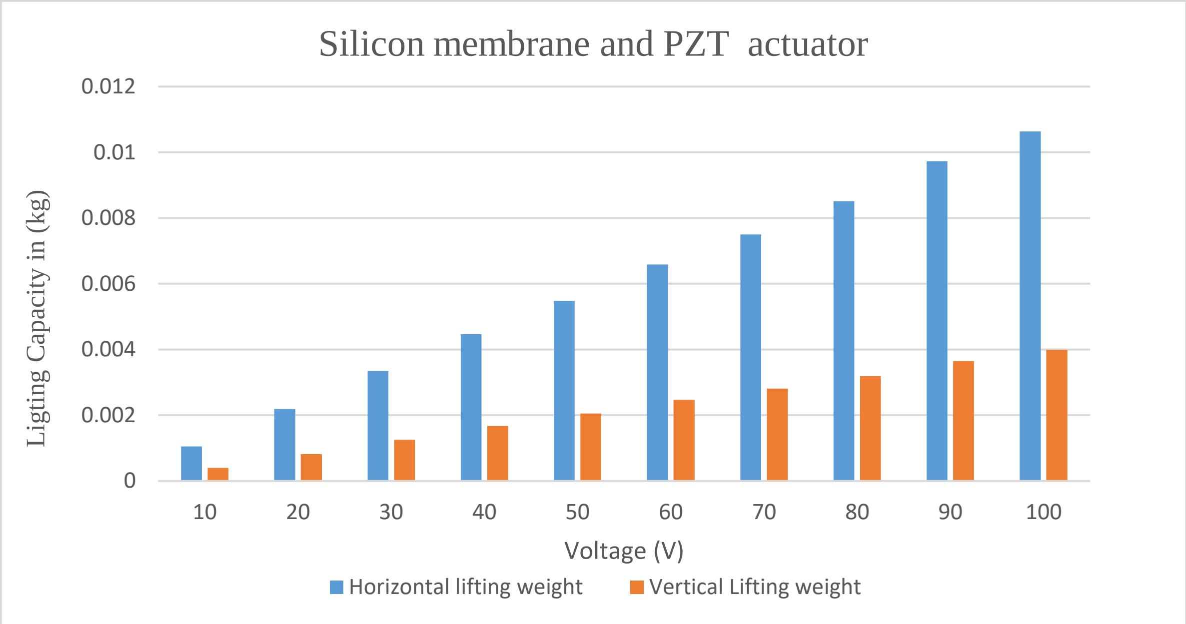
As seen in Graph 6, the relationship between the horizontal and vertical theoretical lifting capacity for the Copper membrane actuated by PZT, as seen, the horizontal lifting capacity is more than the vertical lifting capacity, as vertical direction lifting requires a safety factor of 2 and takes in to consideration the friction coefficient between the workpiece and the suction cup. While in the horizontal directional lifting the safety, factor is 1.5 and frictional coefficient is assumed zero. The highest lifting capacity is observed at 100V with around 11.5 g horizontal lifting capacity and 4g of vertical lifting capacity.



Graph 7:Dependency of lifting capacity with the applied voltage for brass membrane actuated using PZT

As seen in Graph 7, the relationship between the horizontal and vertical theoretical lifting capacity for the Brass membrane actuated by PZT, the highest lifting capacity is observed at 100V with around 11.5 g horizontal lifting capacity and 4.5 g of vertical lifting capacity. Using very high voltage is not generally recommended hence, we can consider 50 to 70 V to be operated voltage. Hence by the graph 7, we get the horizontal lifting power to be around 5 to 8 g, while vertical lifting capacity to be in range of 2 to 3 grams.

As seen in Graph 8, the relationship between the horizontal and vertical theoretical lifting capacity for the Brass membrane actuated by PZT, the highest lifting capacity is observed at 100V with around 10.6 g horizontal lifting capacity and 3 g of vertical lifting capacity.



Graph 8: Dependency of lifting capacity with the applied voltage for silicon membrane actuated using PZT

Considering 50 to 70 V suitable range of voltage, the horizontal lifting capacity will be around 5.6 to 7.5 grams, while vertical lifting capacity to be around 2 to 2.8 grams.

6 Experimental analysis of brass membrane actuated by PZT

In the laboratory of KTU, Faculty of Mechanical engineering and Design, experiment was conducted to find the displacement of brass membrane actuated by PZT when voltage is applied.

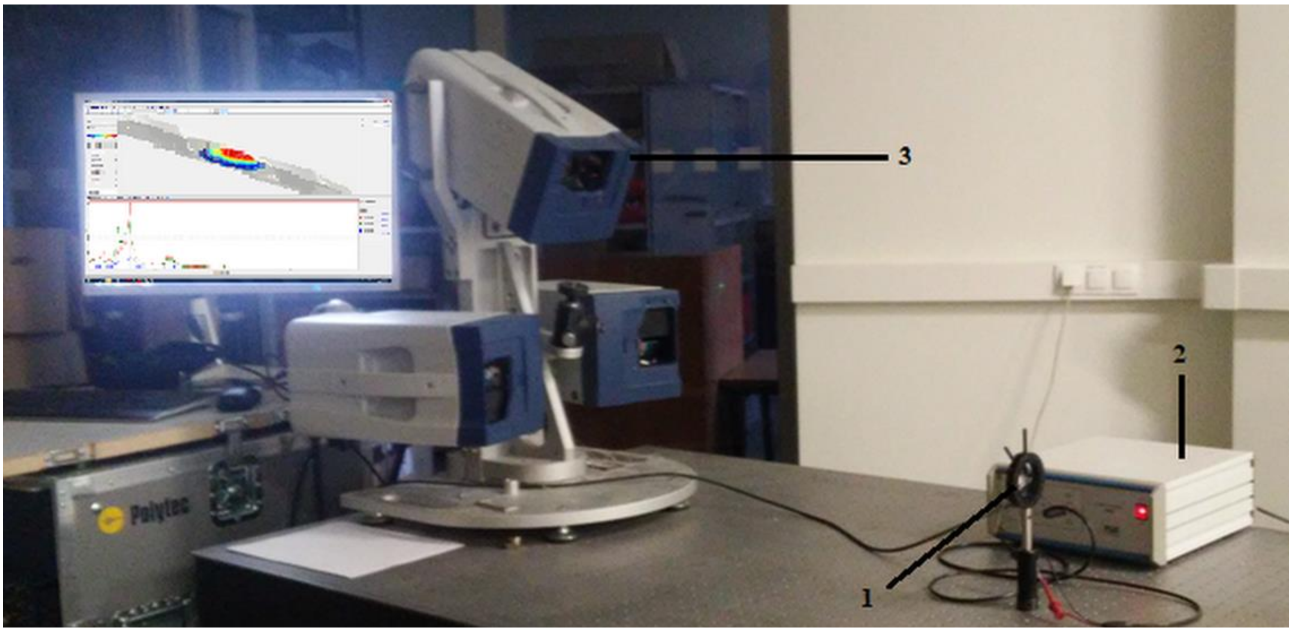


Figure 31:Experimental setup: 1) brass membrane with piezoelectric actuator; 2) liner amplifier P200 (FLC Electronics AB, Sweden), 3) 3D scanning vibrometer PSV-500-3D-HV (Polytec GmbH, Germany)

In Figure 31, the experimental setup of the experiment is shown. The brass membrane attached to PZT as seen the Figure 32, the brass membrane attached to the PZT, which is fixed to plastic frame.

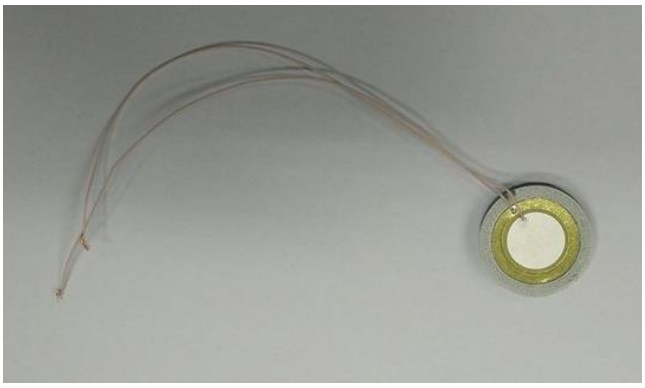
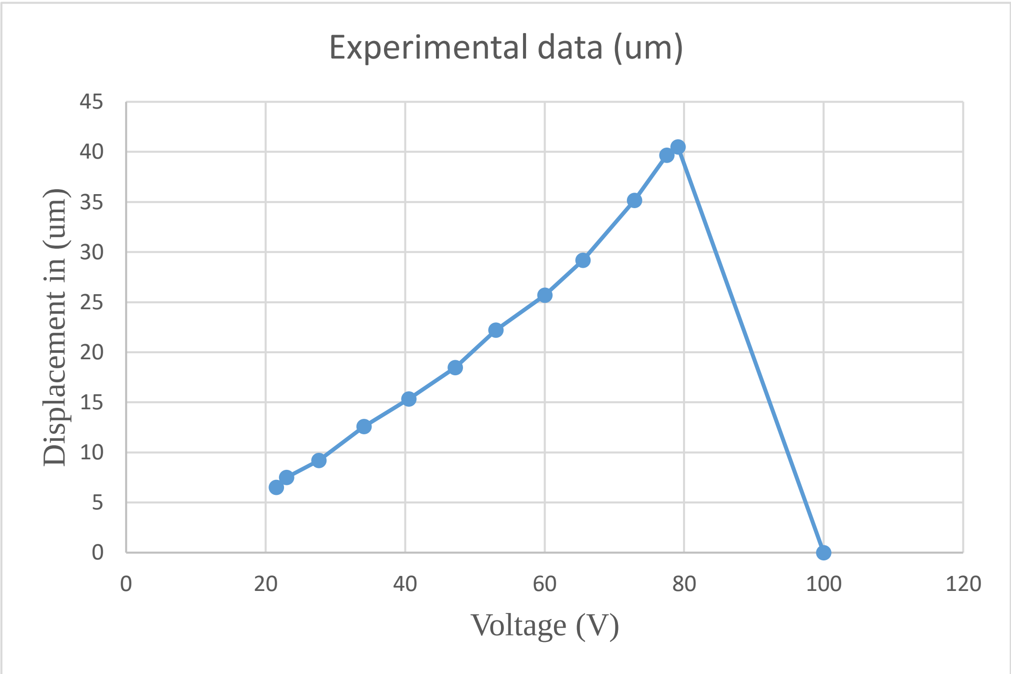


Figure 32: Brass membrane attached to PZT, fixed to platic frame

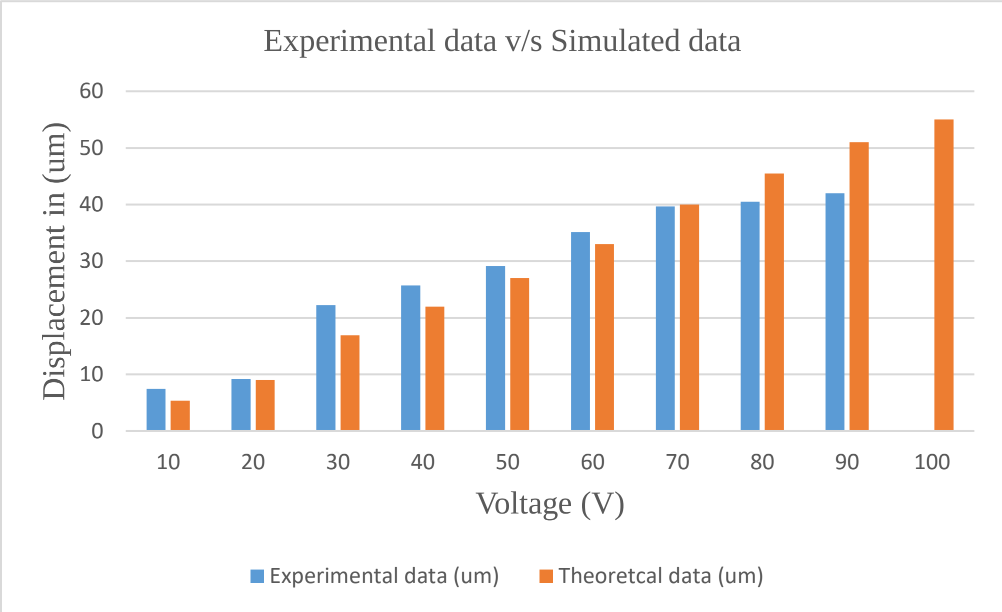
The frame is then setup as show in the Figure 31, then voltage is applied, and the displacement is measured using the 3D scanning vibrometer PSV-500-3D-HV.

The data from experiment is as given in the Graph 9. As, seen from the graph, the displacement steady increases as the voltage applied increases, as expected. The value reaches zero at 100, because the PZT reaches a polarization point and hence further increase in displacement with increase in voltage can't be applied.



Graph 9: Experimental data of brass membrane actuated using PZT

Experimental data is compared with the simulated data as seen in Graph 10.



Graph 10: Experimental data v/s simulated data for brass membrane actuated by PZT

As seen in the Graph 10, a comparison of the experimental data with theoretical data is done, as evident the difference between the experimental data and simulated data is not very high, which means the modeled simulated data is correct. The little difference between the two values can be associated with external physical factors, the properties of the PZT and membrane used for the experiment used and used for simulation might not have coincide 100 percent, the fixing frame, the glue that attaches PZT to brass membrane influence the performance of the membrane greatly. The difference however not large enough to concerned. At 100 V, the PZT in real world is polarized and hence can’t be used to achieve any displacement with further increase of voltage.

7 Applications of suction cup

Suction cups are used in many industries, meteorological industries, medical, Paper, Electronic, food and beverage industries, construction industries and automotive industries.

Suction cups proposed in this project produces a theoretical force enough to support about 1g to 12g, with the highest produced by Aluminum membrane actuated by PZT, with 12g in horizontal directional lift.

Which is relatively low, compared to the industrial requirements, but can be used for lifting light weights, like papers and electronic chips, food and bakery items.

Another field of application could be small scale Robotics which weigh less than 100g, a bunch of suction cups i.e. 4 or 6 could be used, to give them the lifting power enough to support the weight of the robot. Since, there is a micro controller on board a robot, the suction cups can be integrated with them, and this can be programmed to synch with the motion of the robot, giving the robot a better control and grip to move. As seen in Figure 33, shows the example of using many suction cups in an array or series, modular technology used by COVAL industry, the same principle can be used.

Figure 33: Modular vacuum gripper technology by COVAL [31]

From the simulated results, it shows with higer voltage higher lifting force can be achieved, but it is not advisable to use large voltage, hence a range of 50 to 70V would be ideal range to work with. A single cup with 30 mm^3, produces can support a weight of about 6 to 8.5g, by using a larger number of cups in an series or array, we can effectively multiply the suppoorting power, for instance using 10 cups with 70V applied can theoretically supoort 85 grams. On industrial scale a larger number of cups can be used to get a larger supoorting capapcity, and have the capacity to control all of the togther or in a sequency, also automate it by programing it, giving a greater range of flexibility.

a)  b) 

Figure 34: Industrial applications of scution cup: a) array of suction cups used in food industry; b) packaging industry [32]

Conclusion

1. A suction cup of silicon with a volume of 30 mm3, with cup outer radius of 28.5 mm and height of 11mm, PZT with radius 7.5mm and thickness 0.15 mm, membrane radius of 10mm was selected and designed.
2. The suction cup was modeled and simulated and the data from the simulation was tabulated and Aluminum membrane actuated by PZT was found to produce the best result with a displacement of 62 micro meters.
3. Experment with the brass membrane actuated using PZT was performed and the experimental data was compared with the simulated data and found to have an error percentage of less than 5%, that can be associated to external factors.
4. Numerical calculations are done to calculate the theoretical forces generated by the suction cup, like expected aluminum gives the highest theoretical lifting force of about 10g for about 70V applied.

Reference

1. Allcock, Andrew (2006). "Anthropomorphic hand is almost human". Machinery. http://www.machinery.co.uk/machinery-products/anthropomorphic-hand-is-almost-human/7593/. [accessed on June 2016]
2. Shirinov A and Oberbeck S. High vacuum side channel pump working against atmosphere. Vacuum 2011; 85:1174 – 1177. [accessed on July 2016]
3. Ahmad Y Hassan. "The Origin of the Suction Pump: Al-Jazari 1206 A.D." Cambridge university press. ISBN 0-521-42239-6. [accessed on December 2016]
4. “Choosing the right suction cup”, [accessed on March 2017], < http://www.festo-didactic.com/ov3/media>
5. Mohd Jani, Jaronie; Leary, Martin; Subic, Aleksandar; Gibson, Mark A. "A review of shape memory alloy research, applications and opportunities". Materials & Design. April 2014. [accessed on April 2017]
6. Manbachi, A. and Cobbold R.S.C. "Development and Application of Piezoelectric Materials for Ultrasound Generation and Detection" Ultrasound. 2011. [accessed on June 2017]
7. Wang, Youqi; Changjie Sun; Eric Zhou; Ji Su. "Deformation Mechanisms of Electrostrictive Graft Elastomers". Smart Materials and Structures (Institute of Physics Publishing). 2004. [accessed on June 2017]
8. U. L Peng, Q, Dai, L., Spinks, G.M., Wallace, G.G., Baughman, R.H. "Carbon Nanotube Electroactive Polymer Materials: Opportunities and Challenges",2008. [accessed on July 2017]
9. Hu Bing-shan1, Wang Li-wen2, Fu Zhuang1 and Zhao Yan-zheng. “Bio-inspired Miniature Suction Cups Actuated by Shape Memory Alloy”, 2006. [accessed on August 2017]
10. Walker, I.D., Dawson, D.M., Flash, T., Grasso, F.W., Hanlon, R.T., Hochner, B., Kier, W.M., Pagano, C.C., Rahn, C.D. and Zhang, Q.M. (2005). Continuum Robot Arms Inspired by Cephalopods, Proceedings of SPIE, Gerhart, G.R.; Shoemaker, C.M. & Gage, D.W., Vol. 5804, pp. 303-314. [accessed on August 2017]
11. “Soft robotics: Biological inspiration, state of the art, and future research” Deepak Trivedi,a Christopher D. Rahn, William M. Kierb and Ian D. Walkerc, The Pennsylvania State University, University Park, PA 16802, 2008. [accessed on June 2017]

12. Chad C. Kessens, Joppa. “Design, Fabrication, and Implementation of Self-sealing Suction Cup Arrays for Grasping”, 2010. [accessed on August 2017]
13. IEEE RAS, and Jaydev P. Desai, Senior Member, IEEE. “Versatile Passive Grasping for Manipulation” Chad C. Kessens, Member, 2016. [accessed on Septemeber 2017]
14. Rahim Mutlu, Gursel Alici and Weihua Li. “Electroactive Polymers as Soft Robotic Actuators: Electromechanical Modeling and Identification”, 2013. [accessed on July 2017]
15. Takahiro Matsuno, Dingxin Ge, Shugen Ma and Atsushi Kakogawa. “Study on Air Inflow of a Passive Suction Cup”, 2013. [accessed on December 2017]
16. Ravi K. Jain, Surajit Saha and Somajoyti Majumder. “Development of Piezoelectric Actuator Based Compliant Micro Gripper for Robotic Peg-in-hole Assembly”,2013.
17. Soichiro KAWASAKI and Koki KIKUCHI. “Development of a Small Legged Wall Climbing Robot with Passive Suction Cups”, 2014. [accessed on Nov 2017]
18. Gursel Alici and Nam N. Huynh. “Performance Quantification of Conducting Polymer Actuators for Real Applications: A Micro Gripping System’’,2007.
19. Francesca Tramacere, Lucia Beccai, Member, Ieee, Fabio Mattioli, Edoardo Sinibaldi, Barbara Mazzolai, Member, Ieee. “Artificial Adhesion Mechanisms Inspired by Octopus Suckers”, Nov 2012. [accessed on Nov 2017]
20. Yu Yoshida and Shugen Ma. “A Wall-Climbing Robot without any Active Suction Mechanisms”, 2011. [accessed on Nov 2017]
21. Tao Zhu Rong Liu, Xu D. Wang, Kun Wang. “Principle and Application of Vibrating Suction Method”, 2006. [accessed on August 2017]
22. Dingxin Gea, Takahiro Matsunoa, Yi Suna, Chao Rena, Yongchen Tanga, Shugen Ma. “Quantitative study on the attachment and detachment of a passive suction cup”, Nov 2013. [accessed on August 2017]
23. “Piezoelectric materials for sale”, <https://www.piceramic.com/en/>, [accessed on Nov 2017].
24. “Dimensions of Piezoelectric materials”, <https://www.piceramic.com/en/products/piezoceramic-components/rings/>
25. Rouquette, J.; Haines, J.; Bornand, V; Pintard, M.; Papet, Ph; Bousquet, C.; Konczewicz, L.; Gorelli, F. A.; Hull, S. "Pressure tuning of the morphotropic phase boundary in piezoelectric lead zirconate titanate", 2004.

26. Moazzami, Reza; Hu, Chenming; Shepherd, William H. "Electrical Characteristics of Ferroelectric PZT Thin Films for DRAM Applications", (September 1992).

27. “Piezoelectric materials”, https://www.piceramic.com/en/products/piezoceramic-materials> [accessed on August 2017]

28. “Suction cups availability” <https://www.piab.com/en-US/products/suction-cups/>

29. “Gas laws” <https://www.britannica.com/science/Boyles-law>,[accessed on August 2017]

30. “Calculating theoretical force” <https://www.schmalz.com/en/vacuum-knowledge/the-vacuum-system-and-its-components/system-design-calculation-example/theoretical-holding-force-of-a-suction-cup/>, [accessed on August 2017]

31. “Modular vacuum cup technology” [accessed on August 2017] <https://www.coval-inc.com/document/12p_mvg_2017_us_web_05.pdf>

32. Manbachi, A. and Cobbold R.S.C. "Development and Application of Piezoelectric Materials for Ultrasound Generation and Detection" Ultrasound. 2011. [accessed on Nov 2017]