

**DESIGN AND ADDITIVE MANUFACTURE OF A HIGH-SPEED
PIEZOELECTRICALLY ACTUATED COMPLIANT MESOSCALE
PARALLEL ROBOT**

ARIEL TABAK

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

MASTER OF SCIENCE

GRADUATE PROGRAM IN EARTH AND SPACE SCIENCE
YORK UNIVERSITY
TORONTO, ONTARIO
AUGUST 2023

©Ariel Tabak, 2023

Abstract

This work presents the design of an additively manufactured mesoscale parallel robot that is actuated by piezoelectric bimorphs through a compliant transmission mechanism. The piezoelectric bimorph actuators are modeled via finite element and experimentally tested to verify their performance. A transmission mechanism is designed using finite element analysis to determine the critical parameters for the conversion of the piezoelectric actuators small linear displacements to large rotational motion. Multiple transmissions are fabricated using additive manufacturing and are tested experimentally. The transmission mechanism is then used to create a six-bar parallel robot that is driven by the piezoelectric bimorphs, which is simulated and tested experimentally. The planar parallel robot is 37.88 by 20.54 millimeters in size and has a workspace of 14.36 by 8.66 millimeters for a total area of 65.6 millimeters squared. The robot is capable of following trajectories within the workspace at a frequency of up to 10 Hz.

“If I have seen further, it is by standing on the shoulders of giants.” - Isaac Newton

Acknowledgements

This thesis would not have been possible without the patience, support, and guidance of my supervisor, Dr. Ryan Orszulik. His encouragement and push to attend conferences and apply for scholarships have been invaluable during my degree, and I could not have asked for a better supervisor.

I want to thank my labmates Arvin, Rita, Rafael, and Annamalai for their feedback and for listening to my thoughts and frustrations throughout my degree. I would like to thank Annamalai in particular for his prompt help when processing results for my work, which was invaluable as I neared the finish line.

I am forever grateful for my parents, Boris and Inna, my brother, Daniel, and all my cousins, aunts, uncles, grandparents, and others who have encouraged and supported me over the years.

Table of Contents

Abstract	ii
Dedication	iii
Acknowledgements	iv
Table of Contents	v
List of Tables	xi
List of Figures	xiii
1 Introduction	1
1.1 Piezoelectricity	3
1.1.1 The piezoelectric effect	3
1.1.2 Piezoelectric materials	9
1.1.3 Piezoelectric sensors	11

1.1.4	Piezoelectric actuators	12
1.1.4.1	Stack actuators	12
1.1.4.2	Cantilever actuators	13
1.2	Compliant mechanisms	15
1.3	Additive manufacturing	17
1.3.1	Comparison to traditional manufacturing	17
1.3.2	Pre-processing	18
1.3.3	Additive manufacturing processes	19
1.3.3.1	Photo-polymerization	19
1.3.3.2	Material extrusion	21
1.3.3.3	Powder bed fusion	22
1.4	Robotics	25
1.4.1	Basic terminology	25
1.4.2	Serial robots	26
1.4.3	Parallel robots	27
1.4.3.1	Delta robots	29
1.4.4	SCARA robots	30
1.4.5	Mesoscale parallel robots	31
1.5	Research Objectives and Contributions	32

2	Piezoelectric actuator characterization	34
2.1	Implementing multi-layer piezoelectric materials	37
2.1.1	Finite element analysis of piezoelectric bimorphs	40
2.1.2	Static deflection	41
2.1.3	Blocked force	43
2.1.4	Resonant frequency	44
2.1.4.1	Rayleigh damping	46
2.1.5	Dynamic analysis	48
2.1.6	Bimorph simulation results	50
2.2	Experimental characterization	51
2.2.1	Experimental setup	51
2.2.2	Experimental results	53
2.3	Conclusion	57
3	Transmission mechanism design	58
3.1	Initial finite element design	58
3.2	Simplified finite element model	68
3.3	Transmission finite element analysis in ABAQUS	73
3.4	Finite element model of experimental test model	76
3.5	Experimental results	79

3.5.1	Experimental setup	79
3.5.1.1	Rotation measurement error for the transmission mechanism	81
3.5.2	Results and verification of finite element models	82
3.5.3	Revised transmission mechanism and experimental setup . .	85
3.5.3.1	Design changes	85
3.5.3.2	Results	89
3.6	Conclusion	94
4	Parallel robot design	95
4.1	Kinematic model predictions	96
4.1.1	Model setup	96
4.1.2	Parametric analysis of the kinematic model	98
4.2	Finite element model of the parallel robot	100
4.2.1	Static deflection	101
4.2.1.1	Eight basic movements	104
4.2.1.2	Workspace determination	107
4.3	Experimental testing	109
4.3.1	Fabrication and post-processing	109
4.3.2	Micrometer-actuated testing	110

4.3.2.1	Experimental setup	110
4.3.2.2	Results	112
4.4	Final parallel robot	117
4.4.1	Design changes	117
4.4.2	Finite element model	120
4.4.2.1	Static deflection	120
4.4.2.2	Resonance frequencies	122
4.4.2.3	Dynamic analysis	123
4.4.2.4	Trajectory 1: Workspace trace	124
4.4.2.5	Trajectory 2: Circle	125
4.4.2.6	Trajectory 3: The letter Y	127
4.4.3	Experimental setup	128
4.4.4	Experimental results	130
4.4.5	Workspace grid	133
4.4.6	Trajectories	137
4.4.6.1	Trajectory 1: Workspace trace	138
4.4.6.2	Trajectory 2: Circle	138
4.4.6.3	Trajectory 3: The letter Y	140
4.4.6.4	Chirp signals	141
4.4.6.5	Fatigue testing	143

4.4.7	Updating simulations with experimental bimorph performance	144
5	Conclusions and Future Work	147
5.1	Future Work	149
A	Performance of experimental trajectories	152
A.1	Trajectory 1: Workspace Trace	153
A.2	Trajectory 2: Circle	155
A.3	Trajectory 3: The letter Y	158
B	Complete List of Publications	161
B.1	Conference Papers	161
B.2	Abstracts	161

List of Tables

1.2	Relevant material properties of PZT-5A and PZT-5H (Source: [44])	11
2.2	Specifications of the PI and Thorlabs bimorphs (Source: [119], [120])	35
2.4	Material properties of PIC 251 and THP 51 (Source: [121], [122])	36
2.5	Differential voltage control modes for a piezoelectric bender	41
2.6	Static deflection results	42
2.7	Blocked force results	44
2.8	Natural frequency results	45
2.9	Rayleigh damping coefficients results	48
2.10	Chirp signal frequency response results	50
2.11	Experimental testing for static displacement	54
2.12	Experimental resonance frequency results	57
3.2	Revised transmission mechanism results	93
4.2	Basic movement cases and results for the parallel robot	107

4.4	Basic movements for the parallel robot, actuated by micrometer stage	116
4.6	Basic movement cases and results for the parallel robot	122
4.8	Basic movements for the parallel robot (bimorph actuated)	133
4.10	Basic movement cases and results for the parallel robot, reduced voltage	146

List of Figures

1.1	Piezoelectric effect on a molecular scale (Image source: [25])	3
1.2	Polarization process of piezoelectric ceramics (Image source: [27]) .	4
1.3	Piezoelectric transducer diagram (Image source: [25])	7
1.4	Piezoelectric stack actuator diagram (Image source: [52])	13
1.5	Piezoelectric unimorph diagram (Image source: [59])	14
1.6	Piezoelectric bimorph diagram (Image source: [52])	14
1.7	Piezoelectric multimorph diagram (Image source: [52])	14
1.8	Compliant pliers (Image source: [65])	16
1.9	Converting a 3D model to the STL file format	19
1.10	SLA printing process (Image source: [76])	21
1.11	FFF printing process (Image source: [77])	22
1.12	Powder bed fusion printing process (Image source: [79])	23
1.13	Serial and parallel linkages (Image source: [85])	26
1.14	Serial welding robot (Image source: [91])	27

1.15	6-axis hexapod (parallel) robot (Image source: [99])	28
1.16	Commercial pick-and-place delta robots (Image source: [103]) . . .	29
1.17	Different SCARA configurations	30
1.18	The milliDelta, a milli-meter scale delta robot (Image source: [116])	32
2.1	Selected bimorph actuators	34
2.2	Free length and piezoelectric element height for a multilayer bimorph (Image source: [52])	38
2.3	Ten layer diagram for a piezoelectric bimorph	39
2.4	Two layer diagram for a piezoelectric bimorph	39
2.5	CAD model of the PL127.10 bimorph	41
2.6	Deflection results for the PL127.10 bimorph, displacement taken at the node highlighted in red	43
2.7	Blocked force results for the PB4NB2W bimorph in ABAQUS . . .	44
2.8	Boundary conditions for the PL127.10 bimorph in ABAQUS	45
2.9	Alternate boundary conditions for the PB4NB2W bimorph in ABAQUS	45
2.10	Frequency response of the chirp signal on the PL127.10 bender . . .	49
2.11	Frequency response of the chirp signal on the PB4NB2W bender . .	49
2.12	Experimental setup for bimorph characterization	52
2.13	Wiring diagram for bimorph testing	52
2.14	Peak displacements of the piezoelectric bimorphs	54

2.15	Chirp signal results for piezoelectric bimorph A	55
2.16	Chirp signal results for piezoelectric bimorph B	55
2.17	Chirp signal results for piezoelectric bimorph C	56
2.18	Chirp signal results for piezoelectric bimorph D	56
3.1	Initial transmission designs	59
3.2	Relevant parameters for the initial transmission design	60
3.3	Initial single flexure results	61
3.4	Initial double flexure results	61
3.5	Parametric analysis of single driven flexure design	62
3.6	Parametric analysis of double driven flexure design	62
3.7	Isometric view of the revised design	64
3.8	Diagram showing revised design to allow for angled flexures	65
3.9	Flexure thickness T_d, T_g vs. flexure offset L_o	66
3.10	Flexure length L_d, L_g vs. flexure width	67
3.11	Driven flexure angle θ_d vs. grounded flexure angle θ_g	67
3.12	Diagram of the simple finite element model	69
3.13	Predicted rotation for varying critical parameters using MATLAB, isolines indicate the rotation results and are displayed in degrees . .	72

3.14	Simplified model used for finite element analysis with the mechanically grounded faces highlighted in red and the displaced face highlighted in blue.	73
3.15	Predicted rotation for varying critical parameters using ABAQUS, isolines indicate the rotation results and are displayed in degrees . .	75
3.16	CAD model of the transmission for numerical analysis and testing .	76
3.17	Comparison of the different finite element models for 196, 308, and 392 micron flexure thicknesses	78
3.18	Transmission mechanism with 308 micron flexure thickness fabricated from Agilus30 black	80
3.19	Experimental setup for transmission mechanism testing	80
3.20	Determining the rotation of the transmission arm, neutral position in purple, rotated position in green	81
3.21	Comparison of numerical and experimental results for 196, 308, and 392 micron flexure thicknesses	83
3.22	Overlay of the numerical and experimental results at the negative, neutral, and positive limits	84
3.23	The 3D printed transmission in the actuated position next to a Canadian dime	84
3.24	Revised transmission design	86

3.25	Experimental setup for the revised transmission mechanism	87
3.26	Points for image processing	88
3.27	Trapezoidal waveform input to the motorized stage	89
3.28	Experimental results in time for 308 and 392 micron flexure thick- nesses with different bases	91
3.29	Comparison of simulated and experimental results for 308 and 392 micron flexure thicknesses with different bases	92
4.1	Simplified six-bar parallel robot design	96
4.2	Parallel robot model generated using Simscape Multibody	97
4.3	Retraction, neutral, and extension states of the kinematic model . .	98
4.4	Example of a kinematic singularity that occurs during retraction . .	99
4.5	R_{1t} and R_{1b} length vs R_{2t} and R_{2b} length	100
4.6	Initial parallel robot design with the piezoelectric bimorphs high- lighted in beige, flexures highlighted in black, and the rigid material highlighted in white.	101
4.7	Forward and backward movement of the initial parallel robot with the neutral position overlaid in white	102
4.8	Deflection under gravity of the initial parallel robot	102

4.9	Second parallel robot design with the piezoelectric bimorphs highlighted in beige, flexures highlighted in black, and the rigid material highlighted in white.	103
4.10	Basic movements of the parallel robot with the neutral position overlaid in white	105
4.11	End effector displacement of the 8 basic cases, arrows denote end effector orientation	106
4.12	Workspace grid	108
4.13	CAD model of the parallel robot	109
4.14	Parallel robot before post-processing	110
4.15	Micrometer setup for the parallel robot	111
4.16	Processing results of parallel robot	112
4.17	Basic movements of the parallel robot	113
4.18	Micrometer test of the parallel robot	115
4.19	Deflection under gravity for the final parallel robot design.	118
4.20	Final parallel robot with the piezoelectric bimorphs highlighted in orange, flexures highlighted in black, and the rigid material highlighted in white.	119
4.21	CAD model of the final parallel robot	119

4.22	End effector displacement for 8 basic movements, arrows denote end effector orientation	121
4.23	Workspace grid	121
4.24	Resonant frequencies of the final parallel robot	123
4.25	Workspace Grid Trace	124
4.26	High-frequency results for the workspace trace	125
4.27	Workspace Grid Circle	126
4.28	High-frequency results for a circle	126
4.29	Workspace Grid Letter Y	127
4.30	High-frequency results for the letter Y	128
4.31	Experimental setup for the parallel robot and piezoelectric bimorphs	129
4.32	Wiring Diagram for actuating the parallel robot	130
4.33	Basic movements of the parallel robot	131
4.34	Basic movements of the parallel robot (bimorph actuated)	132
4.35	Varying workspace trace directions and initial positions	134
4.36	Different inner traces used for workspace determination	135
4.37	Workspace trace results for different directions and initial positions	136
4.38	Workspace grid	137
4.39	Overlay of trajectory results	137
4.40	Trajectory 1 Experimental Results	138

4.41	Trajectory 2 Experimental Results	139
4.42	Trajectory 2 Experimental Results, revised transformation data . .	140
4.43	Trajectory 3 Experimental Results	141
4.44	Chirp signal results for horizontal motion	142
4.45	Chirp signal results for vertical motion	142
4.46	Comparison of parallel robot performance before and after fatigue testing	144
4.47	Workspace Grid	145
A.1	Expected and actual performance for Trajectory 1	153
A.2	Positon error for Trajectory 1: 0.5 Hz	153
A.3	Positon error for Trajectory 1: 2 Hz	154
A.4	Positon error for Trajectory 1: 5 Hz	154
A.5	Positon error for Trajectory 1: 10 Hz	155
A.6	Expected and actual performance for Trajectory 2	155
A.7	Positonal error for Trajectory 2: 0.5 Hz	156
A.8	Positon error for Trajectory 2: 2 Hz	156
A.9	Positon error for Trajectory 2: 5 Hz	157
A.10	Positon error for Trajectory 2: 10 Hz	157
A.11	Expected and actual performance for Trajectory 3	158
A.12	Positon error for Trajectory 3: 0.5 Hz	158

A.13 Positon error for Trajectory 3: 2 Hz	159
A.14 Positon error for Trajectory 3: 5 Hz	159
A.15 Positon error for Trajectory 3: 10 Hz	160

1 Introduction

The fabrication of mesoscale robotics is a growing area of research that occupies the space between traditional manufacturing methods and microelectromechanical systems (MEMS) fabrication [1], [2], with potential applications in micro-assembly, micro-robotics, or medical applications [3]. Manufacturing at the mesoscale involves the fabrication of millimeter-sized parts and requires dimensional accuracy within microns [4] [5]. Due to the complexity of construction at this scale, the time required to design, fabricate, and assemble mesoscale robots is a hurdle for both prototyping and mass production [6].

For the actuation of mesoscale robots, piezoelectric actuators are frequently used, in particular, piezoelectric bimorphs, which have precise, high-speed linear displacement and relatively large blocked force [7]. These actuators use the converse piezoelectric effect, converting electrical energy to mechanical strain. However, the approximately linear displacement of these actuators is in the sub-millimeter range and must be magnified with an amplification mechanism to be useful. Various

methods have been investigated to achieve this such as a lamina microrobot with piezoelectric actuators, using a four-bar linkage to amplify the displacement [8], or a lamina millimeter-scale delta robot that uses linkages, crank sliders, and flexible revolute joints to convert and amplify the displacement of piezoelectric actuators [9]. These mechanisms rely on planar manufacturing methods to maintain a small overall size and effectively amplify the displacement of the piezoelectric actuators.

As an alternative to planar manufacturing methods, additive manufacturing has been investigated for fabricating compliant robots [10]. Additive manufacturing fabricates parts by depositing layers of material layer by layer and excels at low-volume manufacturing by allowing multiple designs to be fabricated at once [11] [12] while requiring little to no post-processing before assembly and integration. Printing smart structures directly has been investigated with methods such as pattern magnetization [13] [14] and thermal shape-memory polymers [15]. With additive manufacturing, compliant mechanisms can be fabricated with flexible filaments and photopolymers with low-cost printers or printing services [16], or integrated with additively manufactured parts [17]. Compliant mechanisms, which rely on flexible members to transfer force and motion, show potential for conversion of small linear displacement to large rotational motion [18]. These mechanisms can be additively manufactured, enabling rapid prototyping of compliant monolithic structures [19].

1.1 Piezoelectricity

1.1.1 The piezoelectric effect

The piezoelectric effect is behind the behavior of specific materials that generate an electrical charge in response to mechanical stress. It was discovered in 1880 by Pierre and Jacques Curie, who identified various crystals exhibiting piezoelectric behavior [20]. Gabriel Lippmann predicted the converse piezoelectric effect in 1881, where an applied electrical field would result in mechanical strain [21]. Since then, piezoelectricity has found widespread use in ignition systems [22], sensors [23], and actuators [24].

The piezoelectric effect relies on the dipole moments of piezoelectric crystals, which are neutral while at rest. When these crystals are deformed, a dipole moment is created due to the new positions of the charged atoms (see Fig. 1.1).

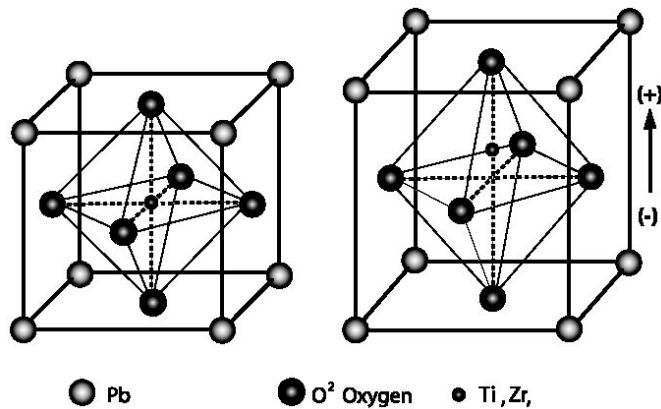


Fig. 1.1 Piezoelectric effect on a molecular scale (Image source: [25])

Piezoelectric ceramics are composed of multiple crystals, each crystal initially having a dipole moment in a random direction, resulting in a net change of zero [26] (see Fig. 1.2a). To align the electric field in these crystals, an electric field is applied, as shown in Fig. 1.2b, while the material is just below its Curie temperature (the temperature where a specific material loses permanent magnetic properties). As a result, the crystal domains in the piezoelectric material become aligned with the applied electric field (see Fig. 1.2c). After the electric field and heat is removed, the crystal domains remain largely aligned to the applied electric field [25].

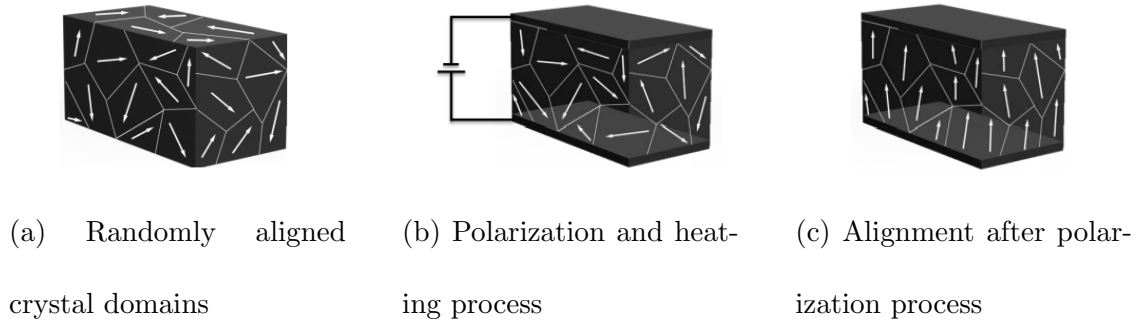


Fig. 1.2 Polarization process of piezoelectric ceramics (Image source: [27])

Piezoelectric transducers have been studied extensively and constitutive equations from the Institute of Electrical and Electronics Engineers (IEEE) are widely used. The IEEE standard assumes a linear theory of piezoelectricity [28], which is valid for small electric fields, stresses, and strains (which ignores effects such as hysteresis and creep) [29]. The piezoelectric constitutive equations can be written

as:

$$T_{ij} = c_{ijkl}^E S_{kl} - e_{kij} E_k \quad (1.1)$$

$$D_i = e_{ikl} S_{kl} + \epsilon_{ij}^S E_k \quad (1.2)$$

where T_{ij} is the stress tensor, D_i is the electric displacement tensor, c_{ijkl}^E is the elastic stiffness constant, e_{kij} is the piezoelectric constant (coulomb per square meter), ϵ_{ij} is the dielectric constant, S_{kl} is the strain, and E_k is the electric field. The superscript for c_{ijkl} indicates whether the coefficient was obtained with the piezoelectric in short circuit (superscript E) or in open circuit (superscript D). The superscript for ϵ_{ik} indicates whether the coefficient was obtained at constant strain (superscript S) or at constant stress (superscript T)

Assuming constant values for the elastic compliance constants, piezoelectric strain constants, and dielectric constants, the constitutive equations can be written as:

$$S_{ij} = s_{ijkl}^E T_{kl} + d_{kij} E_k \quad (1.3)$$

$$D_i = d_{ikl} T_{kl} + \epsilon_{ik}^T E_k \quad (1.4)$$

where s_{ijkl} is the elastic compliance constant, and d_{kij} and d_{ikl} are piezoelectric strain constants.

It is possible to convert the tensor notation of equations (1.3) and (1.4) to matrix notation by replacing ij and kl with p and q , respectively (where i, j, k, l

have indices 1, 2, 3 and p, q have indices 1, 2, 3, 4, 5, 6). This gives:

$$S_p = s_{pq}^E T_q + d_{kp} E_k \quad (1.5)$$

$$D_i = d_{iq} T_q + \epsilon_{ik}^T E_k \quad (1.6)$$

where

$$S_{ij} = S_p \text{ when } i = j, p = 1, 2, 3$$

$$2S_{ij} = S_p \text{ when } i \neq j, p = 4, 5, 6$$

It is possible to express equations (1.5) and (1.6) in matrix form as follows:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & s_{14}^E & s_{15}^E & s_{16}^E \\ s_{21}^E & s_{22}^E & s_{23}^E & s_{24}^E & s_{25}^E & s_{26}^E \\ s_{31}^E & s_{32}^E & s_{33}^E & s_{34}^E & s_{35}^E & s_{36}^E \\ s_{41}^E & s_{42}^E & s_{43}^E & s_{44}^E & s_{45}^E & s_{46}^E \\ s_{51}^E & s_{52}^E & s_{53}^E & s_{45}^E & s_{55}^E & s_{56}^E \\ s_{61}^E & s_{62}^E & s_{63}^E & s_{46}^E & s_{65}^E & s_{66}^E \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} d_{11} & d_{21} & d_{31} \\ d_{12} & d_{22} & d_{32} \\ d_{13} & d_{23} & d_{33} \\ d_{14} & d_{24} & d_{34} \\ d_{15} & d_{25} & d_{35} \\ d_{16} & d_{26} & d_{36} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (1.7)$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \epsilon_{11}^T & \epsilon_{12}^T & \epsilon_{13}^T \\ \epsilon_{21}^T & \epsilon_{22}^T & \epsilon_{23}^T \\ \epsilon_{31}^T & \epsilon_{32}^T & \epsilon_{33}^T \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (1.8)$$

where d_{ij} is the piezoelectric strain constant (or piezoelectric charge coefficient).

It is obtained by dividing the strain that occurs in the j -axis by the electric field applied in the i -axis for a piezoelectric material at rest. The units are in meters per volt, equivalent to coulombs per newton. An alternative material property often

used in place of d_{ij} is g_{ij} , known as the piezoelectric voltage coefficient. This is obtained by dividing the electric field generated along the i -axis by the applied stress in the j -axis. The units for g_{ij} are volt meters per newton, equivalent to meters squared per coulomb. The elastic compliance coefficients s_{ij}^E (or elastic compliance constants) are the strain in the i -axis divided by the stress in the j -axis. The dielectric coefficient (or dielectric constant) ϵ_{ij}^T is the charge per unit area along the i -axis caused by an electric field in the j -axis [30].

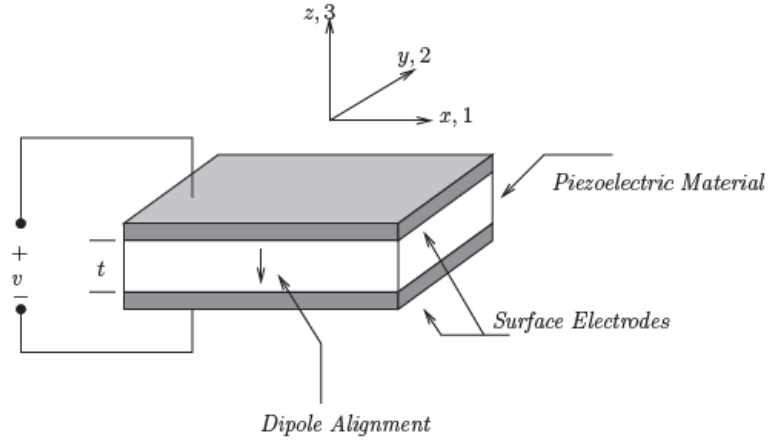


Fig. 1.3 Piezoelectric transducer diagram (Image source: [25])

Subscripts 1, 2, and 3 correspond to x , y , and z directions of a Cartesian coordinate system. Subscripts 4, 5, and 6 correspond to directions that are dependant on the crystal system of the piezoelectric material [31]. Many piezoelectric ceramics (such as lead zirconate titanate and barium titanate) fall under hexagonal crystal systems with a crystallographic class of $6mm$ [28]. When these transversely

isotropic materials are polarized along axis 3 (see Fig. 1.3), the elastic compliance coefficients may be simplified as follows [32]

$$s_{11}^E = s_{22}^E$$

$$s_{13}^E = s_{31}^E = s_{23}^E = s_{32}^E$$

$$s_{12}^E = s_{21}^E$$

$$s_{44}^E = s_{55}^E$$

$$s_{66}^E = 2(s_{11}^E - s_{12}^E)$$

$$s_{pq}^E = 0 \text{ when } p \neq q \text{ for } p = q = 4, 5, 6$$

The piezoelectric strain coefficients are zero except for $d_{15}, d_{24}, d_{31}, d_{32}, d_{33}$, and the constants have the relation that

$$d_{15} = d_{24}$$

$$d_{31} = d_{32}$$

Finally, the dielectric coefficients are zero except for $\epsilon_{11}^T = \epsilon_{22}^T, \epsilon_{33}^T$. Applying these changes to equations (1.7) and (1.8) results in the constitutive equations for a

transversely isotropic piezoelectric material as:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{12}^E & s_{11}^E & s_{13}^E & 0 & 0 & 0 \\ s_{13}^E & s_{13}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{44}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s_{11}^E - s_{12}^E) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (1.9)$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \epsilon_{11}^T & 0 & 0 \\ 0 & \epsilon_{11}^T & 0 \\ 0 & 0 & \epsilon_{33}^T \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (1.10)$$

A relative dielectric constant, K , used instead of ϵ^T by many piezoelectric ceramic suppliers, is defined by the following equation

$$K_{ij} = \frac{\epsilon_{ij}^T}{\epsilon_0}$$

where ϵ_0 is the permittivity of free space (dielectric permittivity in a vacuum), measured in farads per meter.

1.1.2 Piezoelectric materials

In the years after the discovery of the piezoelectric effect by the Curie brothers, Rochelle salts and quartz became the most popular piezoelectric material due to their strong piezoelectric response [33] [34]. Both of these crystals were heavily researched in the following years, with the goal of using them as underwater transducers to detect submarines [35]. In the 1940s, the first piezoelectric ceramic -

barium titanate (BTO) - was discovered, and was easier to manufacture compared to piezoelectric crystals [36] [37]. In 1952, lead zirconate titanate (PZT) was discovered, and due to its higher Curie point and stronger piezoelectric effect, it rapidly became the most commonly used piezoelectric ceramic [38] [39] [40]. Numerous lead-free alternatives have been developed, but at this time are not as effective as PZT, or are cost prohibitive to manufacture [41]. Heavily used by the U.S. Navy during WWII, it became common to refer to PZT variants by the military standard, which classifies PZT by a “Navy Type” [42]. The most popular PZT variants, PZT-5A and PZT-5H, are known as Navy Type II and Navy Type VI, respectively [43]. The piezoelectric material properties of PZT-5A and PZT-5H are shown in Table 1.2.

Property	Symbol	Units	PZT-5A	PZT-5H
Density	ρ	kg/m ³	7500	7500
Relative dielectric constant	K_{33}^T		1700	3400
	K_{11}^T		1730	3130
Piezoelectric strain constant	d_{33}	m/V	374×10^{-12}	585×10^{-12}
	d_{31}	m/V	-171×10^{-12}	-285×10^{-12}
	d_{15}	m/V	585×10^{-12}	730×10^{-12}
Piezoelectric voltage constant	g_{33}	m ² /C	24.8×10^{-3}	19.7×10^{-3}
	g_{31}	m ² /C	-11.4×10^{-3}	-8.5×10^{-3}
	g_{15}	m ² /C	38.2×10^{-3}	29.0×10^{-3}
Elastic compliance constant	s_{33}^E	m ² /N	18.8×10^{-12}	20.0×10^{-12}
	s_{11}^E	m ² /N	15.0×10^{-12}	15.6×10^{-12}

Table 1.2 Relevant material properties of PZT-5A and PZT-5H (Source: [44])

1.1.3 Piezoelectric sensors

Piezoelectric sensors use the direct piezoelectric effect to convert mechanical stress into electric charge. As the mechanical stress changes, so does the electric charge, allowing for the piezoelectric to sense changes in stress. Uses of piezoelectric sen-

sors include microphones, sonar detection, and accelerometers (among many other applications) [45].

1.1.4 Piezoelectric actuators

Piezoelectric actuators use the converse piezoelectric effect to convert an input voltage to mechanical displacement. They are capable of high-speed yet precise displacement, and have found use in micro-positioning applications such as mirrors [46] and lenses [47]. The primary trade-off with piezoelectric actuators is displacement versus force, which influences the decision on which actuator to use for a given purpose [7]. Piezoelectric actuators have a long operating lifetime but must be handled carefully as piezoelectric ceramics are brittle [48].

1.1.4.1 Stack actuators

Piezoelectric actuators are available commercially in various forms. Stack actuators are comprised of thin piezoelectric ceramic layers that are stacked in alternating orientations (see Fig.1.4). They are capable of producing a large blocked force (thousands of newtons) and a small but precise linear displacement (on the order of microns). Stack actuators have been a subject of research for applications in energy harvesting [49], vibration control [50], and nano-positioning [51].

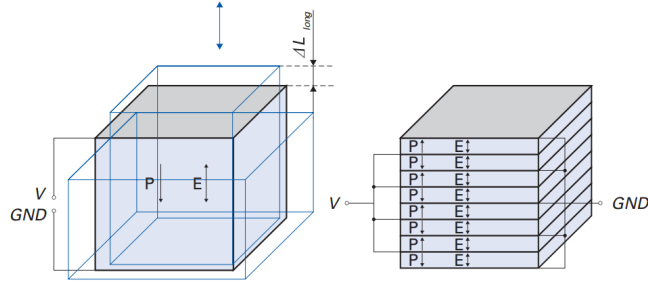


Fig. 1.4 Piezoelectric stack actuator diagram (Image source: [52])

1.1.4.2 Cantilever actuators

By elongating the piezoelectric layer into a cantilever beam, the deflection increases significantly (on the order of hundreds of microns), but at the expense of blocked force (around 1 Newton). Cantilever actuators are categorized by the number of piezoelectric layers they possess: unimorph, bimorph, and multimorph. Piezoelectric unimorph actuators consist of one layer of piezoelectric material, joined to a passive layer (see Fig. 1.5) [53]. Bimorphs consist of two piezoelectric ceramic layers stacked with opposing orientations (see Fig. 1.6). For a given set of actuator parameters and voltage, at best a unimorph actuator will have half the displacement of a bimorph actuator [54] [55]. As the number of layers for a given actuator increases, so will the blocked force and tip displacement. Multimorphs (or multilayer actuators) take advantage of this; each half of the actuator consists of thin piezoelectric layers in alternating orientations (see Fig. 1.7). While the increased displacement

and blocked force are clear advantages for bimorphs and multimorphs, decreasing the thickness of each layer results in a significant cost increase [56]. The benefits of increased displacement and blocked force therefore must be weighed against increased costs. Applications of cantilever actuators include small-scale stepper motors [57], micro-robotics [9], and valves [58].

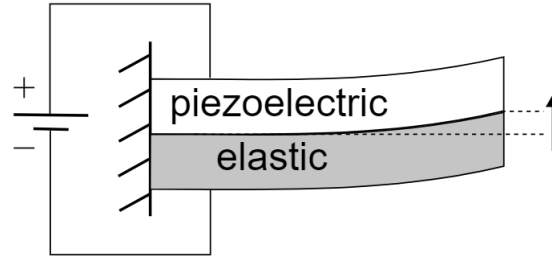


Fig. 1.5 Piezoelectric unimorph diagram (Image source: [59])

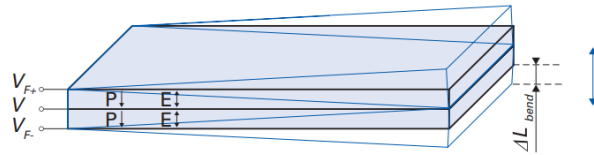


Fig. 1.6 Piezoelectric bimorph diagram (Image source: [52])

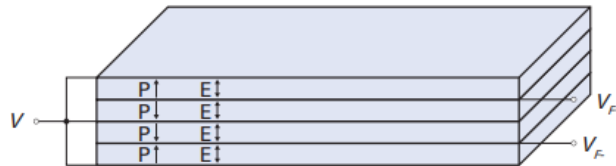


Fig. 1.7 Piezoelectric multimorph diagram (Image source: [52])

While cantilever actuators have relatively high displacement for piezoelectric actuators as a whole, the displacement is small relative to the total size of the actuator. For this displacement to be usable in mesoscale robotics, it must be amplified with the use of a transmission mechanism. By integrating cantilever piezoelectric actuators with compliant mechanisms, this small linear displacement can be converted into large rotary motion.

1.2 Compliant mechanisms

A compliant mechanism is any mechanism that uses flexible members to transfer motion or force [60] [61]. An ancient example of a compliant mechanism is the bow and arrow, where energy is stored in the limbs of the bow as they bend, and is later released. To present a usable alternative to rigid mechanisms, research has been done to create compliant joints that can achieve the same range of motion as rigid connections such as revolute joints, planar joints, and other kinematic pairs [62]. Compliant mechanisms have a wide range of applications, including common tools such as binder clips [63] or pliers (see Fig. 1.8). Compliant mechanisms are often monolithic, as joints that would require multiple segments are fabricated in one part, resulting in fewer total parts compared to an equivalent rigid-body mechanism. They can eliminate the need for sliding contact and do not require lubrication as there is no friction. For flexure joints, compliant mechanisms are effective as they

have no backlash, no deadzone, and motion is transferred directly. The amplification of motion using compliant mechanisms has been investigated by Bachta et al. for stabilization during cardiac surgery [64], where a parallel structure driven by piezoelectric stack actuators uses a kinematic singularity to amplify linear motion to rotate a stabilizing shaft. Downsides of compliant mechanisms include a complex design process, inability to do continuous rotational motion, stress relaxation, and fatigue from cyclical motion.



Fig. 1.8 Compliant pliers (Image source: [65])

Due to the difficulty of manufacturing complex structures for compliant mechanisms, fabrication methods such as lamina emergent mechanisms have been investigated, where all manufacturing is done in plane [66]. With the widespread adoption of additive manufacturing, it is now possible to fabricate monolithic compliant mechanisms, allowing for significant time savings in the design and fabrication phases.

1.3 Additive manufacturing

Additive manufacturing (or 3D printing) is a process in which a model is built layer by layer, allowing for rapid prototyping. In 1984, Chuck Hull patented the first stereolithography 3D printer, beginning an era of rapid prototyping technology [67].

1.3.1 Comparison to traditional manufacturing

Compared to traditional manufacturing methods (such as forging, machining, or injection molding), additive manufacturing has its own advantages and challenges. Additive manufacturing is effective at low-volume manufacturing, as models can be fabricated without the need for molds or equipment swapping [11] [12]. Perhaps the largest advantage is that complex structures that would be cost or time prohibitive to manufacture with traditional methods can be readily fabricated [68]. However, additive manufacturing is not without its limitations:

- Maximum part size is limited by the size of the printer (the majority of consumer 3D printers have a build volume smaller than 300 x 300mm x 300mm).
- Minimum feature size is limited by printer accuracy while also being worse than traditional manufacturing methods. [69]
- Tolerances are significantly worse than traditional manufacturing methods.

- Parts may require post-processing such as support removal, surface finishing, or curing before they are complete [70].
- Material availability is limited primarily to plastic as metal printing technology is not as mature and is currently cost prohibitive [71].
- Parts designed for additive manufacturing processes have different design considerations that need to be accounted for, including (but not limited to) support for overhangs and bridges, drain holes for unused material, and printing orientation [72].
- Traditional manufacturing methods are optimized for high volume production, significantly reducing the cost and time required for each part compared to additive manufacturing [68].

Despite these limitations, additive manufacturing offers the opportunity to create complex monolithic mechanisms that are immediately ready for use after printing without assembly, with significant time savings compared to traditional manufacturing.

1.3.2 Pre-processing

For all additive manufacturing processes, a 3D model must first be prepared. Using CAD software (or any software that can generate 3D models), the 3D model is

exported as an STL file. Created in 1987 by 3D Systems (founded by Chuck Hull), the STL file format is the most common format used for 3D printing today. An STL file is a tessellated representation of the surface geometry of a 3D model using triangles [73].



Fig. 1.9 Converting a 3D model to the STL file format

1.3.3 Additive manufacturing processes

3D printers can be classified by the process they use, with the majority falling into one of the following processes: photo-polymerization, material extrusion, and powder bed fusion.

1.3.3.1 Photo-polymerization

The first additive manufacturing method, photo-polymerization, began with stereolithography (SLA), where an ultraviolet (UV) laser cures a UV-reactive resin. A platform is located in a vat of liquid photopolymer resin, and a scanning mirror

guides the laser as it cures the current layer. Once the layer is completed, the platform moves one layer height lower, and the process is repeated until the print has been completed. Upside-down (or bottom-up) SLA printers have the laser positioned underneath the platform. Parts printing top-down can only be as tall as the liquid resin vat, as opposed to bottom-up SLA printing where the liquid resin only needs to be deep enough for the current print layer. In most cases, the part is then post-cured after removal by exposing it further to UV light, improving part strength. Aside from part prototyping (a common application of all 3d printers), SLA printers are heavily used in the medical industry to make orthodontic devices [74]. Other resin printer technologies include digital light processing (DLP) and liquid crystal display (LCD) printers. DLP printers use a projector to cure one layer of resin at a time [75]. Similarly, LCD printers use an LCD screen to selectively expose each layer of resin at a time. DLP and LCD are faster than SLA printers but are limited by the pixel density of their respective light sources. Inkjet 3D printers are a notable variant of resin printers, such as the Objet PolyJet line of printers from Stratasys. Inkjet printers deposit and immediately cure the resin layer by layer with a UV lamp, and can print support material simultaneously. This saves on resin costs and eliminates the need for post-curing a part. Multi-material capabilities are available with PolyJet printers, a notable advantage over vat resin printers.

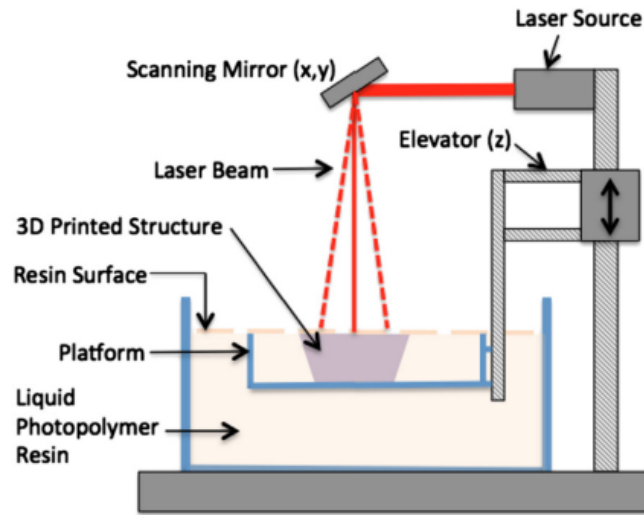


Fig. 1.10 SLA printing process (Image source: [76])

1.3.3.2 Material extrusion

Material extrusion 3D printers melt a thermoplastic, which is then extruded onto a build surface, where it solidifies after cooling. This process is known as fused filament fabrication (FFF) (sometimes known as fused deposition modeling (FDM), which is trademarked by Stratasys)). Material extrusion printers have a variety of configurations but always include a heating element and filament extrusion system. The filament is fed into a heating element (known as the hot end or extruder), and the melted filament exits through a nozzle opening.

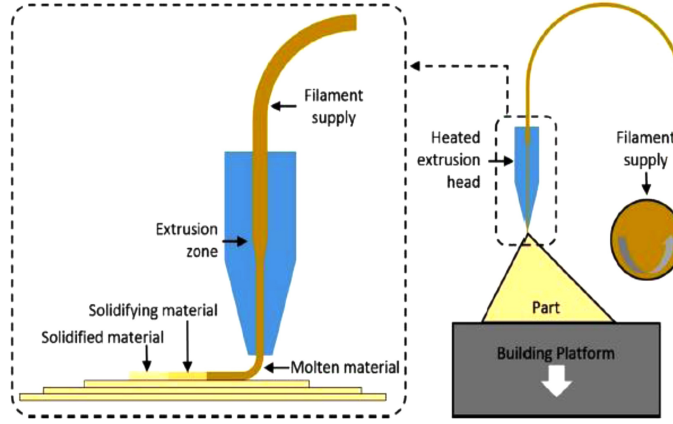


Fig. 1.11 FFF printing process (Image source: [77])

Common rigid materials include PLA, ABS, and PETG. Flexible materials such as TPU are available, and support materials such as PVA [77]. Typically, FFF printers print each layer in the XY plane, and the layers are built up along the Z axis. FFF printing results in anisotropic parts, as the bonds between layers in the Z axis have lower tensile strength [78]. FFF printers are mainly used for rapid prototyping, as other additive manufacturing processes are better suited for production parts.

1.3.3.3 Powder bed fusion

Powder bed fusion builds each layer by fusing granules together, typically with a laser. The earliest method, selective laser sintering (SLS), partially melts a powder material to create each print layer [79]. Once a layer is completed, a new layer of

powder is placed over the previous layers, until the process finishes.

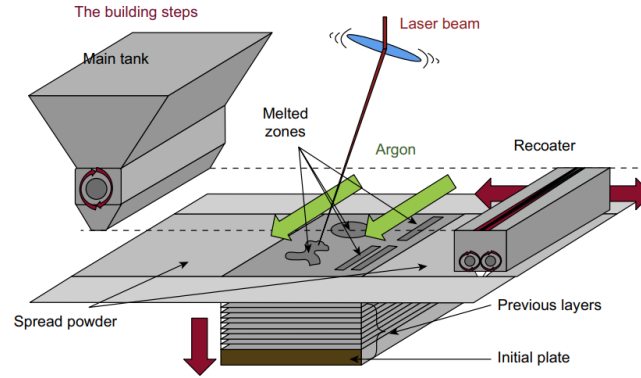


Fig. 1.12 Powder bed fusion printing process (Image source: [79])

Other powder bed fusion processes exist, such as direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM) which uses high-energy electron beams rather than a laser [80]. DMLS functions similarly to SLS but is used to make metal parts. SLM and EBM are also used to make metal parts, but fully melt the powder for fusion, rather than partial melting of sintering methods. Powder bed fusion is a common choice for end-use applications and functional prototyping for plastic parts. While powder bed fusion primarily uses nylon for plastic parts, common metal powders include steel, aluminum, and titanium.

Each additive manufacturing process has advantages and disadvantages. While the price and build quality of a printer can significantly impact the differences between manufacturing methods, some general comparisons can still be made:

- Resin and powder printers have higher resolution than material extrusion printers.
- Resin printers have a larger material variety than material extrusion printers, and both have a higher material variety than powder printers.
- Resin and powder printing materials are significantly more expensive than filament for material extrusion printers.
- Powder printers do not require support structures when printing overhangs and similar features (reducing material cost, print time, and improving final appearance), which are necessary for resin and material extrusion printers.

The resolution of PolyJet printers, combined with flexible material and multi-material printing, makes them an attractive option for the rapid prototyping of monolithic mechanisms containing flexure joints. Flexible PolyJet materials include Agilus30 and Tango from Stratasys. Tango polymer is highly flexible, with a shore hardness (the hardness of a material that states how resistant it is to indentation) of 26-28A, and a tensile strength of 0.8-1.5 MPa. Agilus30 is still flexible, but tougher than the Tango material, with a shore hardness of 30-35A and tensile strength of 2.4-3.1 MPa. Agilus30 is capable of withstanding repeated bending, making it a material of interest for flexible mechanisms [81]. If a flexible transmission mechanism can be readily fabricated with additive manufacturing, there is a

significant advantage in going further and making the entire robot out of a flexible material, allowing for a truly monolithic design. Rather than fabricating and assembling many individual components to utilize a flexible transmission mechanism, significant time savings could be realized by manufacturing an entire robot in one step.

1.4 Robotics

Industrial robotics started in the 1950s with the Unimate, a robot arm that extracted die-casted parts at a General Motors factory [82]. Today, robots today can be found in countless industries such as manufacturing, healthcare, and agriculture, among many others.

1.4.1 Basic terminology

Robots are composed of links and joints. Links are the rigid body elements that comprise a mechanism. Links are connected by joints (which constrain the movement between links) [83]. Together, links and joints form a kinematic chain. Kinematic chains are either open-loop, closed-loop, or hybrid. An open-loop kinematic chain is when every link is connected to the other links by only one path, in a closed-loop kinematic chain every link is connected to other links by more than one path (see Fig.1.13) [84]. A hybrid kinematic chain contains both open and

closed-loop chains. Robots are commonly classified by their kinematic structure: serial robots are open-loop kinematic chains, while parallel robots are closed-loop kinematic chains.

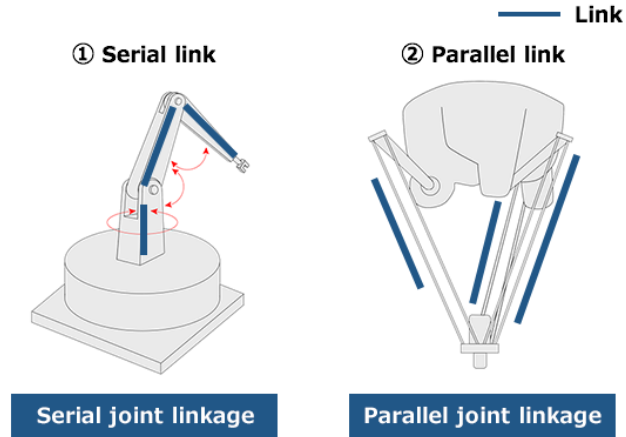


Fig. 1.13 Serial and parallel linkages (Image source: [85])

1.4.2 Serial robots

Serial robots contain one fixed end and a link with a free end [86]. The free end is known as the end effector [84] which often has a gripper or tool attached to it (see Fig. 1.14). To determine the location of the end effector, the relevant kinematic equations must be solved. One method is to use direct (or forward) kinematics, where the joint parameters are given, and the position of the end effector is calculated. The other method is to use inverse kinematics, where an end position is defined, and the necessary joint parameters are calculated. For serial robots,

direct kinematics is preferred to inverse kinematics, as it is significantly less difficult [84] [87]. Serial manipulators are commonly used in assembly lines for pick-and-place, machining, or welding [88] [89]. They have a larger workspace, but lower accuracy and poorer dynamic characteristics when compared to parallel robots [90].

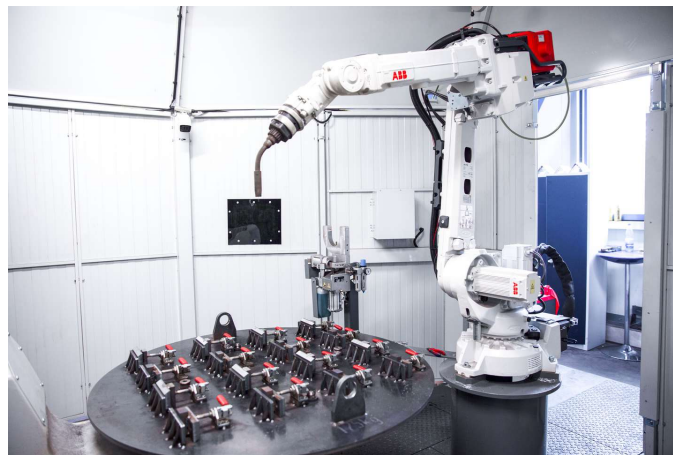


Fig. 1.14 Serial welding robot (Image source: [91])

1.4.3 Parallel robots

Parallel robots consist of a platform as an end-effector, connected to a base by multiple links (see Fig. 1.15). Unlike serial robots, solving the direct kinematics for parallel robots is complicated, while solving the inverse kinematics is straightforward [84] [87]. In 1954, Gough created a tire testing machine consisting of six linear actuators in parallel. Over a decade later in 1965, Stewart contributed significantly

to the field of parallel robotics with his work outlining a six-degree-of-freedom parallel robot [92] [93]. Stewart hoped to improve existing flight simulators [92], [93], where parallel robots remain in use today. [94]. This platform is commonly referred to as a Stewart platform, or as a Stewart-Gough platform to recognize the contributions of both authors. Other uses of this platform include automotive assembly, underwater research, and micro-positioning [95] [96] [97]. Parallel robots are capable of accurate, high-speed motion in six degrees of freedom, but are limited to a small workspace [98] [90].



Fig. 1.15 6-axis hexapod (parallel) robot (Image source: [99])

1.4.3.1 Delta robots

A subset of parallel robots, Delta robots, were developed in the early 1980s by Clavel [100] [98]. The end effector is constrained to three degrees of freedom as its orientation is held constant [101]. The delta robot has advantages over the parallel robots prior to it because by removing three degrees of freedom, the design is significantly simpler. This is due to simpler kinematic solutions compared to 6 DOF parallel robots. The precise and rapid movement of delta robots has made them a popular choice for pick-and-place robots (see Fig. 1.16) in areas such as the packaging industry [102].



Fig. 1.16 Commercial pick-and-place delta robots (Image source: [103])

1.4.4 SCARA robots

The Selective Compliance Assembly Robot Arm (or Selective Compliance Articulated Robot Arm, normally known as SCARA) was developed by Hiroshi Makino in 1978 [104]. The selective compliance of SCARA robots refers to the relatively large compliance for the robot arm in the horizontal plane, while being stiff in the vertical direction. This is advantageous in assembly operations such as peg-in-hole assembly processes. Serial SCARA robots (see Fig. 1.17a) are the most popular configuration, although five bar parallel configurations (see Fig. 1.17b) have been investigated [105] [106]. The relative advantages and disadvantages between serial and parallel SCARA configurations follow the comparisons mentioned in 1.4.2 and 1.4.3.



(a) Serial SCARA Robot

(Image source: [107])



(b) Parallel SCARA robot

(Image source: [106])

Fig. 1.17 Different SCARA configurations

1.4.5 Mesoscale parallel robots

One area of research into parallel robots has been into miniaturization (example shown in Fig. 1.18). The field of mesoscale robotics has explored a variety of methods to overcome the difficulties of manufacturing robots at the millimeter to centimeter scale. Limitations of these methods often include a complex design process, expensive fabrication equipment, and lengthy assembly and integration times [6]. Techniques used to overcome these challenges include printed circuit microelectromechanical systems (PC-MEMS) [2] [9] [108], compliant hinges [109] [17], additive manufacturing [10] [110], pop-up mechanisms [111], patterned magnetization [13], or a combination of the aforementioned methods. At the mesoscale, traditional macroscale manufacturing methods such as machining run into resolution and minimum feature size limitations [112], hence planar manufacturing methods are commonly used. By manufacturing in plane, methods such as printed circuit microelectromechanical systems (PC-MEMS), lamina emergent mechanisms (LEMs) [66], and origami-inspired design [113] allow for high-volume production of mesoscale robots with a lower per unit-cost and part count. Multi-material laminates have enabled robots to be manufactured with built-in compliant mechanisms such as flexures [114]. With these advantages comes the complexity of going from two-dimensional manufacturing to the final three-dimensional form. As these mech-

anisms do not yet have general design principles that allow for quick modification [115] design revisions may involve substantial design changes and the modification of multiple manufacturing steps.

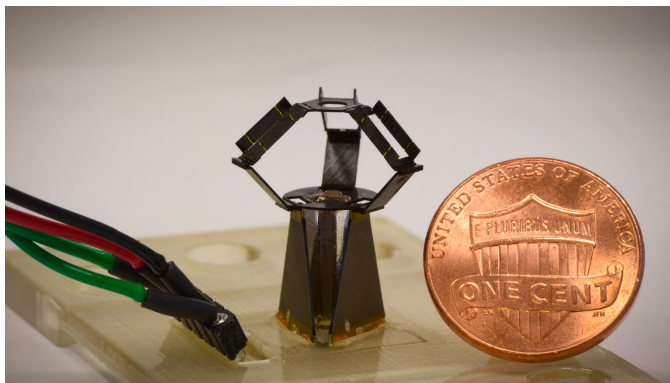


Fig. 1.18 The milliDelta, a milli-meter scale delta robot (Image source: [116])

1.5 Research Objectives and Contributions

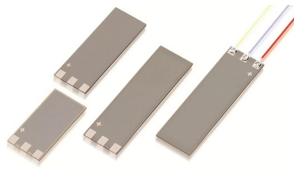
This work focuses on the development of a parallel robot using piezoelectric bimorph actuators, flexible materials, and additive manufacturing for future applications such as pick-and-place or micro-positioning. The small linear displacement of a piezoelectric bimorph can be controlled precisely at high frequencies. This small displacement is converted to large rotational motion via a compliant transmission mechanism. To enable monolithic manufacture, compliant joints are used, significantly reducing the assembly and integration time while reducing the total part count. In order to achieve these goals, additive manufacturing is explored as an av-

enable to fabricate compliant parts, allowing for design revisions to be implemented with minimal changes during fabrication, reducing the length of each design cycle. In addition, compared to other manufacturing methods, additive manufacturing has a low barrier to entry with regard to both the cost and expertise required to design and fabricate mesoscale mechanisms. Bringing these areas of research together, the objectives of this thesis are as follows:

1. Design a compliant transmission mechanism using additive manufacturing for the conversion and amplification of small linear displacement to large rotational motion.
2. Fabricate and experimentally test the compliant transmission mechanism to verify the conversion and amplification of linear to rotational motion.
3. Design a six-bar planar parallel robot using piezoelectric bimorphs as actuators and compliant flexure joints.
4. Fabricate and experimentally test the parallel robot, demonstrating control of the end effector in-plane.

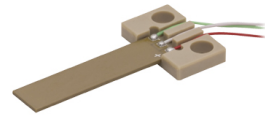
2 Piezoelectric actuator characterization

Bimorph actuators (shown in Fig. 2.1) are selected for the transmission design due to their precise, high-speed linear displacement and relatively large blocked force. The piezoelectric bimorphs chosen for these tests are the Physik Instrumente PICMA PL127.10 (shown in Fig. 2.1a) and the Thorlabs PB4NB2W (shown in Fig. 2.1b). A FEA model of the piezoelectric bimorphs is made to compare model performance with manufacturer specifications (shown in Table 2.2 and Table 2.4). The PL127.10 is composed of a PZT-5A type material (PIC 251), while the PB4NB2W is composed of a PZT-5H type material (THP 51).



(a) PICMA bimorphs (Image

source: [117])



(b) PB4NB2W bimorph (Image

source: [118])

Fig. 2.1 Selected bimorph actuators

Property	Units	PL127.10	PB4NB2W
Length	mm	31 ± 0.5	32 ± 0.5
Free length	mm	27	28
Width	mm	9.60 ± 0.2	7.8 ± 0.1
Thickness	mm	0.67 ± 0.1	0.8 ± 0.1
Operating voltage range	V	± 30	± 75
Displacement	μm	$\pm 450 \pm 20\%$	$\pm 450 \pm 15\%$
Blocking force	N	$\pm 1.1 \pm 20\%$	± 1.5
Resonant frequency	Hz	$420 \pm 20\%$	370
Capacitance	μF	$2 \times 1.1 \pm 20\%$	$2 \times 0.55 \pm 15\%$
Operating temperature range	$^{\circ}\text{C}$	-20 to 85	-25 to 130
Material		PIC 251	THP 51

Table 2.2 Specifications of the PI and Thorlabs bimorphs (Source: [119], [120])

Property	Symbol	Units	PIC 251	THP 51
Density	ρ	kg/m ³	7800	7700
Relative dielectric constant	K_{33}^T		1750	3300
	K_{11}^T		1650	3370
Piezoelectric strain constant	d_{33}	m/V	400×10^{-12}	710×10^{-12}
	d_{31}	m/V	-180×10^{-12}	-320×10^{-12}
	d_{15}	m/V	550×10^{-12}	950×10^{-12}
Piezoelectric voltage constant	g_{33}	m ² /C	25×10^{-3}	25×10^{-3}
	g_{31}	m ² /C	-11.3×10^{-3}	-11×10^{-3}
Elastic compliance constant	s_{11}^E	m ² /N	15.9×10^{-12}	17×10^{-12}
	s_{12}^E	m ² /N	-5.7×10^{-12}	-4.8×10^{-12}
	s_{13}^E	m ² /N	-7.38×10^{-12}	-9.9×10^{-12}
	s_{33}^E	m ² /N	20.97×10^{-12}	23×10^{-12}
	$s_{44}^E = s_{55}^E$	m ² /N	44.9×10^{-12}	71×10^{-12}
	s_{66}^E	m ² /N	43.2×10^{-12}	38.8×10^{-12}
Q factor	Q		80	$60 \pm 5\%$
Poisson's Ratio	v_{12}		0.3584	0.2824
	$v_{13} = v_{23}$		0.4639	0.5824

Table 2.4 Material properties of PIC 251 and THP 51 (Source: [121], [122])

2.1 Implementing multi-layer piezoelectric materials

Both bimorphs investigated use multi-layer technology, where each half of the bimorph is composed of multiple piezoelectric layers with alternating polarization. The number of layers varies depending on material thickness and manufacturing technology. Modeling each layer using finite element software may be computationally prohibitive, so the voltages applied to the bimorph are scaled corresponding to the total number of piezoelectric layers. As both bimorph suppliers did not provide an exact number of layers, piezoelectric beam bending equations can be used to determine this scaling factor. The bending displacement of a piezoelectric ceramic bimorph actuator is:

$$\Delta L_{bend} = \frac{3}{8} d_{31} n \frac{l_f^2}{h_p^2} V \quad (2.1)$$

where ΔL_{bend} is the displacement due to bending in m , n is the number of layers in half of the bimorph (shown in Fig.2.2), d_{31} is a piezoelectric strain coefficient dependant on the bimorph material in m/V , l_f is the free length of the bimorph in m , h_p is the height of the piezoelectric element (half of the bimorph thickness) in m , and V is the operating voltage range in V .

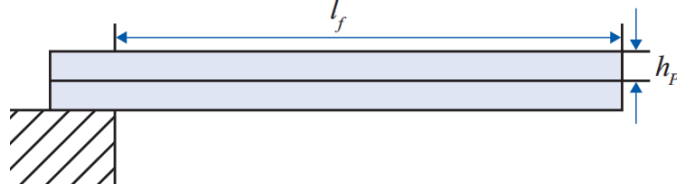


Fig. 2.2 Free length and piezoelectric element height for a multilayer bimorph
(Image source: [52])

The equation can be rearranged to solve for the number of layers in each half of the bimorph

$$n = \frac{\Delta L_{bend}}{\frac{3}{8}d_{31}\frac{l_f^2}{h_p^2}V} \quad (2.2)$$

By inputting the values from Table 2.2 and 2.4, the expected number of layers for half of the PL 127.10 bimorph is 17, while the expected number of layers for half of the PB4NB2W bimorph is 5. If each bimorph is modeled with only two layers, the voltage should be scaled by 17 (from $\pm 30\text{V}$ to $\pm 510\text{V}$) for the PL127.10 bimorph and by 5 (from $\pm 75\text{V}$ to $\pm 375\text{V}$) for the PB4NB2W bimorph. Due to the smaller number of layers, all 10 layers of the PB4NB2W bimorph are modeled without voltage scaling as shown in 2.3, where $V_{\sim}$ is the variable voltage, V_+ is the high bias voltage, V_- is the low bias voltage and the arrows indicate the polarization direction. The PL127.10 bimorph is modeled using two layers (shown in 2.4) where all voltages are scaled by 17.

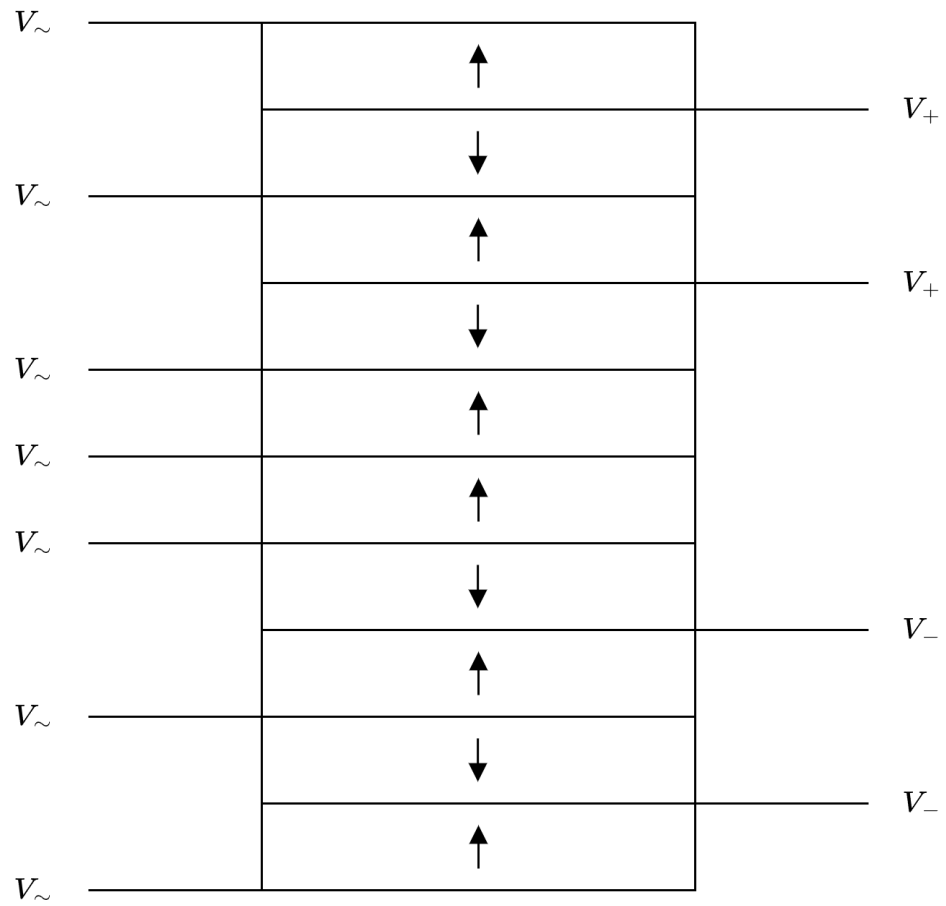


Fig. 2.3 Ten layer diagram for a piezoelectric bimorph

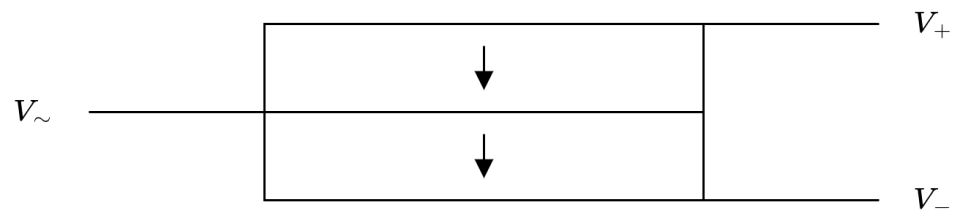


Fig. 2.4 Two layer diagram for a piezoelectric bimorph

2.1.1 Finite element analysis of piezoelectric bimorphs

Finite element models of the piezoelectric bimorphs are created with the finite element analysis software ABAQUS. A piezoelectric bimorph is modeled as one rectangular body with length l and width w (see Fig. 2.5) and partitioned into two equal bodies through the thickness t to create two equal halves for the PL127.10 bimorph, while the PB4NB2W model has 10 layers of equal thickness. The model is partitioned along the length of the bimorph to separate it into the free length l_f and the constrained length l_c . Material orientation and material properties are applied to the model (Axis 1: $+X$, Axis 2: $+Y$, Axis 3: $+Z$). The model is meshed using quadratic hexahedral piezoelectric elements with reduced integration (C3D20RE in ABAQUS).

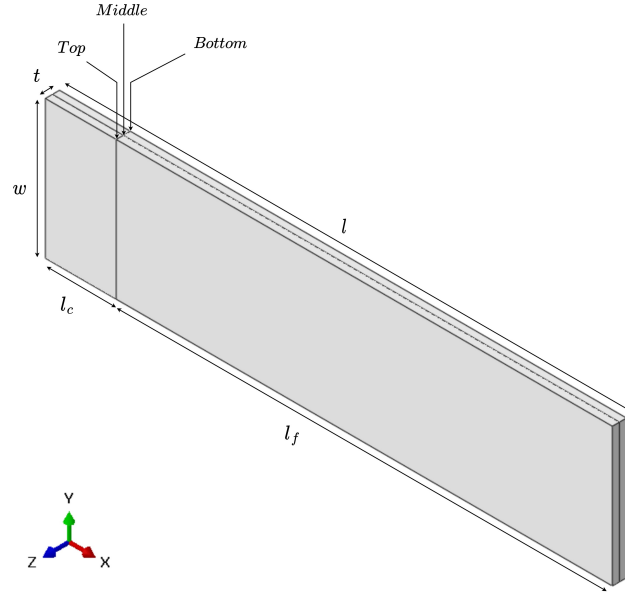


Fig. 2.5 CAD model of the PL127.10 bimorph

2.1.2 Static deflection

For differential (bi-directional) control of a bimorph actuator the applied and bias voltage modes are shown in Table. 2.5, where the second mode is used for the finite element models.

Mode	V_+	$V_{\sim}$	V_-
Option 1	$V_{\max}$	0 to $V_{\max}$	0
Option 2	$V_{\max}/2$	$-V_{\max}/2$ to $V_{\max}/2$	$-V_{\max}/2$

Table 2.5 Differential voltage control modes for a piezoelectric bender

To determine the deflection of the bimorphs, electric potential boundary conditions are applied to the bottom, top, and middle faces for the low bias voltage, high bias voltage, and variable voltage, respectively. Finally, the faces along the constrained length l_c are constrained in all directions. The static displacement is determined by taking the displacement of the furthest node along the central axis of the bimorph, shown in Fig. 2.6. The global element size is 0.0007 meters, determined using a mesh convergence test, where the element size is varied to identify an element size where results are accurate while balancing computational cost.

Bimorph	Given displacement (μm)	ABAQUS result (μm)	Percent difference (%)
PL127.10	$450 \pm 20\%$	443.01	1.55
PB4NB2W	$450 \pm 15\%$	411.275	8.6

Table 2.6 Static deflection results

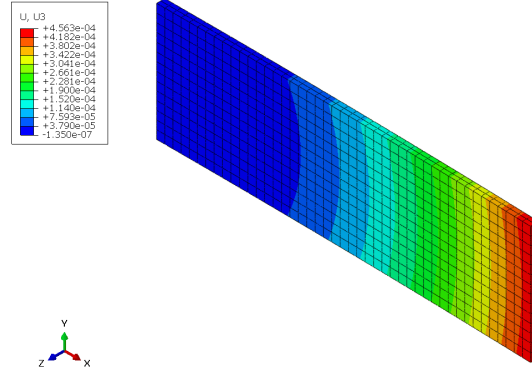


Fig. 2.6 Deflection results for the PL127.10 bimorph, displacement taken at the node highlighted in red

The deflection results (shown in Table.2.6) show that the results for both bimorphs are close to the given values, with the results for the PL127.10 actuator being closer. It should be noted that the peak displacement is taken at the midpoint through the width as seen in Fig.2.6, as the curvature through the width of the bimorph results in slightly larger displacement at the corners.

2.1.3 Blocked force

For the blocked force analysis, the end node furthest along the central axis of the bimorph (shown in Fig.2.7) is set to a displacement of zero along the Z axis. The blocked force is determined by retrieving the reaction force at the end node.

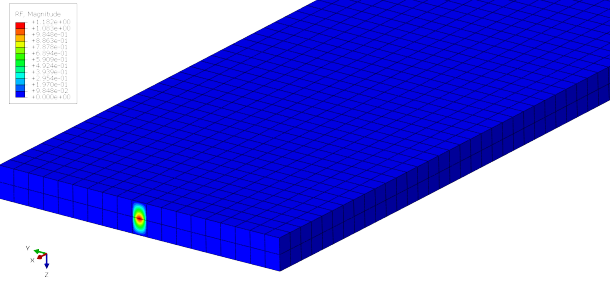


Fig. 2.7 Blocked force results for the PB4NB2W bimorph in ABAQUS

Bimorph	Given blocked force (N)	ABAQUS result (N)	Percent difference (%)
PL127.10	$1.1 \pm 20\%$	1.099	0.091
PB4NB2W	1.5	1.182	21.2

Table 2.7 Blocked force results

The blocked force of the PL127.10 bender is extremely close to the specified value, while the blocked force of the PB4NB2W bender is significantly different.

2.1.4 Resonant frequency

To determine the resonance frequencies of the bimorphs, a frequency step is created to extract the first ten eigenvalues corresponding to the first ten resonance frequencies of the system. Each bimorph is fixed at the faces shown in Fig. 2.8, and the electric potential is set to zero for all voltage inputs.

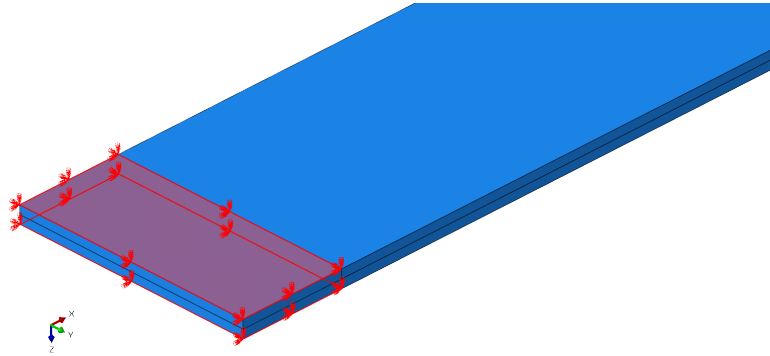


Fig. 2.8 Boundary conditions for the PL127.10 bimorph in ABAQUS

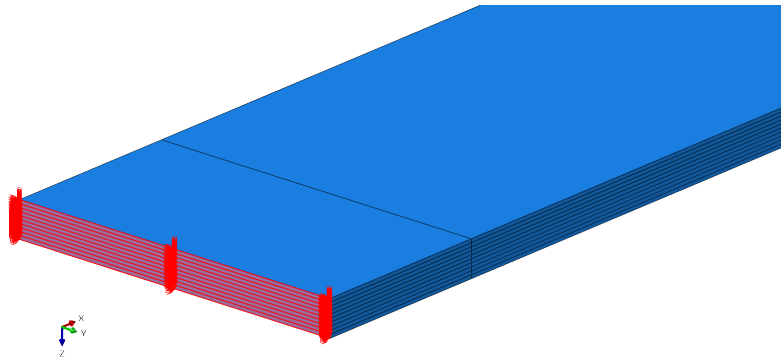


Fig. 2.9 Alternate boundary conditions for the PB4NB2W bimorph in ABAQUS

Bimorph	Given resonant frequency (Hz)	ABAQUS result (Hz)	Percent difference (%)
PL127.10	$420 \pm 20\%$	441.04	5.01
PB4NB2W	370	353.55	4.45

Table 2.8 Natural frequency results

The simulated results for the resonant frequencies (shown in Table.2.8) are reasonable for both bimorphs. The PB4NB2W bimorph is constrained at the end face (shown in Fig. 2.9) instead of the partitioned fixed faces where the holder would be, as Thorlabs indicated that this is how the resonance frequency was acquired for the specification sheet. If the bimorph mount faces are constrained, the resonant frequency for the PB4NB2W bimorph is 458.73 Hz.

2.1.4.1 Rayleigh damping

To determine the dynamic response of the system the bimorphs are driven at varying frequencies to find the peak displacements which occur at resonance. If there is no energy dissipation in the model, it will become unstable when driven at resonance. Rayleigh damping is implemented as a material damping model to overcome this, which relates the natural frequencies of the system ω_i with the critical damping ratios ζ_i . For the i -th mode of the system, the critical damping ratio can be expressed as:

$$\zeta_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \quad (2.3)$$

where α is the mass proportional damping coefficient, and β is the stiffness proportional damping coefficient. The critical damping ratios for the first two modes are therefore:

$$\zeta_1 = \frac{\alpha}{2\omega_1} + \frac{\beta\omega_1}{2} \quad (2.4)$$

$$\zeta_2 = \frac{\alpha}{2\omega_2} + \frac{\beta\omega_2}{2} \quad (2.5)$$

To have equal damping applied at the first two modes the first two damping ratios ζ_1 and ζ_2 must be identical, which allows equation (2.4) and (2.5) to be combined:

$$\frac{\alpha}{2\omega_1} + \frac{\beta\omega_1}{2} = \frac{\alpha}{2\omega_2} + \frac{\beta\omega_2}{2} \quad (2.6)$$

To solve equation (2.6), the damping ratio ζ can be equated to the Q factor of the material:

$$\zeta = \frac{1}{2Q} \quad (2.7)$$

where Q is the Q factor provided by the manufacturer. Equation (2.4) and (2.5) can be re-arranged as:

$$\frac{1}{Q} = \frac{\alpha}{\omega_1} + \beta\omega_1 \quad (2.8)$$

$$\frac{1}{Q} = \frac{\alpha}{\omega_2} + \beta\omega_2 \quad (2.9)$$

Plugging in values for the Q factor and the natural frequencies of the system then solving for α and β leads to the Rayleigh damping coefficients shown in Table 2.9.

Material	α	β
PIC 251	29.274	6.987×10^{-7}
THP 51	41.391	8.001×10^{-7}

Table 2.9 Rayleigh damping coefficients results

2.1.5 Dynamic analysis

Dynamic analysis is performed to determine damped resonance frequencies after material damping was implemented. A chirp signal is applied to the variable voltage for each bimorph sweeping from 1 to 1000 Hz with an amplitude of 1V. The peak frequency response of each bimorph (shown in Fig. 2.10 and Fig. 2.11) is used to determine the resonant frequency of the system (shown in Table 2.10).

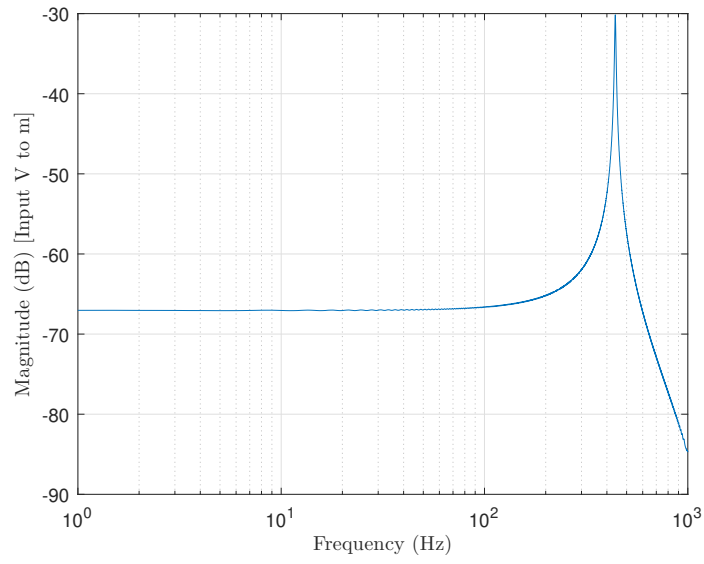


Fig. 2.10 Frequency response of the chirp signal on the PL127.10 bender

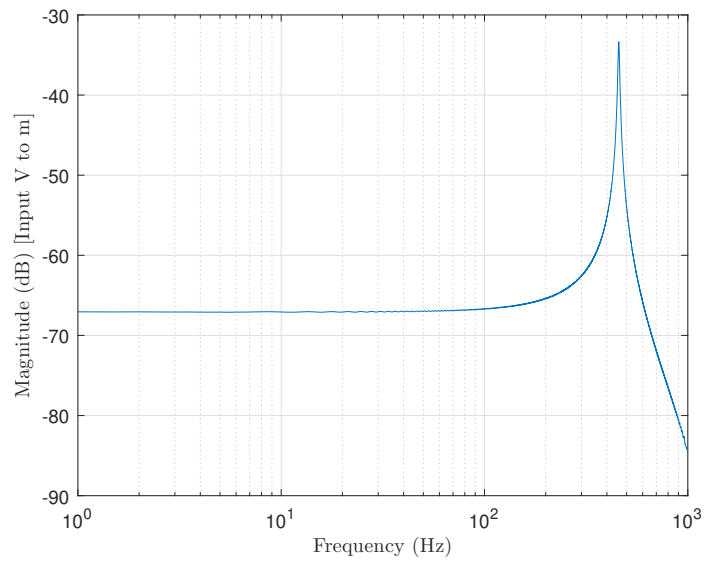


Fig. 2.11 Frequency response of the chirp signal on the PB4NB2W bender

Bimorph	Undamped Resonant Frequency (ABAQUS) (Hz)	Damped Resonant Frequency (ABAQUS) (Hz)
PL127.10	441.04	440
PB4NB2W	458.73	457

Table 2.10 Chirp signal frequency response results

The damped resonant frequencies determined in ABAQUS are close to the predicted undamped resonant frequencies.

2.1.6 Bimorph simulation results

For the static deflection and resonant frequencies, the differences between the specification sheet and ABAQUS results are within the tolerances given. The blocked force for the PL127.10 bender is accurate, while there is a notable discrepancy for the PB4NB2W bender. One possible reason for the differences between the benders is that the material properties of the PL127.10 bender were readily available, while some material properties of the PB4NB2W bender were only available on request, such as the relative dielectric constant (K_{11}^T), piezoelectric strain constant (d_{15}). Despite the larger discrepancies between the specification sheet and the results, the

Thorlabs PB4NB2W bender is chosen for future use as an actuator for a transmission mechanism due to the practical considerations as they have a significantly lower cost compared to the Physik Instrumente PL127.10 bender, as well as an option to purchase the bender mounted to a holder.

2.2 Experimental characterization

2.2.1 Experimental setup

To determine the experimental performance of the Thorlabs PB4NB2W benders, four benders are tested to determine peak displacements and resonance frequencies. Each bender is mounted to an XY micrometer stage connected to an optical table (shown in Fig. 2.12) and a Keyence LK-H082 laser displacement sensor is positioned to obtain the displacement at the tip of the bimorph. The piezoelectric bimorph is connected to a PiezoDrive PD200X4 Voltage Amplifier with a DC offset of 75V applied to the output, driving the bender according to the first mode in Table. 2.5. The low-bias voltage input of the bender is connected to the ground terminal of the amplifier (shown in Fig. 2.13), the high-bias voltage input is connected to the high voltage output of the amplifier and the variable voltage input is connected to the first output of the amplifier. To actuate the bimorph, the voltage signal is sent from Simulink using a real-time target machine (specifically, a Speedgoat IO133

module) to input 1 of the amplifier, which is amplified with a fixed gain of 20 at the output. The peak displacement of the bimorphs is obtained at $\pm 20\text{V}$, $\pm 40\text{V}$, $\pm 60\text{V}$, and $\pm 74\text{V}$ ($\pm 74\text{V}$ is used rather than ± 75 to not exceed the high voltage output of the amplifier, which is measured at 149.6V).

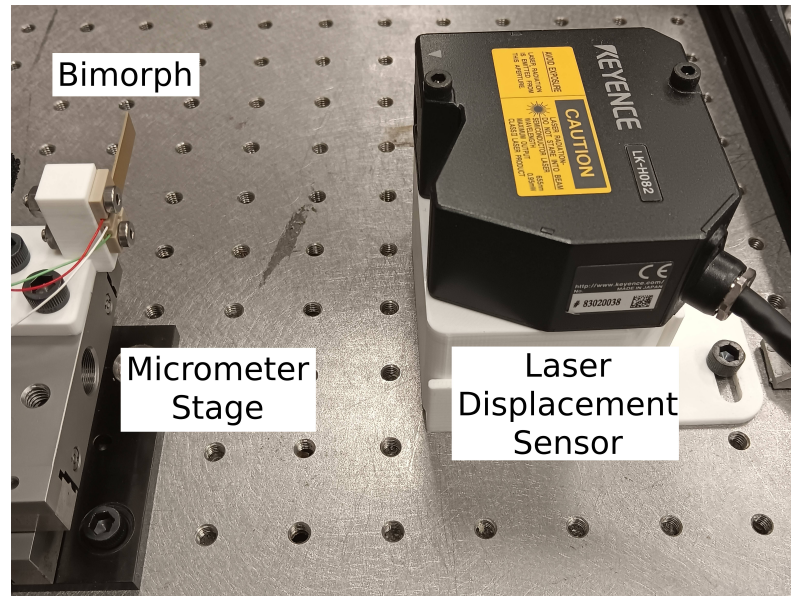


Fig. 2.12 Experimental setup for bimorph characterization

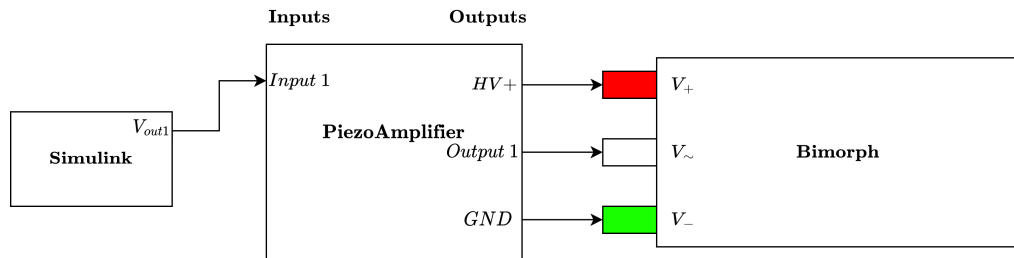


Fig. 2.13 Wiring diagram for bimorph testing

2.2.2 Experimental results

The deflection of all bimorphs tested is lower than expected, with all but one bimorph showing deviation from their specifications (shown in Table.2.11). Examining the results when the bimorphs are tested at 20, 40, 60, and 74 volts (shown in Fig. 2.14), bimorphs B and D closely match, while bimorphs A and C have slightly larger displacements. The resonance frequencies of all four bimorphs (shown in Table.2.12) closely match the given specifications, with an error of around 1%. The experimental results are closer to the simulated results than the specification sheet, as the specification sheet has a significantly higher displacement than the simulation and experimental tests. The resonance frequencies for the experimental results are significantly more accurate, matching the values given in the specification sheet. The simulated result for the resonance frequency is close to the specified value. It should be noted that the simulated result is more accurate only when the alternate boundary conditions specified in the previous section are used.

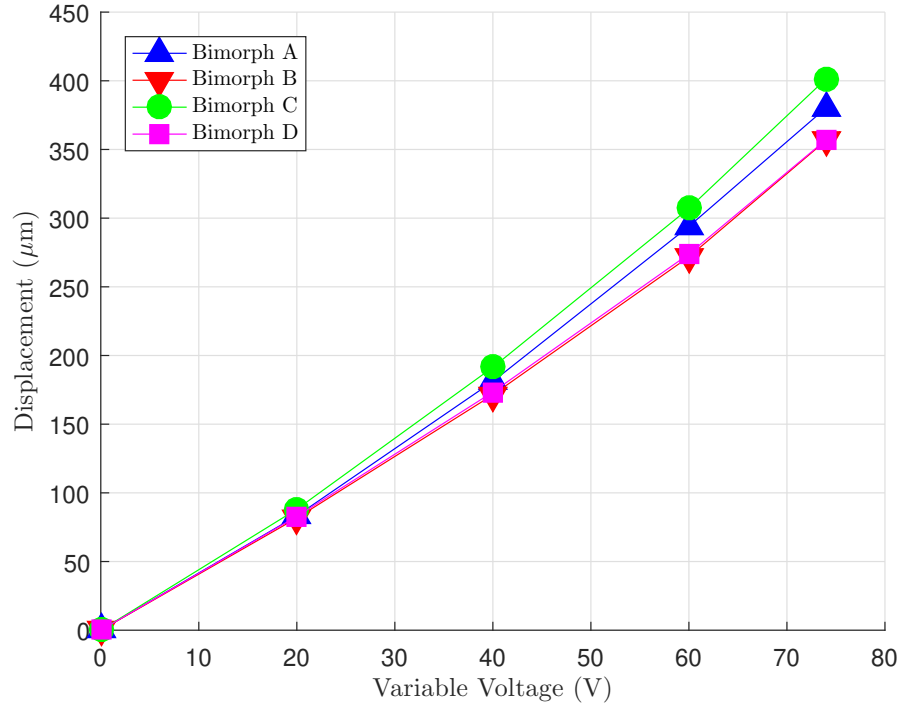
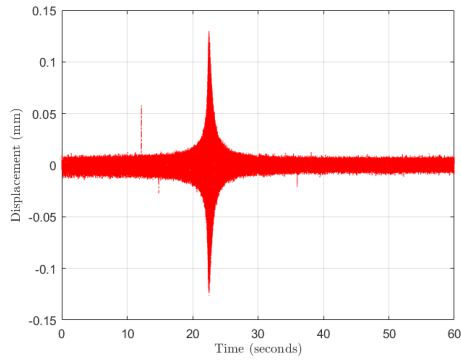


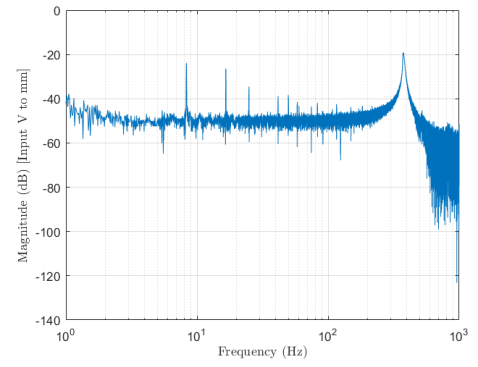
Fig. 2.14 Peak displacements of the piezoelectric bimorphs

Bimorph	Given displacement (μm)	Experimental result (μm)	Percent difference (%)
A	$450 \pm 15\%$	380.35	15.48
B	$450 \pm 15\%$	356.65	20.74
C	$450 \pm 15\%$	401.5	10.78
D	$450 \pm 15\%$	357.1	20.64

Table 2.11 Experimental testing for static displacement

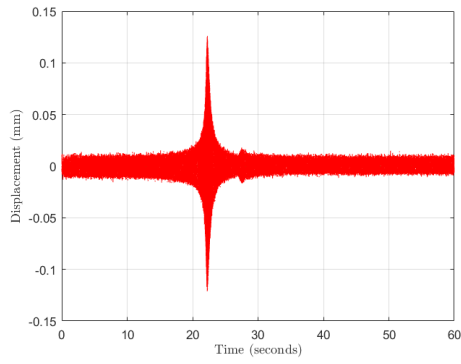


(a) Displacement results

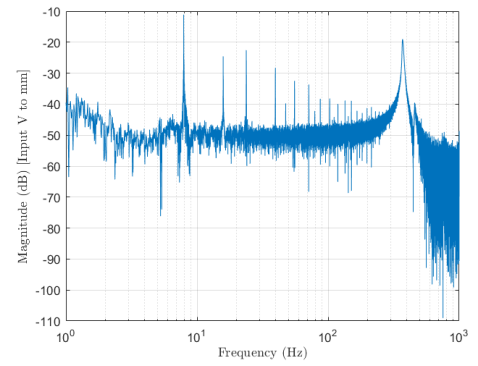


(b) Frequency Results

Fig. 2.15 Chirp signal results for piezoelectric bimorph A

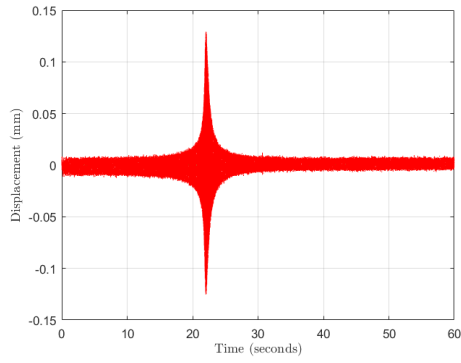


(a) Displacement results

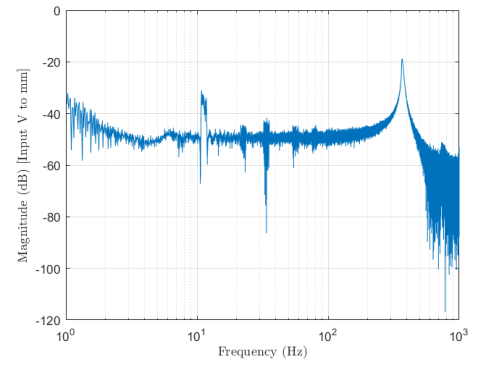


(b) Frequency Results

Fig. 2.16 Chirp signal results for piezoelectric bimorph B

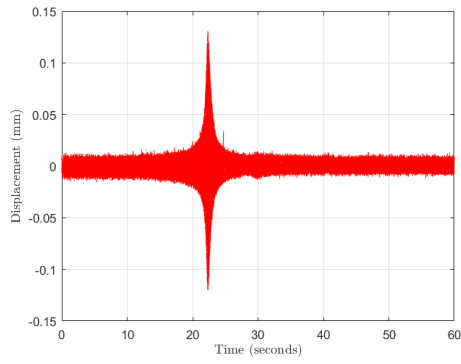


(a) Displacement results

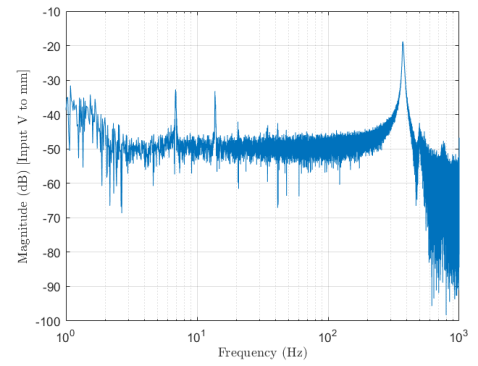


(b) Frequency Results

Fig. 2.17 Chirp signal results for piezoelectric bimorph C



(a) Displacement results



(b) Frequency Results

Fig. 2.18 Chirp signal results for piezoelectric bimorph D

Bimorph	Given resonant frequency (Hz)	Experimental result (Hz)	Percent difference (%)
A	370	374.4	1.189
B	370	370.1	0.027
C	370	366.5	0.946
D	370	371.9	0.514

Table 2.12 Experimental resonance frequency results

2.3 Conclusion

To select the bimorphs for further implementation in a transmission mechanism, the peak displacement is the most significant parameter, while having a pair of bimorphs with close peak displacements is also advantageous. Due to the larger displacement of bimorphs A and C, they are selected for future integration in a transmission mechanism and parallel robot.

3 Transmission mechanism design

To actuate a parallel robot with piezoelectric bimorphs, a transmission mechanism is developed to convert the small displacement of the piezoelectric bimorphs into a large rotational motion. As a mesoscale design and use of compliant flexure joints are planned for the parallel robot, the transmission mechanism design is performed with multi-material additive manufacturing methods in mind. Various designs are investigated using finite element analysis to determine the critical parameters for the conversion and amplification of small linear displacement to large rotational motion using flexible materials.

3.1 Initial finite element design

To better understand the critical parameters for a compliant amplification mechanism, a transmission design powered by a piezoelectric bimorph actuator is developed. Two proposed designs are investigated (shown in Fig. 3.1) to achieve this result. A single driven flexure design (shown in Fig. 3.1a) consisting of two flexures

connected by an offset (shown in Fig. 3.2), where δ is the bimorph displacement, L_d is the length and T_d is the thickness of the driven flexure, L_g is the length and T_g is the thickness of the mechanically grounded flexure, and L_o is the length of the offset between flexures. The flexures have caps to connect to the bimorph and mechanical ground. For the single driven flexure design, it was believed that the driven flexure would function as a revolute joint where the transmission base would swing back and forth as an angle formed between the start and end of the driven flexure. The second design (shown in Fig. 3.1b) is identical to the first, except another flexure is added on top of the driven flexure. This was done to determine if multiple driven flexures would linearize the output of the transmission mechanism.

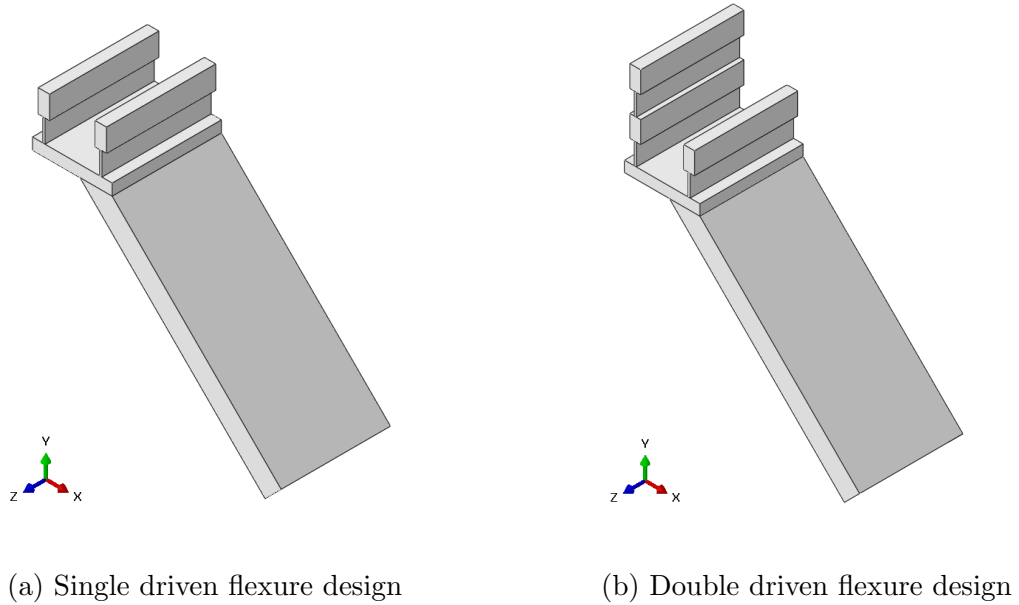


Fig. 3.1 Initial transmission designs

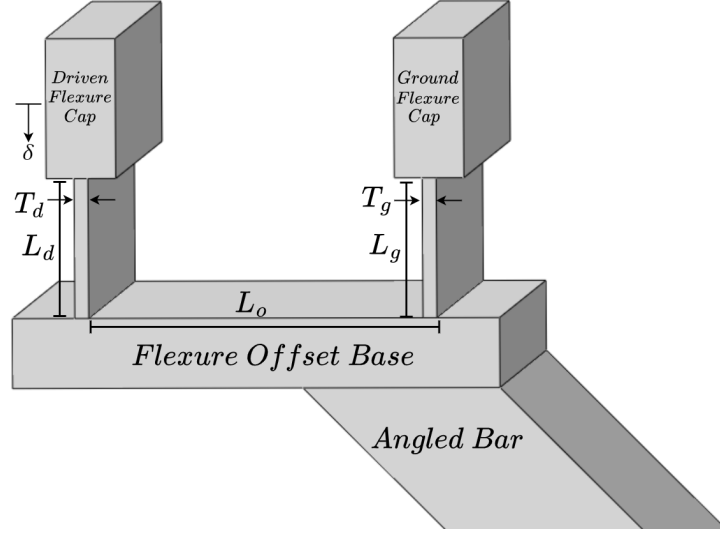


Fig. 3.2 Relevant parameters for the initial transmission design

Due to the long flexural members and large deformations, neither a rigid kinematic analysis nor a pseudo-rigid-body model without a large number of serial joints is appropriate to model the mechanism's performance. Instead, the two designs are modeled in ABAQUS, and the driven flexure cap is connected to the end of the bimorph model. The bimorph was driven to peak static displacement in both directions. The initial designs rotate a few degrees in each direction (shown in Fig. 3.3 and Fig. 3.4), suggesting the offset length L_o determined the transmission ratio, so further analysis is performed.

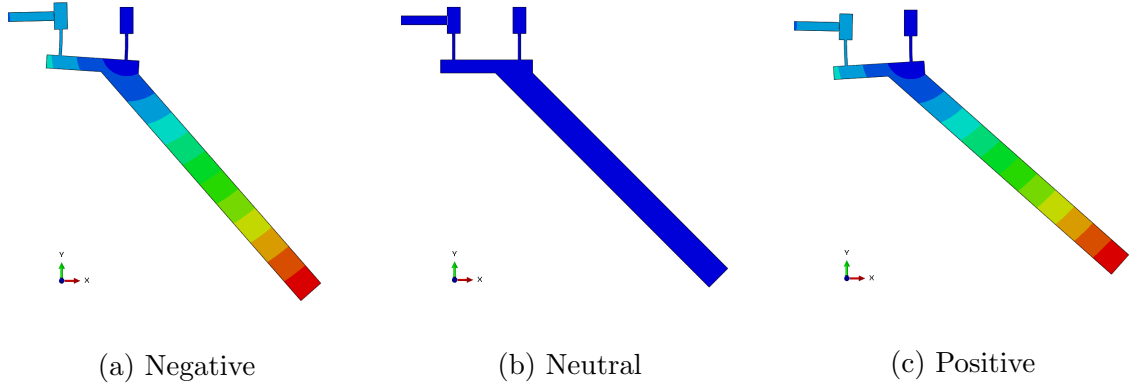


Fig. 3.3 Initial single flexure results

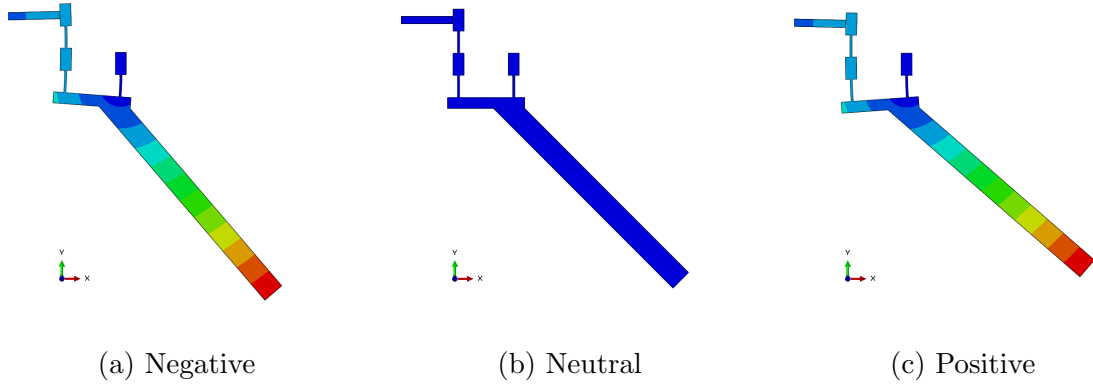
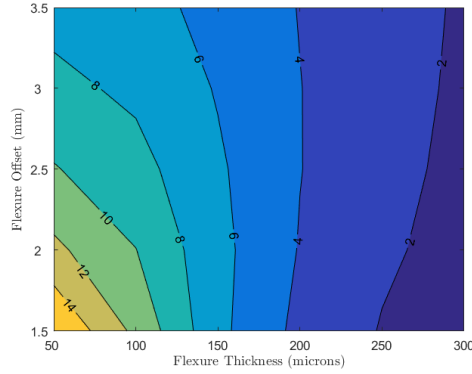


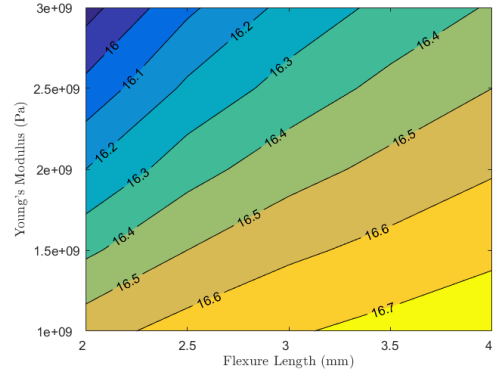
Fig. 3.4 Initial double flexure results

To optimize the design and determine the critical design parameters, a parametric analysis is performed. Both designs are investigated by iterating through two parameters while keeping other design parameters constant to determine critical parameters for maximizing rotation. After preliminary testing, a few critical parameters emerged, as the flexure thicknesses and flexure offset have the greatest

impact on rotation (shown in Fig. 3.5a and Fig. 3.6a). Beyond that, the flexure length and Young's modulus of the material has a slight impact on the rotation (shown in Fig. 3.5b and Fig. 3.6b).

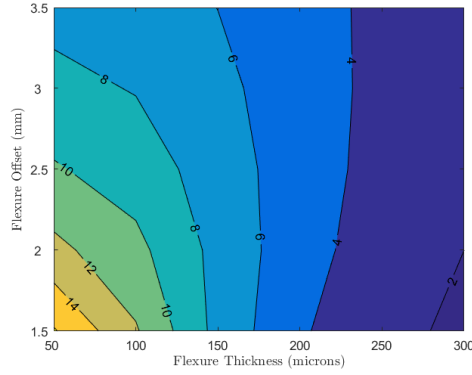


(a) Flexure thickness vs. flexure offset

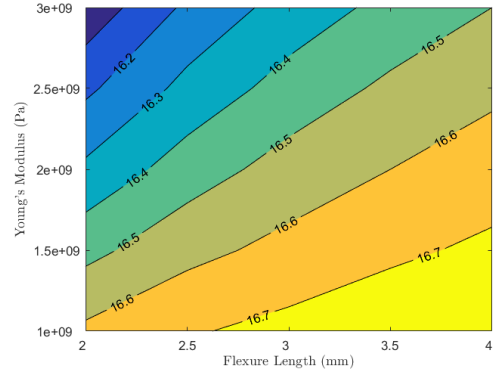


(b) Flexure length vs. Young's modulus

Fig. 3.5 Parametric analysis of single driven flexure design



(a) Flexure thickness vs. flexure offset



(b) Flexure length vs. Young's modulus

Fig. 3.6 Parametric analysis of double driven flexure design

Some of the critical design parameters can be understood by looking at beam bending equations. If the flexures are treated as a beam, the maximum deflection is proportional to I , the area moment of inertia. For a rectangular cross-section, the area moment of inertia is

$$I = \frac{bh^3}{12} \quad (3.1)$$

where b is the width of the rectangular cross section in m , and h is the height in m . In this case, b would correspond to the width of the flexures, while h would correspond to the thickness of the flexures. It would thus be expected that an increase in thickness would significantly decrease bending, in particular when compared to other relevant parameters such as the flexure width, length, and Young's modulus of the material.

Comparing the performance of the two designs, the results are nearly identical. The double driven flexure design is abandoned as it has similar performance to the single flexure design while being more difficult to fabricate and assemble, so the single driven flexure design is selected for future testing. However, to further reduce the flexure offset the design must be reworked. For a flexure offset of zero, it would be impossible to move the flexures close enough, as the flexures and their caps would begin to overlap. To overcome this, the mechanically grounded flexure is divided in two and placed at opposing ends of the driven flexure (shown in Fig. 3.7). In contrast to the parallel design used in Cardiolock [64], an angle is added between

the flexures and the base (shown in Fig.3.8) as an alternate method to reduce flexure offset and to determine if a non-parallel configuration improves the rotation of the mechanism.

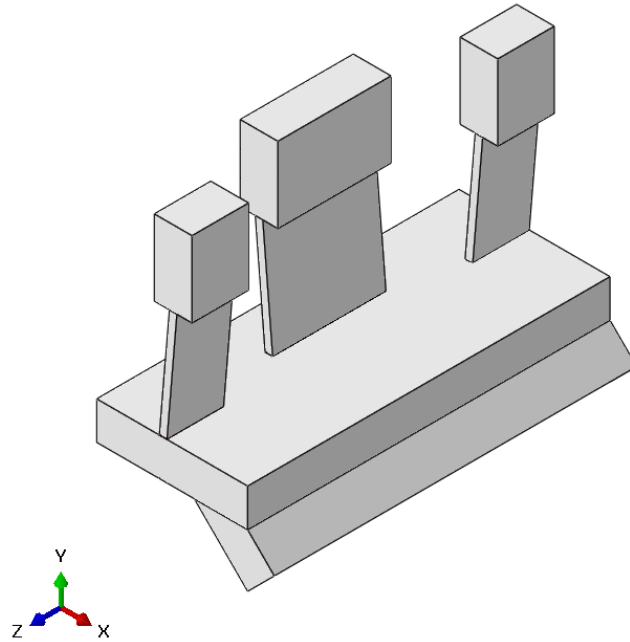


Fig. 3.7 Isometric view of the revised design

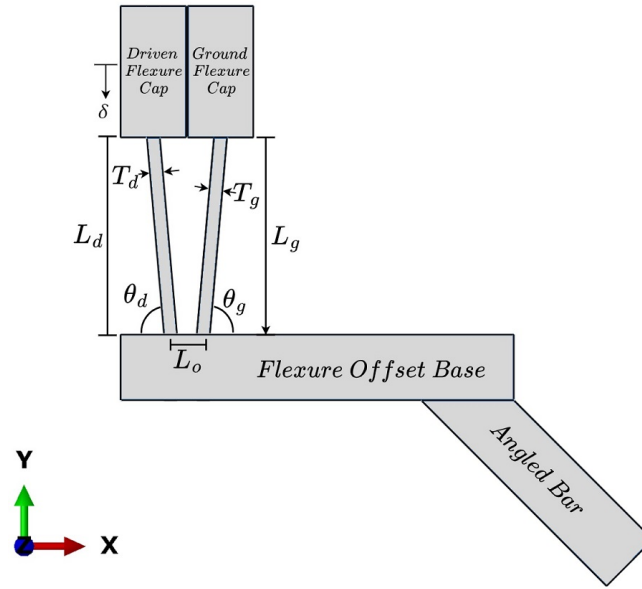


Fig. 3.8 Diagram showing revised design to allow for angled flexures

The initial tests of this revised design do not use angled flexures, in order to compare the results to the previous model. Comparing the results for flexure thickness and offset for this design (shown in Fig. 3.9), it is apparent that these two parameters are critical to the rotation of the transmission mechanism. As seen previously, there is a notable increase in the rotation when the flexure offset begins to approach zero. When the flexure offset is zero, there is further improvement to the rotation by reducing the thickness of the flexures. Next, the flexure length and width are examined (shown in Fig. 3.10). Reducing the flexure length results in a noteworthy increase in rotation, while changing the flexure width has a smaller impact. Finally, to investigate the impact of using angled flexures, the angles of

the driven and grounded flexures are varied (shown in Fig.3.11), suggesting that minimizing the driven and grounded flexure angles is optimal. At this stage, the predicted rotation of the mechanism is close to 70 degrees, exceeding the initial goal of 45 degrees.

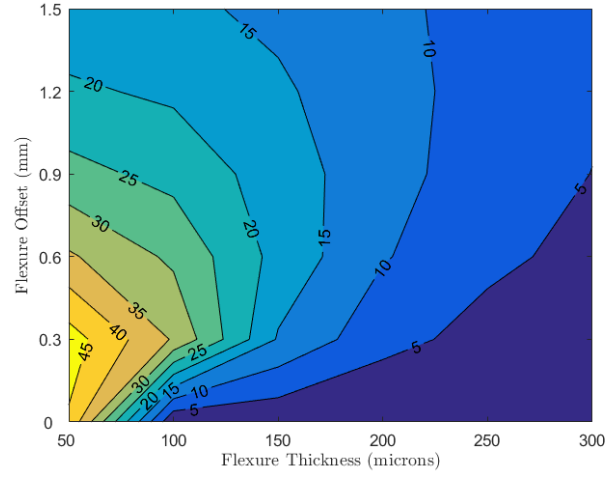


Fig. 3.9 Flexure thickness T_d, T_g vs. flexure offset L_o

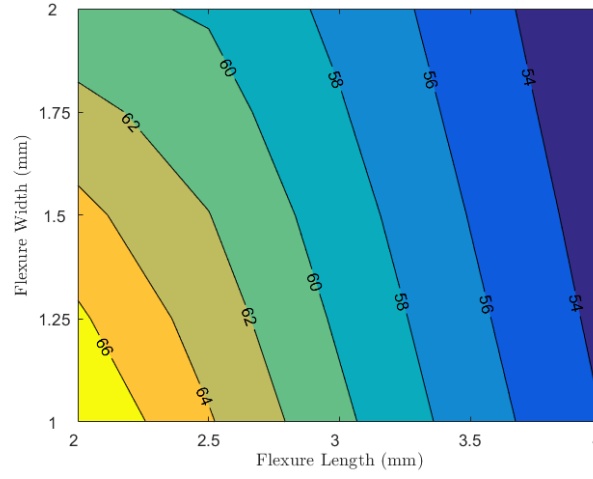


Fig. 3.10 Flexure length L_d, L_g vs. flexure width

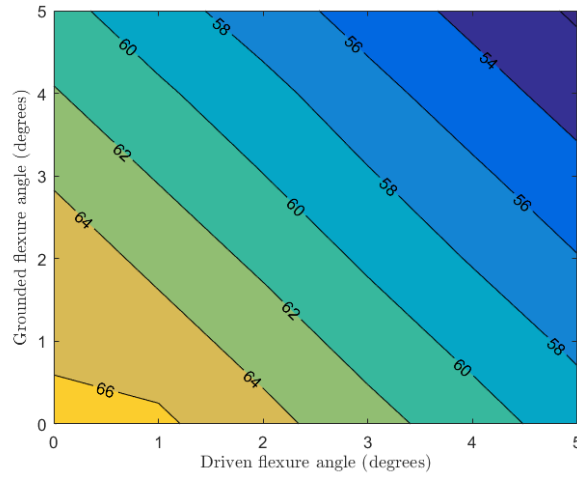


Fig. 3.11 Driven flexure angle θ_d vs. grounded flexure angle θ_g

At this stage, the material for the transmission mechanism is switched to Agilus30 (a flexible polymer), as a rigid material for flexures was determined to be

too fragile at the sub-millimeter scale. Using additive manufacturing limits the material choices to a selection of 3D printable materials, but brings significant time savings for manufacturing compared to fabricating and assembling flexures otherwise. Before moving on to further tests or improvements with the current finite element model in ABAQUS, a simplified model using 2D elements is created to better understand the transmission mechanism performance.

3.2 Simplified finite element model

The design for the simplified finite element model consists of two flexures connected by an offset (shown in Fig. 3.12), where δ is a prescribed displacement along the y -axis, L_d is the length and T_d is the thickness of the driven flexure, L_g is the length and T_g is the thickness of the mechanically grounded flexure, L_o is the length and T_o is the thickness of the offset between flexures, θ_d is the angle offset of the driven flexure, and θ_o is the angle made by the flexure offset when driven and therefore the output quantity of interest. Dimensions not shown in this diagram include the width of the segments which are into the page of the diagram.

To investigate this design, a finite element model with 2-node linear beam elements is programmed in MATLAB. For a 2-node linear beam element with horizontal displacement, vertical displacement, and rotation components at each node, the element stiffness matrix $[K]$ is given as:

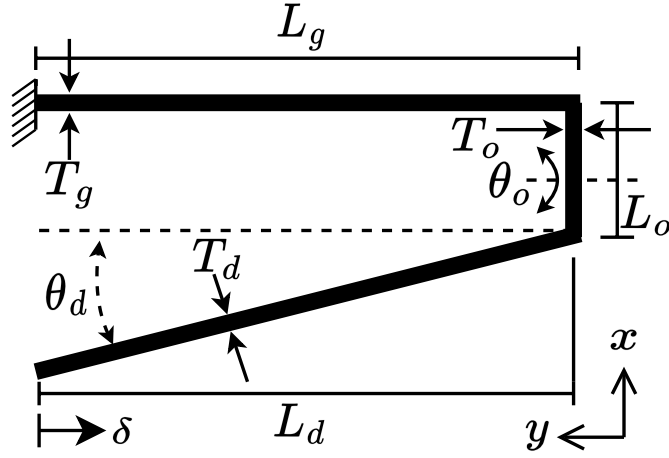


Fig. 3.12 Diagram of the simple finite element model

$$[K] = \frac{E}{L} \begin{bmatrix} k_1 & k_2 & -k_4 & -k_1 & -k_2 & -k_4 \\ & k_3 & k_5 & -k_2 & -k_3 & k_5 \\ & & 4I & k_4 & -k_5 & 2I \\ & & & k_1 & k_2 & k_4 \\ & & & & k_3 & -k_5 \\ sym. & & & & & 4I \end{bmatrix} \quad (3.2)$$

where $k_1 = AC^2 + \frac{12I}{L^2}S^2$, $k_2 = (A - \frac{12I}{L^2})CS$, $k_3 = AS^2 + \frac{12I}{L^2}C^2$, $k_4 = \frac{6I}{L}S$, $k_5 = \frac{6I}{L}C$,

with Young's modulus E , length L , cross-sectional area A , and moment of inertia

I . The terms $C = \cos\theta$ and $S = \sin\theta$, where θ is the angle of the element measured

counterclockwise from the global x -axis. The nodal and force vectors are:

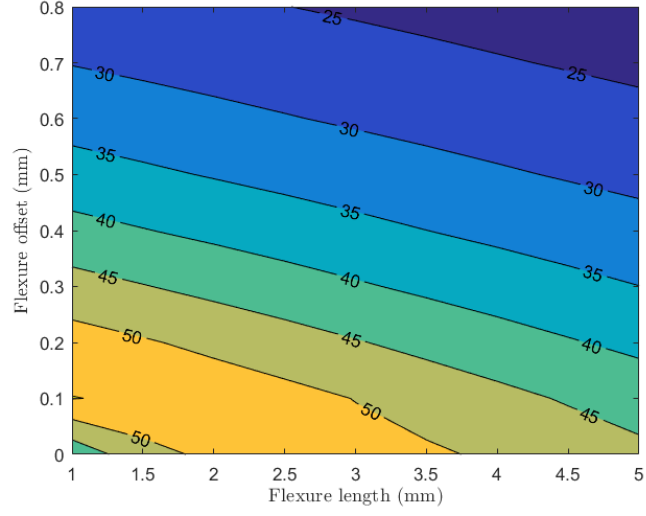
$$\{\delta\} = \begin{Bmatrix} u_1 \\ v_1 \\ \phi_1 \\ \vdots \\ u_i \\ v_i \\ \phi_i \end{Bmatrix}, \{F\} = \begin{Bmatrix} F_{1_x} \\ F_{1_y} \\ M_1 \\ \vdots \\ F_{i_x} \\ F_{i_y} \\ M_i \end{Bmatrix} \quad (3.3)$$

where $\{\delta\}$ is the nodal displacement vector, u_i is the nodal displacement along the x -axis, v_i is the nodal displacement along the y -axis, and ϕ_i is rotation, where i is the number of elements. Similarly, $\{F\}$ is the force vector where F_{i_x} is the nodal force along the x -axis, F_{i_y} is the nodal force along the y -axis, and M_i is the moment. A displacement of -0.45 millimeters is applied to the y displacement component of the end of the driven flexure, while the x displacement component of the end of the driven flexure and the x , y , and rotational components of the end of the grounded flexure are set to zero. Due to the non-zero applied displacement constraint, the boundary conditions are non-homogeneous. The global stiffness matrix is reduced for the variables that have been constrained to zero, and MATLAB is used to solve for the remaining terms in the nodal displacement vector and the vertical force for the applied displacement node. To determine the conversion of linear to rotational motion, the angle made between the start and end of the flexure offset is calculated using the original and deformed nodal positions.

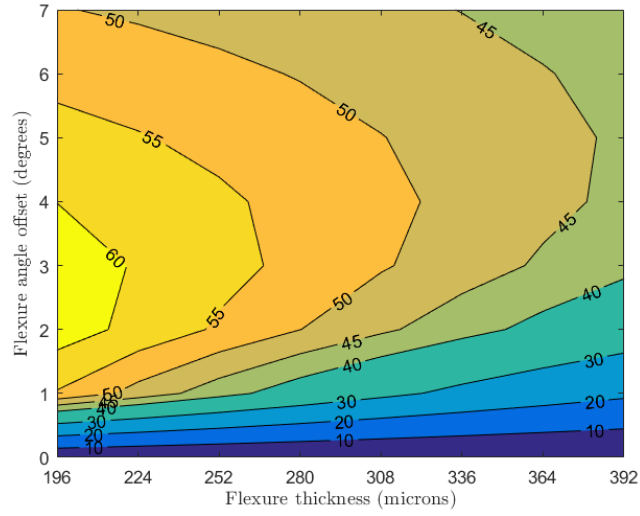
To simplify the analysis and ensure fabrication was feasible, parameters such as length, thickness, and width remain identical between the driven and mechanically

grounded flexures throughout the analyses. Any parameter mismatches, such as differing flexure thicknesses between the grounded and driven flexures, are not tested. The width of all segments is 3 millimeters, and the thickness of the flexure offset is 1 millimeter. For the material properties of Agilus30, a Young's modulus of 3 MPa [123] [124] and an assumed Poisson's ratio of 0.45 is used.

Parametric analysis revealed that the critical parameters for the model are the flexure thicknesses, the offset length between flexures, the angle offset of the driven flexure, and the length of the flexures. The results shown in Fig. 3.13 suggest that rotation is maximized when the flexure thickness, flexure offset, and flexure length is minimized. Due to the prescribed displacement, reducing the flexure length results in increased rotation as the displacement is transmitted more directly to the end of the flexure offset beam. In addition, the ideal value for the angle offset is within an optimal range and is influenced by other factors such as flexure thickness. For a flexure thickness of 196 microns, an angular offset of two to four degrees is optimal, yet for flexure thicknesses of 308 and 396 microns the optimal range is three to five degrees and three to seven degrees, respectively. The results show an extremely low rotation when no flexure angle offset is present. This occurs when both the flexure angle offset and flexure offset equal zero, as the mechanism is locked unless a non-zero flexure offset is present.



(a) Flexure length L_g vs. flexure offset L_o



(b) Flexure thickness T_g, T_d vs. flexure angle offset θ_d

Fig. 3.13 Predicted rotation for varying critical parameters using MATLAB, isolines indicate the rotation results and are displayed in degrees

3.3 Transmission finite element analysis in ABAQUS

After identifying critical parameters with the simplified planar model, the three-dimensional model is revisited in ABAQUS (see Fig. 3.14). To prepare for fabrication, fillets are added at the ends of the flexures, and a horizontal base with a short angled bar is attached near the flexures. Geometric nonlinearity is implemented along with quadratic hexahedral hybrid elements with reduced integration, allowing for greater model accuracy while accounting for nearly incompressible material behavior. Enforced displacement is applied to the side face of the cap connected to the driven flexure, while zero displacement constraints for the grounded flexures are applied to the top of the grounded flexure caps.

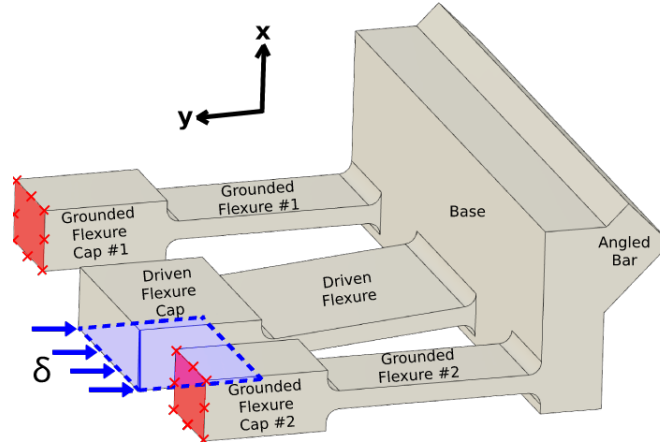
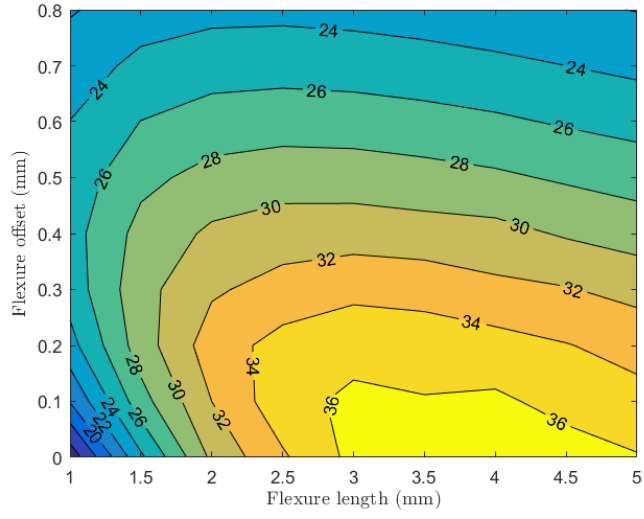
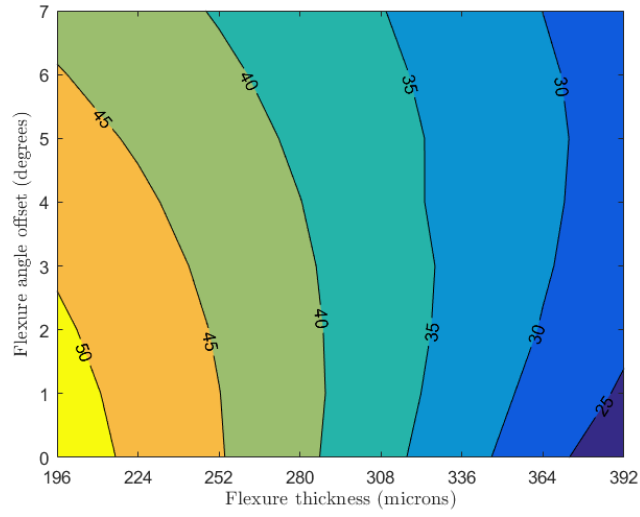


Fig. 3.14 Simplified model used for finite element analysis with the mechanically grounded faces highlighted in red and the displaced face highlighted in blue.

The results of the parametric analysis include key differences when compared to the simplified MATLAB model. The optimal solution for the flexure length is no longer to reduce the length. Rather, the maximum value depends on the flexure offset and is highest between 3 to 5 millimeters when the flexure offset is zero. The ideal angular offset between flexures depends on the flexure thickness, with an ideal angle of under 3 degrees for 196 micron flexure thickness, and a wider range between 2 and 6 degrees for 308 microns and above. Both models suggest that minimizing flexure offset and flexure thickness results in increased rotation.



(a) Flexure length L_g vs. flexure offset L_o



(b) Flexure thickness T_g, T_d vs. flexure angle offset θ_d

Fig. 3.15 Predicted rotation for varying critical parameters using ABAQUS, iso-lines indicate the rotation results and are displayed in degrees

3.4 Finite element model of experimental test model

To verify and test the finite element model, features are added to aid in the collection of data as shown in Fig. 3.16. The caps of the grounded flexures are connected and an offset base is created with mounting holes. The driven flexure cap is enlarged, extending it outward for the connection to the experimental setup. Line markers are added to the faces of the flexure caps to aid in the alignment of the flexures and flexure driver during testing.

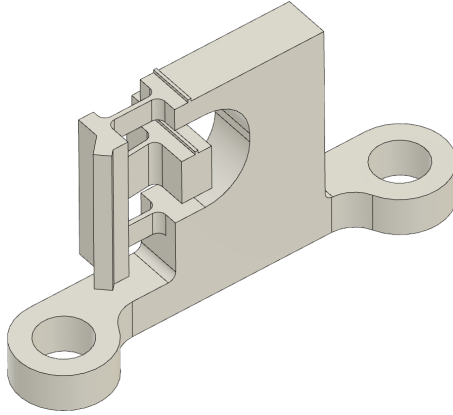
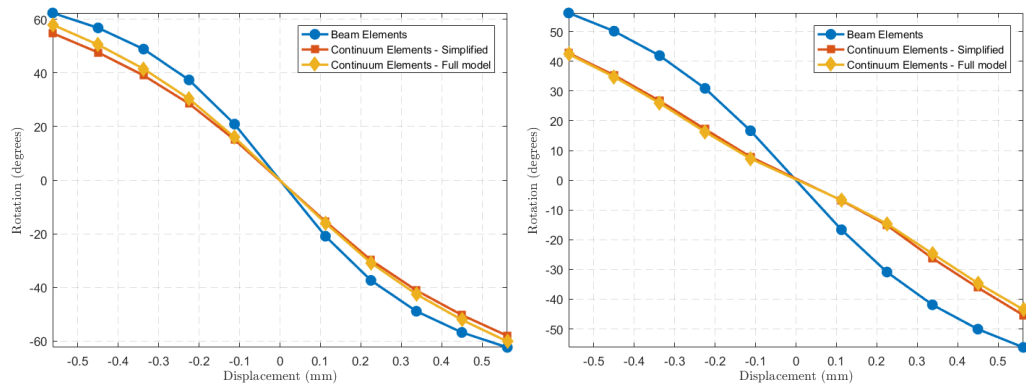


Fig. 3.16 CAD model of the transmission for numerical analysis and testing

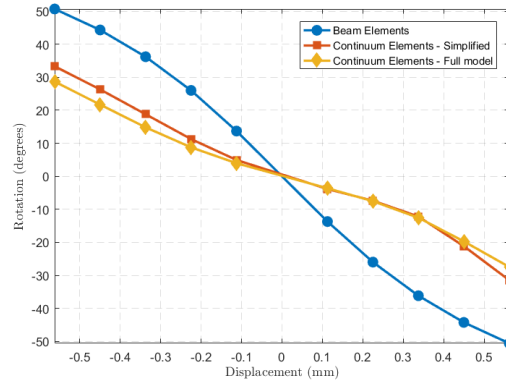
Flexure thicknesses of 196, 308, and 392 microns are chosen for experimental testing. These thicknesses are multiples of 28 microns, which is the layer height resolution for the 3D printer used for fabrication. A flexure offset of zero microns, flexure length of 3.5 millimeters, and flexure angle offset of 5 degrees are used for the remaining critical parameters. A flexure width of 3 millimeters is used for the

driven flexure, and each mechanically grounded flexure has a width of 1.5 millimeters. To determine if the transmission was linear or nonlinear for the displacement interval of interest, the design is driven at 0.25, 0.5, 0.75, 1, and 1.25 times the stated displacement of the piezoelectric bimorph actuator in both directions (or $\pm 0.1125, 0.225, 0.3375, 0.450, 0.5625\text{mm}$), shown in Fig. 3.17. Results for the 196 micron thick flexure thicknesses show an agreement for all finite element models. As the flexure thicknesses increase to 308 and 392 microns, the discrepancy between the analyses grew, with significant losses in rotation between the simplified model and the other two models. The response is less symmetric for negative displacements and the curve in the positive displacement appears to flip. Potential causes for this deviation are the impact of shear, geometric nonlinearity, and material incompressibility in the ABAQUS models.



(a) 196 micron flexure thickness

(b) 308 micron flexure thickness



(c) 392 micron flexure thickness

Fig. 3.17 Comparison of the different finite element models for 196, 308, and 392 micron flexure thicknesses

3.5 Experimental results

3.5.1 Experimental setup

All three designs are fabricated simultaneously, with the print axis aligned perpendicular to the flexure thickness direction. After fabrication, the post-processing of the parts, such as cleaning support material, is performed manually. A fabricated transmission mechanism with 308 micron thick flexures is shown in Fig. 3.18 after post-processing. For experimental testing, the transmission mechanism is connected to an optical table mount as shown in Fig. 3.19. The flexure driver is mounted on a micrometer stage with the external face of the driven flexure cap glued to the end of the flexure driver. The micrometer stage is moved to align visual markers on the transmission mechanism to calibrate the initial position. Once the initial position is determined, the micrometer stage is displaced by $+0.5625\text{mm}$, and then displaced by increments of -0.1125mm until it reaches a displacement of -0.5625mm relative to the initial position. Images are taken from above (seen in Fig. 3.23 and 3.22b) of the initial position and all displaced positions. While the micrometer stage is displaced from $+0.5625\text{mm}$ to -0.5625mm , images are taken when passing the initial position of zero displacement. After all the images are obtained, the results are processed optically by determining the angle made between the neutral and displaced positions of the angled bar.

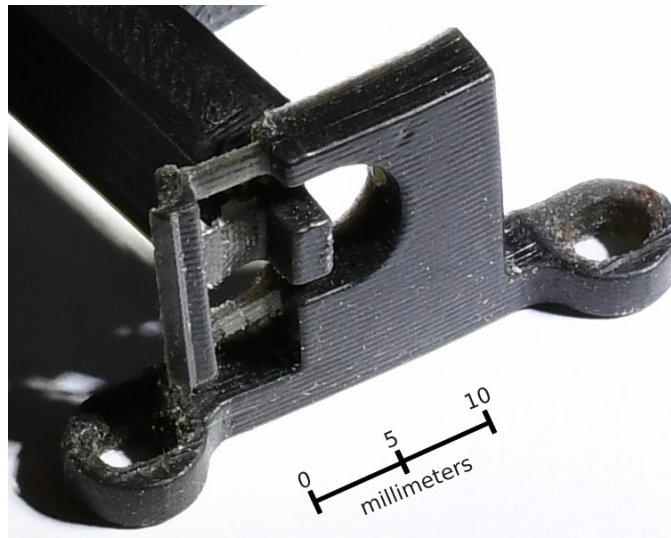


Fig. 3.18 Transmission mechanism with 308 micron flexure thickness fabricated from Agilus30 black

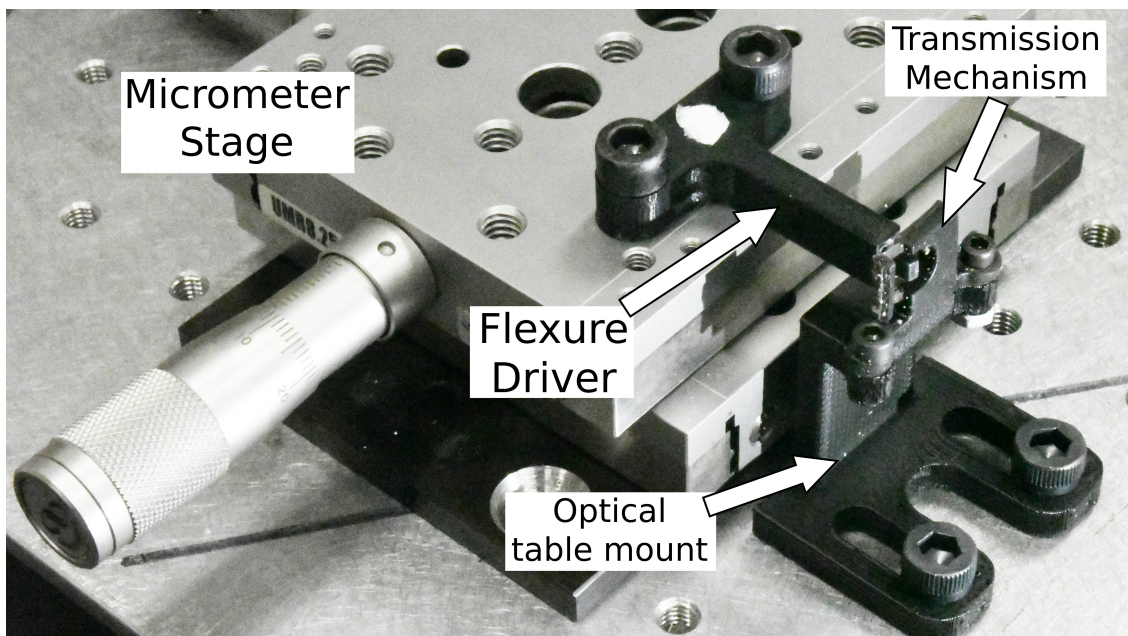


Fig. 3.19 Experimental setup for transmission mechanism testing

3.5.1.1 Rotation measurement error for the transmission mechanism

To determine the rotation of the transmission mechanism, neutral and rotated states are overlaid in MATLAB. A vector is taken along a linear edge in the neutral and rotated states and the angle is determined by taking the dot product of the vectors. To determine the measurement error, 10 measurements are performed (shown in Fig. 3.20a) for the same set of data, and the average of the vectors is taken (shown in Fig. 3.20b). The standard deviation is taken between the average and the data set, resulting in an angle of $45.3294^\circ \pm 0.4152^\circ$, indicating a measurement error of less than one percent.

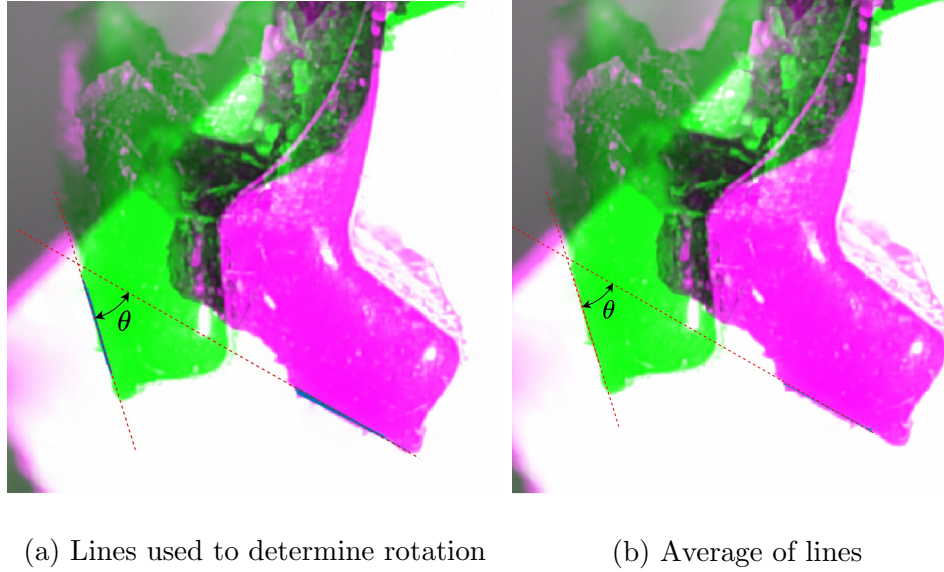
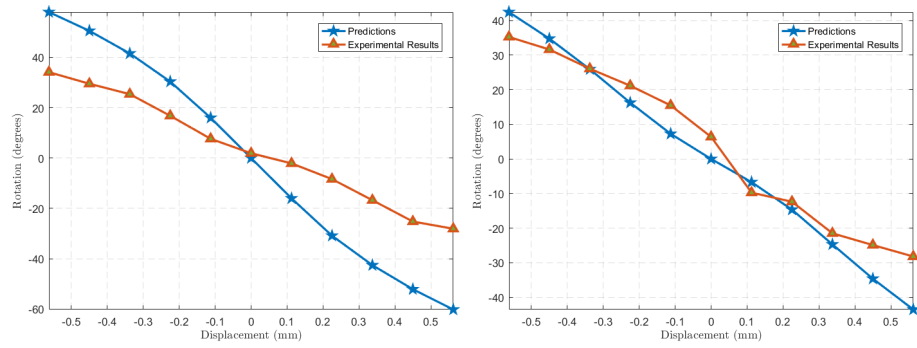


Fig. 3.20 Determining the rotation of the transmission arm, neutral position in purple, rotated position in green

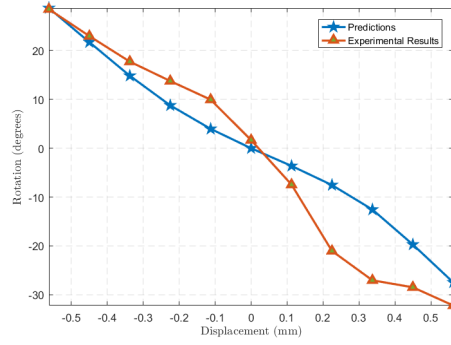
3.5.2 Results and verification of finite element models

The experimental results for 196, 308, and 392 flexure thicknesses are shown in Fig. 3.21 compared against the full numerical model. For the 196 micron flexure thickness, the experimental results have a smaller rotation but are more linear than the prediction. However, the 196 micron thick flexures were extremely difficult to work with due to the difficulties of cleaning such thin flexures without causing damage. The results of the 308 micron flexure thickness show a smaller peak rotation and have less linear results versus predictions, but show the most linear results of the three tested thicknesses. Results of the 392 micron flexure thickness suggest a large divergence in the positive displacement region. The results for all thicknesses show that there is some material hysteresis due to the non-zero rotation that appears when the initial position is revisited as the displacement changes polarity. Due to the scale of the transmission mechanism and the flexible material used for fabrication, calibration of the initial position for the driven flexure is believed to be the predominant source of error in the results. As the entire part is made of flexible material, the mechanical ground moves slightly as the mechanism is driven. This motion is somewhat visible in the overlaid results shown in Fig. 3.22 for a transmission mechanism with a flexure thickness of 308 microns.



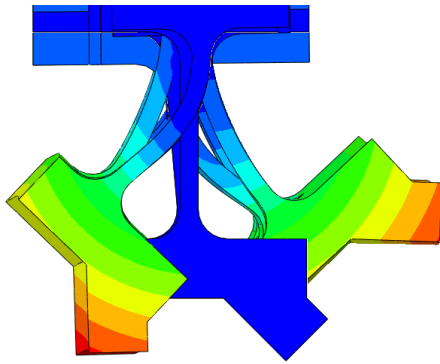
(a) 196 micron flexure thickness

(b) 308 micron flexure thickness



(c) 392 micron flexure thickness

Fig. 3.21 Comparison of numerical and experimental results for 196, 308, and 392 micron flexure thicknesses



(a) Numerical results



(b) Experimental results

Fig. 3.22 Overlay of the numerical and experimental results at the negative, neutral, and positive limits

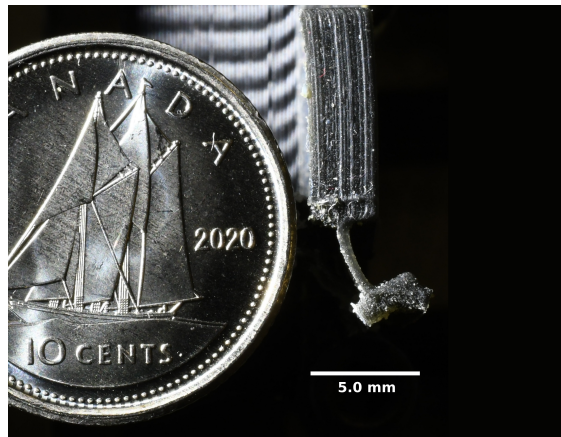


Fig. 3.23 The 3D printed transmission in the actuated position next to a Canadian dime

3.5.3 Revised transmission mechanism and experimental setup

To improve upon the transmission design and prepare the model for use in the parallel robot, the previous design is revised. Specifically, the revised design investigates the impact of a multi-material design, along with changes to reduce errors in the experimental setup.

3.5.3.1 Design changes

Rather than the entire mechanism being composed of flexible Agilus30 material, a new design is produced that uses rigid material to encase or replace the non-flexure components of the transmission (shown in Fig. 3.24). Encasing the flexures within rigid material increases the surface area of the material boundary, reducing the risk of material separation during cleaning. VeroWhite is selected for the rigid material, as it is the default rigid material of choice for PolyJet printers and contrasts with the black Agilus30. VeroWhite has a Young's Modulus of 2.5 GPa and a Poisson's ratio of 0.33, similar to commonly used additive materials such as Polylactic Acid (PLA). Due to the difficulty in calibrating the initial position of the transmission mechanism, the flexure offset between the driven and mechanically grounded flexures is increased to 0.5 millimeters. This accounts for the accuracy of the 3D printer, which has a positional accuracy of 0.2 millimeters. To improve

the experimental setup, the actuation of the mechanism is no longer done using a micrometer stage, and instead is done with a Thorlabs NRT100M linear motorized stage. This allows for precise control of the displacement of the actuator to the mechanism and for the input of waveforms and other trajectories to the system. To reduce assembly error, a supporting beam is added to the transmission to hold the driven flexure in place before it is glued to the flexure driver. In total, four designs are tested, with two of each material type, and two flexure thicknesses (308 and 392 microns).

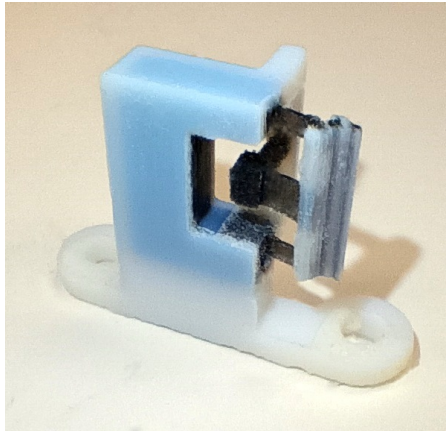


Fig. 3.24 Revised transmission design

For experimental testing of the transmission, it is first connected to a 3D-printed optical table mount. A flexure driver is connected to the motorized stage and positioned to be in contact with the driven flexure of the transmission mechanism. Once the actuator is glued to the driven flexure of the transmission mechanism,

the supporting beam is cut and removed. At this stage (shown in Fig. 3.25), the transmission mechanism is in the neutral position and is ready for testing.

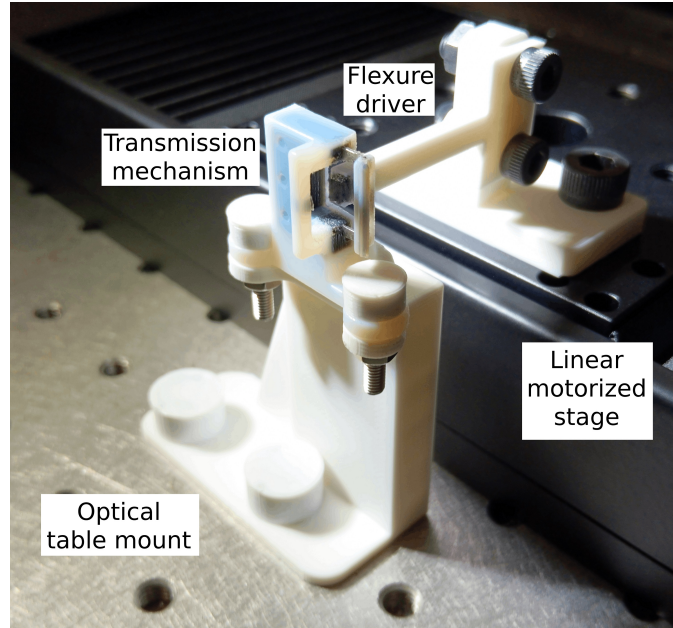


Fig. 3.25 Experimental setup for the revised transmission mechanism

To determine the rotation of the transmission mechanism, two points are marked on the angled bar of the transmission base (shown in Fig. 3.26) and a Chronos 2.1 high-speed camera is positioned above to record the movement as the transmission is actuated, so the recording is synchronized to the motor input signals. Motion tracking software (ProAnalyst) is used to determine the displacement of each point, frame by frame. The rotation is determined using the same method as before, where the vectors between the points at rest and displaced states are compared. Due to the resolution of the video data, small jumps in the results appear as the tracking

software attempts to track points that are only pixels across. To account for this, the smooth function in MATLAB is used, where a moving average filter with 10 points is employed.

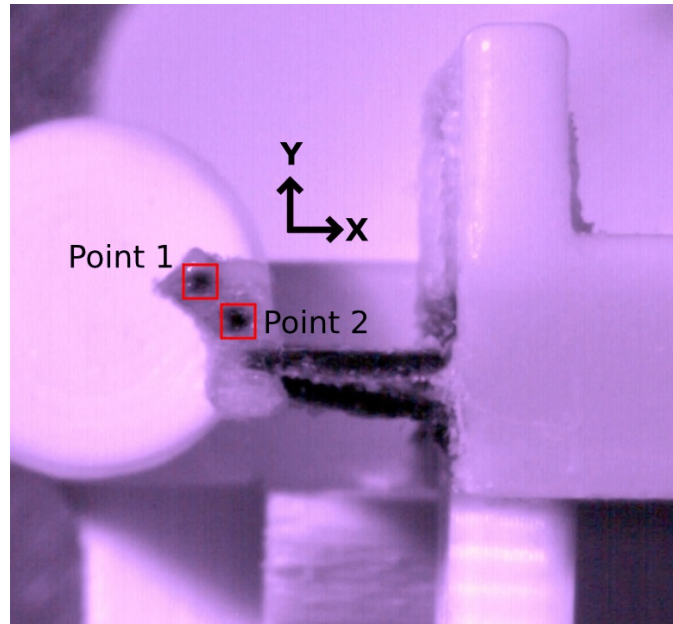


Fig. 3.26 Points for image processing

To actuate the transmission mechanism, the linear motorized stage uses a trapezoidal waveform (shown in Fig. 3.27). Displacement in the positive direction corresponds to a counter-clockwise (CCW) rotation in the transmission mechanism, whereas displacement in the negative direction corresponds to a clockwise (CW) rotation.

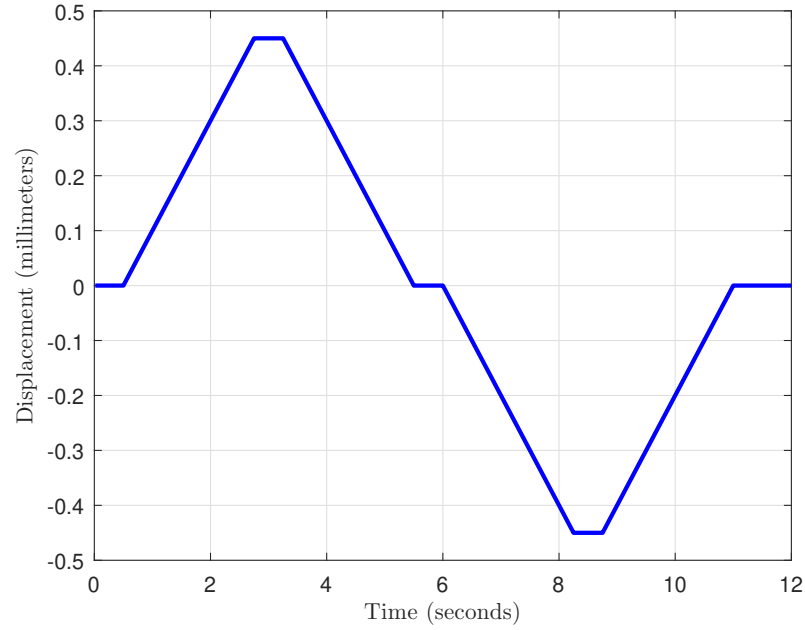
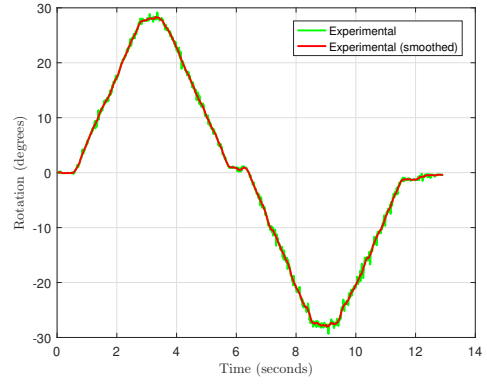
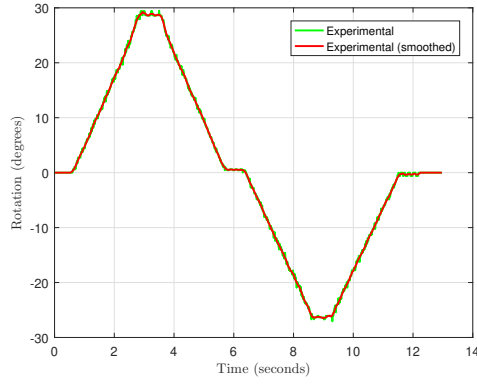


Fig. 3.27 Trapezoidal waveform input to the motorized stage

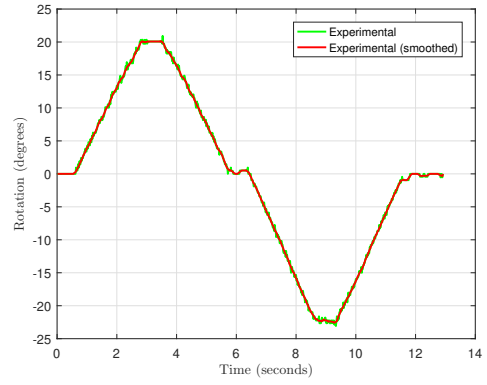
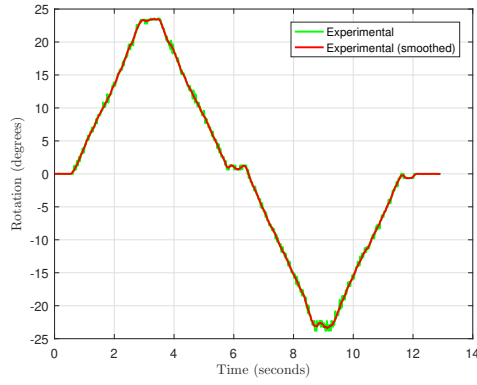
3.5.3.2 Results

Examining the results (plots shown in Fig. 3.29 and Fig. 3.28, numerical results in Table. 3.2), there is a clear difference in the performance of the transmissions that use Agilus30 only for the base and angled bar compared to the transmissions that use both Agilus30 and VeroWhite. The multi-material base has a higher peak rotation and a narrower hysteresis loop compared to the base composed of only Agilus30. Despite predicting a higher rotation for the thinner flexures, the multi-material base performed better using 392 micron thick flexures. The opposite occurs

for the single material base, where the thicker flexures performed slightly worse in the counter-clockwise direction. The simulated results for all transmissions showed similar peak rotations, with only a slight decrease when the flexures are thickened. Due to the increased flexure offset, the simulated peak rotation decreased. However, compared to the original transmission design, the peak rotations of the revised transmissions are close in value. This is likely in part due to the improvements made for the integration and testing of the transmission. If the flexure offset was reduced, there would likely be an increased difference between the results for the 308 and 392 micron thick flexures. Improvements to the positional accuracy during integration would allow for the performance of the transmission mechanism to be improved further.

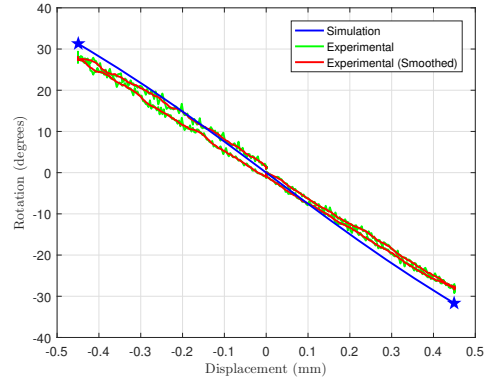
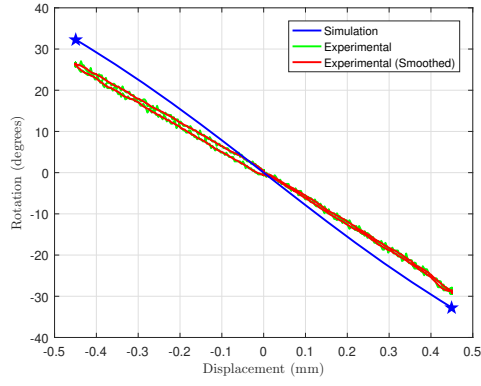


(a) Vero + Agilus base, 308 micron flexures (b) Vero + Agilus base, 392 micron flexures

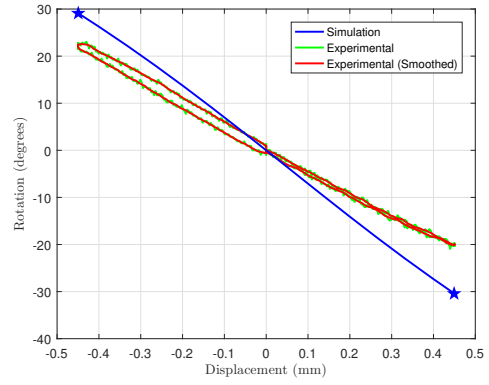
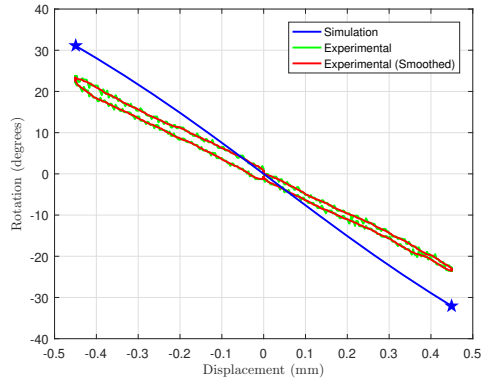


(c) Agilus base, 308 micron flexures (d) Agilus base, 392 micron flexures

Fig. 3.28 Experimental results in time for 308 and 392 micron flexure thicknesses with different bases



(a) Vero + Agilus base, 308 micron flexures (b) Vero + Agilus base, 392 micron flexures



(c) Agilus base, 308 micron flexures

(d) Agilus base, 392 micron flexures

Fig. 3.29 Comparison of simulated and experimental results for 308 and 392 micron flexure thicknesses with different bases

Transmission	Simulated peak rotation [CW/CCW] (degrees)	Experimental peak rotation [CW/CCW] (degrees)	Percent difference [CW/CCW] (%)
Vero + Agilus Base, 308 micron flexure thickness	32.32 / 32.76	26.47 / 29.48	18.1 / 10.01
Vero + Agilus Base, 392 micron flexure thickness	31.29 / 31.71	29.35 / 29.19	6.2 / 8.9
Agilus Base, 308 micron flexure thickness	32.1 / 31.14	23.46 / 23.79	23.6 / 26.92
Agilus Base, 392 micron flexure thickness	30.44 / 29.38	23.08 / 20.93	24.18 / 28.76

Table 3.2 Revised transmission mechanism results

3.6 Conclusion

This chapter covered the design and experimental testing of a transmission mechanism to convert the small linear displacement of a piezoelectric actuator to a large rotational motion. The use of additive manufacturing methods allows for significant design changes to be implemented, such as a multi-material design, without an increase in manufacturing time. After investigating the critical parameters of the mechanism and reviewing experimental results, a flexure thickness of 308 microns is chosen as a starting point for the transmission mechanism flexure thickness to implement in a parallel robot powered by piezoelectric actuators.

4 Parallel robot design

A six-bar parallel robot design is investigated that utilizes the transmission mechanism. Two 3R chains are combined with an end effector to form a six-bar parallel robot as shown in Fig. 4.1. This six-bar parallel robot has three degrees of freedom (movement along the x-axis, movement along the y-axis, and the orientation of the end effector), but only two actuators, making it an underactuated system, where the orientation of the end effector cannot be independently controlled at a given position along x and y . The transmission mechanism is implemented (as a simplification) as an active revolute joint (A_t, A_b), while the joints between rigid links ($l_{1t}, l_{2t}, l_{1b}, l_{2b}$) and the end effector (E) are approximated as passive revolute joints ($P_{1t}, P_{2t}, P_{1b}, P_{2b}$).

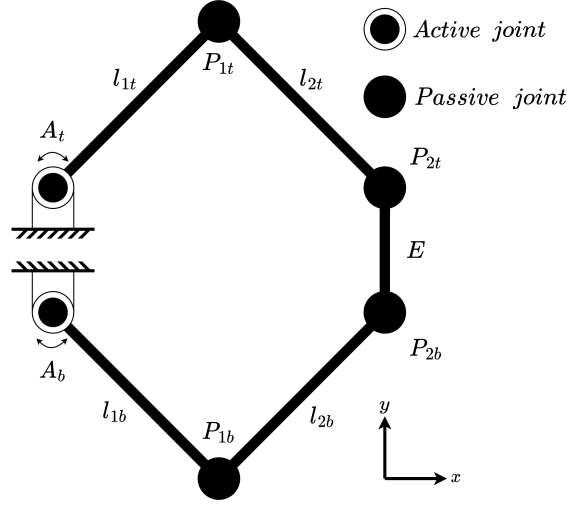


Fig. 4.1 Simplified six-bar parallel robot design

4.1 Kinematic model predictions

4.1.1 Model setup

To investigate the performance of the parallel robot design, Simscape Multibody (a mechanical system simulation environment within Simulink) is used. Each flexure is divided in half through the length with a revolute joint connecting both halves, allowing for the ends of flexures to move as they rotate. To actuate the robot (shown in Fig. 4.2), a rotation is defined between the transmission mechanism flexures (F_{1t} , F_{1b}). Rigid bars (R_{1t} , R_{2t} , R_{1b} , R_{2b}) connect the transmission flexures with the remaining flexures (F_{2t} , F_{3t} , F_{2b} , F_{3b}), and both halves are connected at the end effector (E).

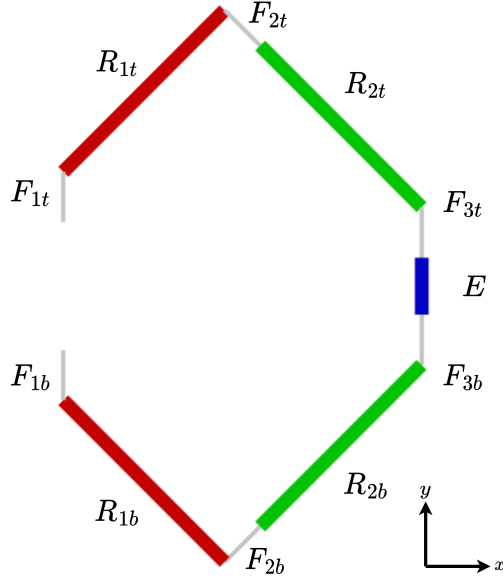


Fig. 4.2 Parallel robot model generated using Simscape Multibody

To quantify the performance of the design, the displacement of the end effector along the x -axis is investigated first. When the rotation of both transmission flexures is equal, the end effector is displaced along the x -axis (shown in Fig. 4.3). The workspace of the parallel robot (δx) is taken as the sum of the extension and retraction displacements.

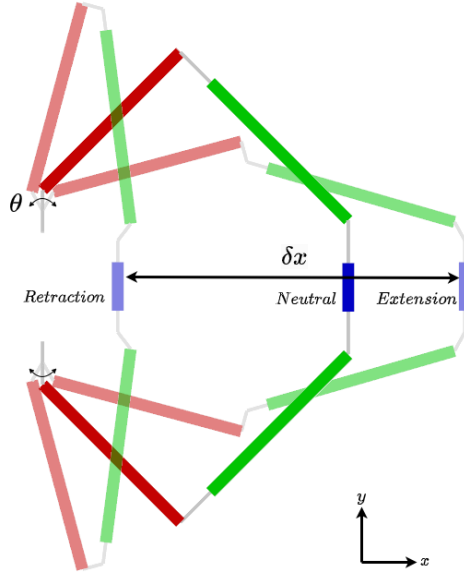


Fig. 4.3 Retraction, neutral, and extension states of the kinematic model

4.1.2 Parametric analysis of the kinematic model

Parametric analysis is performed on the kinematic model to determine the critical parameters to maximize the workspace along the x -axis. The flexure lengths of all flexures are equal, the rigid bar lengths R_{1t} and R_{1b} are equal, and the lengths of R_{2t} and R_{2b} are equal. The rotation for the active joints has an upper bound of 25 degrees, which is taken from the peak rotation of the transmission mechanism. Early results suggest that the lengths of the rigid bars are critical for the x -axis workspace of the robot. However, depending on the lengths chosen for the rigid bars, the model encounters kinematic singularities. This occurs when the robot is

in the retraction state (shown in Fig. 4.4) when four joints of the robot lie along the same line. There are an infinite number of solutions for the angles of the flexures for this position, causing an internal kinematic singularity.

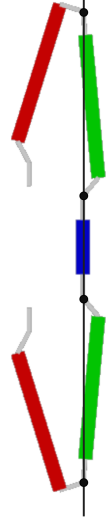


Fig. 4.4 Example of a kinematic singularity that occurs during retraction

After further testing, it appears that the ratio between the length of the rigid bars has an impact on the total workspace, shown in Fig. 4.5. When the rigid bars R_{1t} and R_{1b} are longer than rigid bars R_{2t} and R_{2b} , a kinematic singularity occurs during retraction. When the length of the rigid bars is equal (or close to equal, in some cases), the x -axis workspace is maximized. The x -axis workspace increases as the length of the bars increase, which is to be expected. Other parameters, such as the end effector length and flexure lengths, did not have a significant impact on the horizontal workspace of the parallel robot. The applied rotation in the kinematic

model is not how the rotation would be applied in the real world, as the weight of the rigid bars or the length of the flexures would impact the rotation of the transmission mechanism. The flexures are treated as active joints, but they will experience significant bending in reality and are not truly pin joints. Therefore, the flexures must be more accurately modeled to predict parallel robot performance.

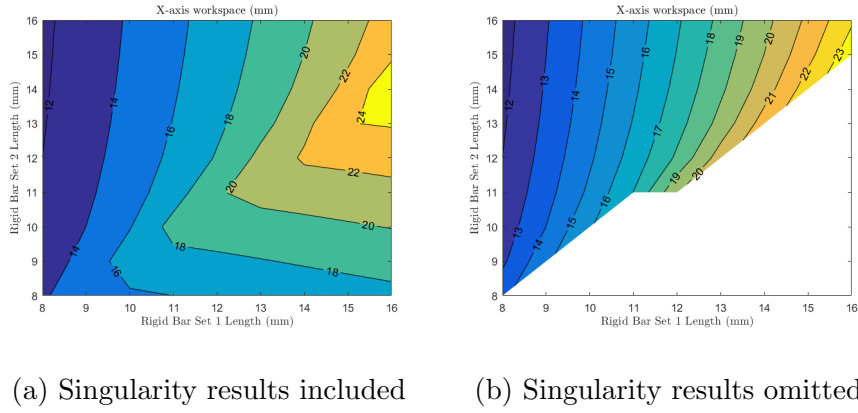


Fig. 4.5 R_{1t} and R_{1b} length vs R_{2t} and R_{2b} length

4.2 Finite element model of the parallel robot

While the rigid body model is useful for initial setup, it is incapable of capturing the bending behavior of the flexure joints and the impact of gravity on the robot. To explore this behavior, a finite element model of the parallel robot is developed. The initial finite element model of the parallel robot (shown in Fig. 4.6) is implemented in ABAQUS to simulate the parallel robot's performance. The first set of rigid

bars connects to the transmission mechanism base which leads to the second set of flexures. The second set of flexures connects to the second set of rigid bars, which leads to the third set of flexures. The third set of flexures connects to the end effector, completing the parallel robot.

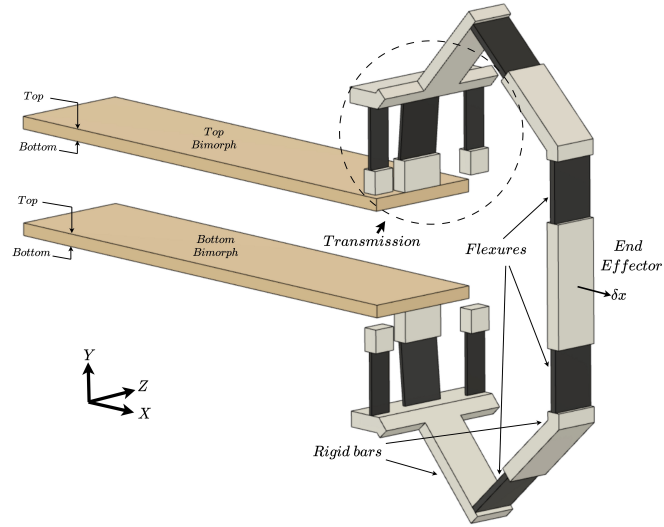


Fig. 4.6 Initial parallel robot design with the piezoelectric bimorphs highlighted in beige, flexures highlighted in black, and the rigid material highlighted in white.

4.2.1 Static deflection

To actuate the robot, the driven flexure of the transmission mechanism is connected to the end of the piezoelectric bimorph. When the bimorph is actuated, it displaces the transmission, which moves the set of rigid bars and flexures connected to it. Combining the movement of both bimorphs and their respective transmission

mechanisms allows for the end effector to be controlled in the x and y axes. The force of gravity is included in the model along the z -axis to realistically model the physical environment.

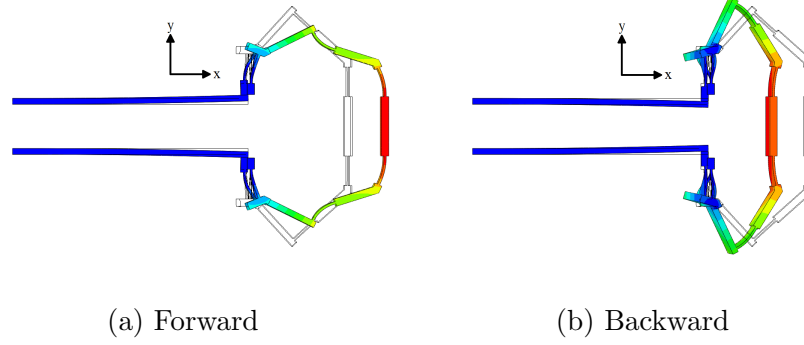


Fig. 4.7 Forward and backward movement of the initial parallel robot with the neutral position overlaid in white

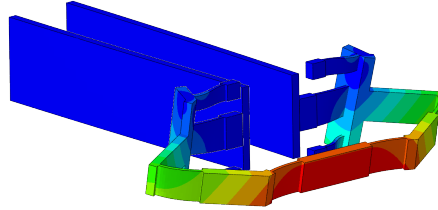


Fig. 4.8 Deflection under gravity of the initial parallel robot

Initial tests (shown in Fig. 4.7) suggest the robot is capable of moving forward and backward similarly to the kinematic model, however, there is a significant displacement along the z -axis of 0.845 millimeters due to gravity (shown in Fig. 4.8).

This is primarily due to the large amount of material used in the rigid links and end effector of the parallel robot. To reduce the mass of the parallel robot, the thickness of the transmission base, rigid links, and end effector is reduced. The length of the end effector is significantly reduced, and the rigid links and flexures after the transmission mechanism are split in half, connected by thin beams at the ends of the flexures (shown in Fig. 4.9).

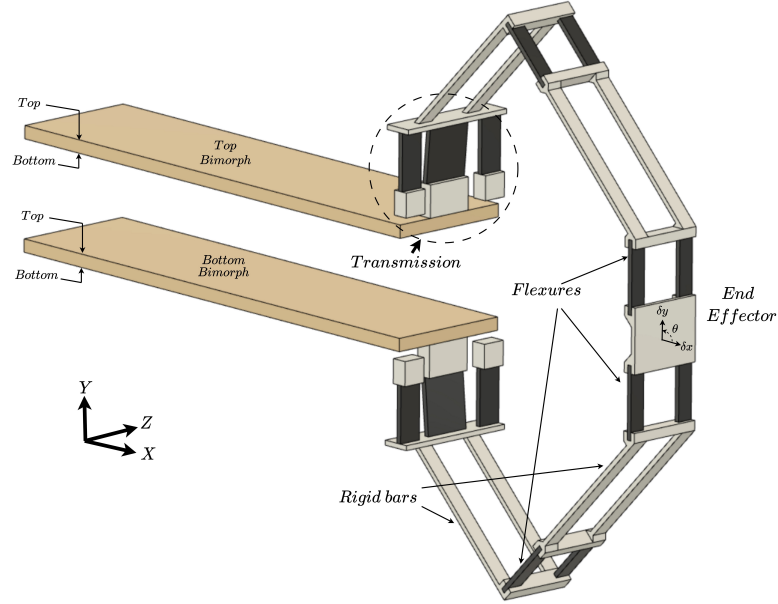


Fig. 4.9 Second parallel robot design with the piezoelectric bimorphs highlighted in beige, flexures highlighted in black, and the rigid material highlighted in white.

4.2.1.1 Eight basic movements

To actuate the parallel robot, each bimorph can be displaced upward, downward, or remain at rest. This results in eight basic inputs for the parallel robot (shown in Table. 4.2) that correspond to a specific direction of movement (shown in Fig. 4.10). When the horizontal displacement (δx), vertical displacement (δy), and end effector angle (θ) is plotted in the $X - Y$ plane (shown in Fig. 4.11) the workspace of the parallel robot appears as a diamond-like shape. The orientation of the end effector is determined by taking the displacement of opposing sides of the end effector and finding the change in angle between the initial and final positions.

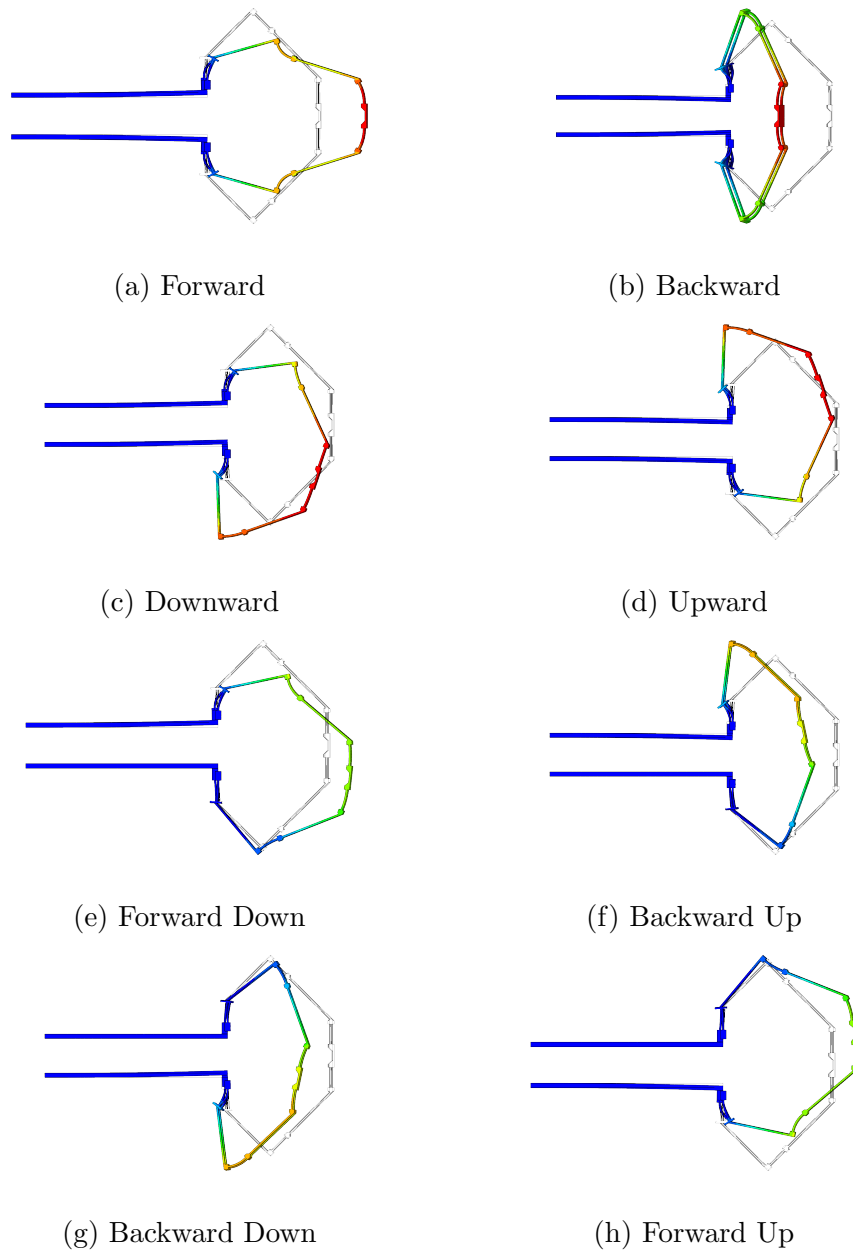


Fig. 4.10 Basic movements of the parallel robot with the neutral position overlaid in white

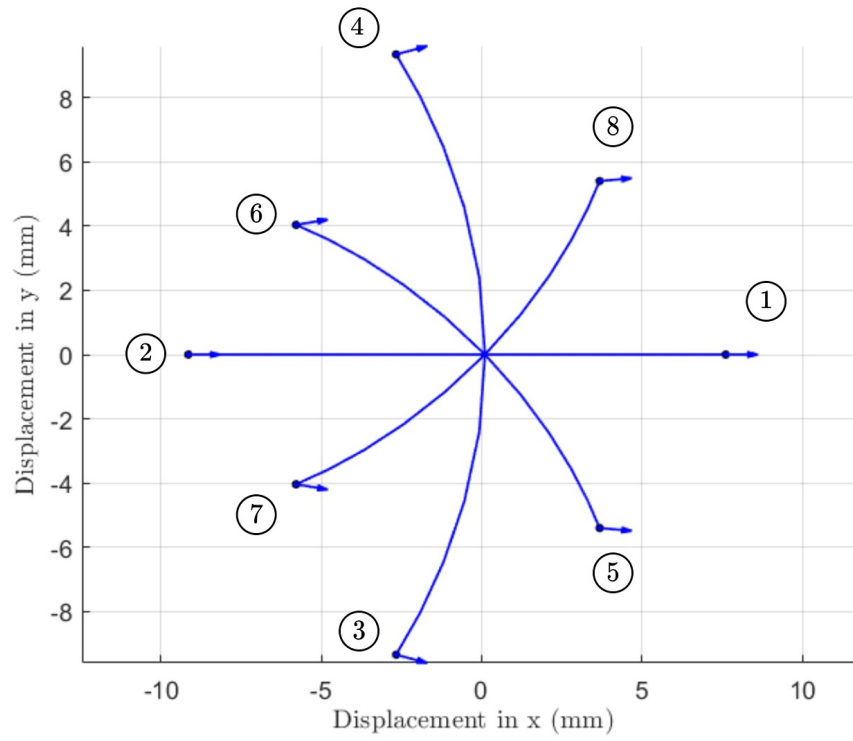


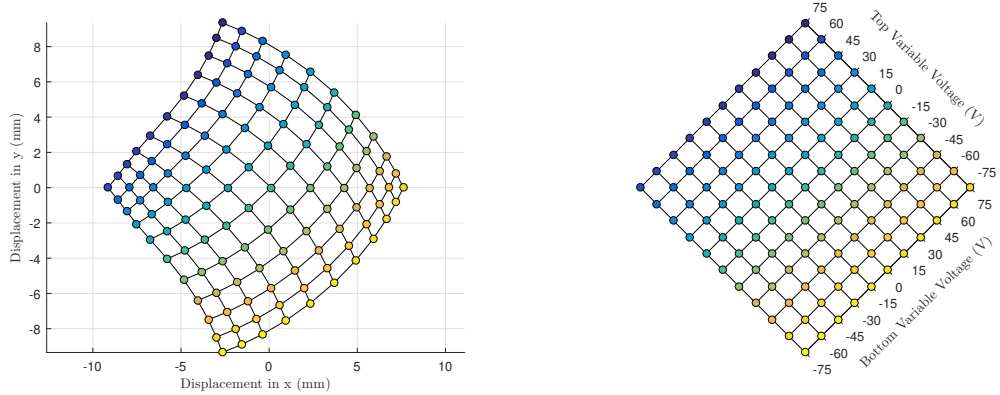
Fig. 4.11 End effector displacement of the 8 basic cases, arrows denote end effector orientation

Case	Movement	$V_{\sim\text{top}}$	$V_{\sim\text{bot}}$	δx (mm)	δy (mm)	θ (deg)
1	Forward (+X)	-75	75	7.606	0	0
2	Backward (-X)	75	-75	-9.14	0	0
3	Down (-Y)	75	75	-2.66	-9.35	-14.8
4	Up (+Y)	-75	-75	-2.66	9.35	14.8
5	Forward Down	75	0	3.68	-5.40	-4.9
6	Backward Up	-75	0	-5.79	4.04	9.5
7	Backward Down	0	75	-5.79	-4.04	-9.5
8	Forward Up	0	-75	3.68	5.40	4.9

Table 4.2 Basic movement cases and results for the parallel robot

4.2.1.2 Workspace determination

To determine the workspace of the parallel robot, the input voltage to each bimorph is varied and the position of the end effector is found, resulting in a plot that relates the input voltage to each bimorph (shown in Fig. 4.12b) and the resulting displacement (shown in Fig. 4.27a). The input voltage to each bimorph is varied from -75 to 75 volts at 15 volt increments, resulting in an 11 by 11 grid of points, with 121 points in total.



(a) Displacement in the XY plane (b) Variable voltages for both bimorphs

Fig. 4.12 Workspace grid

The relationship between the input voltage for the bimorphs and the resulting displacement of the end effector is clearly visible. Points near the origin are spaced out further compared to the points near the edges of the workspace. Movement along the Y -axis is not straight, as there is an arc in the movement as the end effector moves up or down from the origin. Diagonal movements have an arc as well, with different radii when retracting or extending. The retraction distance is greater than the extension distance. The angle of the end effector depends on the position, with the greatest angle occurring at the peak upward and downward movement. There is a horizontal workspace of 16.75 millimeters, a vertical workspace of 18.70 millimeters, and the area of the workspace is 174.50 square millimeters.

4.3 Experimental testing

To prepare the parallel robot for experimental testing, the mechanically grounded flexures are connected and extended into a base with mounting holes (shown in Fig. 4.13) to assist with setup.

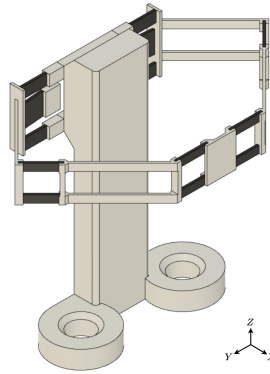


Fig. 4.13 CAD model of the parallel robot

4.3.1 Fabrication and post-processing

Fabrication is performed by an external company using an Objet Connex500 Poly-Jet printer. As the thickness of the flexures is critical to the performance of the transmission, the parallel robot is printed with the flexure thickness direction aligned perpendicular to the plane of the print tray, ensuring the flexures are printed with an accuracy of 28 microns through the thickness. Due to this orientation, there is support material between the end effector and the robot base (shown in Fig. 4.14) that must be removed. As the printed parts are cleaned with handheld

tools, there is a significant challenge in removing support material without permanently damaging the parts. Once the support material is removed the parts are ready for use.

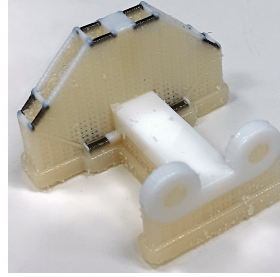


Fig. 4.14 Parallel robot before post-processing

4.3.2 Micrometer-actuated testing

To determine if the parallel robot moves as predicted for given displacements, the parallel robots are first tested using rigid replicas of the bimorphs.

4.3.2.1 Experimental setup

Two imitation bimorphs are fabricated using an Ultimaker S5 3D printer from Tough PLA and connected to a micrometer stage. The tips of the bimorphs are glued to the driven flexure caps of the parallel robot (shown in Fig.4.15). To actuate the parallel robot, the micrometer stages are displaced by $\pm 0.450\text{mm}$, equal to the expected displacement of the bimorphs, moving the driven flexures of the transmission.

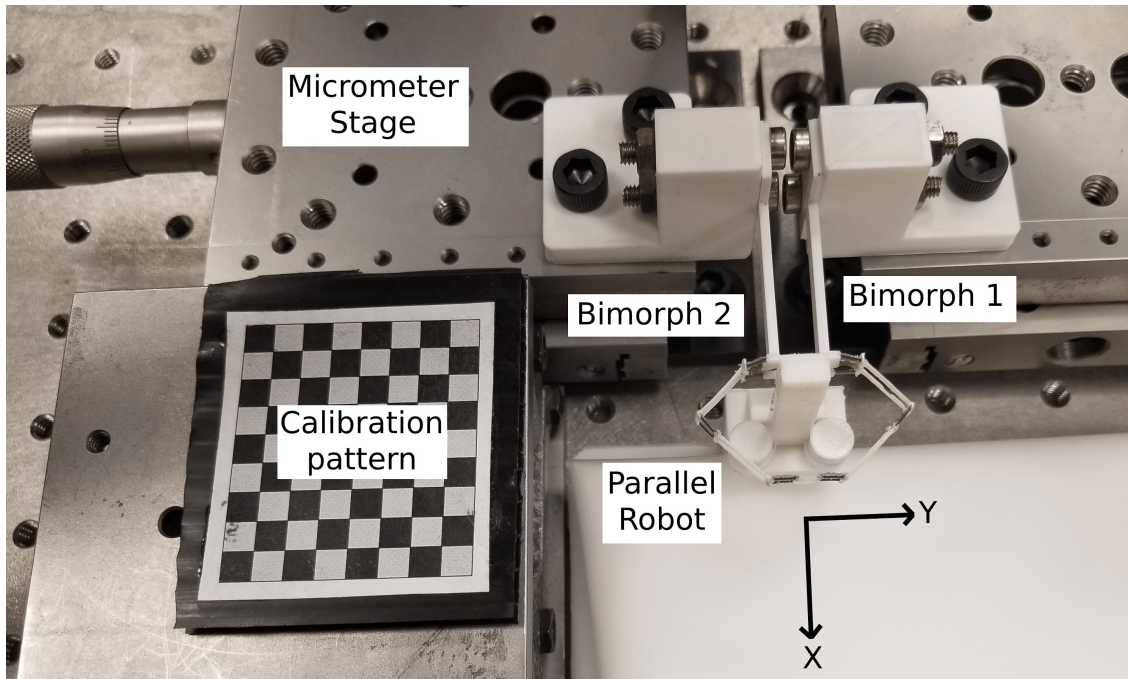


Fig. 4.15 Micrometer setup for the parallel robot

To obtain the displacement results of the parallel robot, a camera is positioned above the parallel robot, recording the movement as the robot is actuated. To extract the displacement of the end effector, a calibration image is placed at the same height as the end effector (shown in Fig.4.16a) containing a checkerboard pattern, where each square has a side length of half a millimeter. The motion tracking software ProAnalyst is used for the motion tracking of the end effector. The checkerboard pattern is used to calibrate the distances within the image, and the flexures encased in the end effector (shown in Fig.4.16b) are used as points for image tracking. The software follows the tracking points as the video is processed

frame by frame, obtaining the displacement of both points at each frame. Using the tracking results, the displacement of the end effector can be obtained by taking the midpoint between points 1 and 2, and the orientation of the end effector can be determined by obtaining the angle between points 1 and 2.

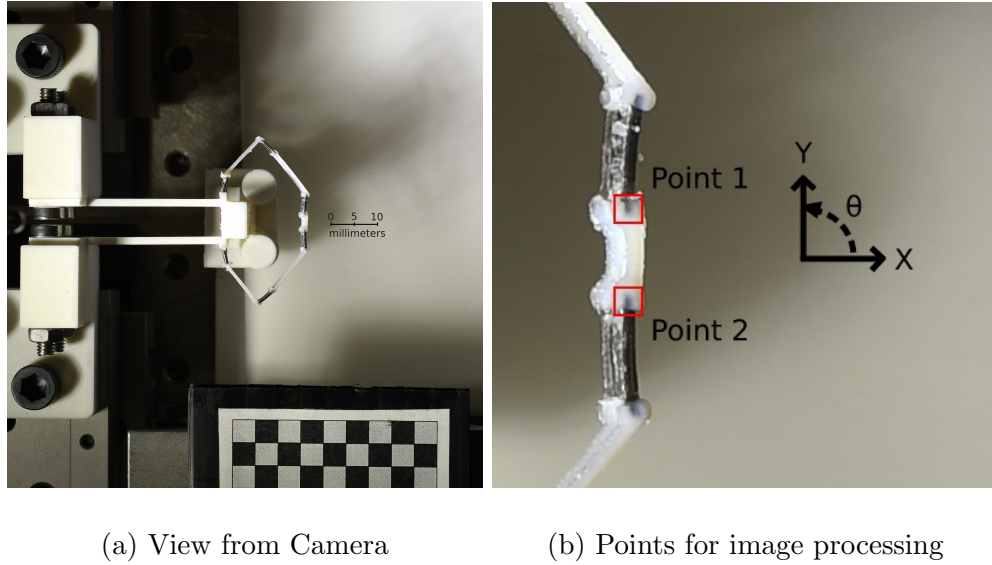


Fig. 4.16 Processing results of parallel robot

4.3.2.2 Results

As predicted, the parallel robot is controllable in eight basic movements (shown in Fig. 4.17) when the bimorphs are displaced.

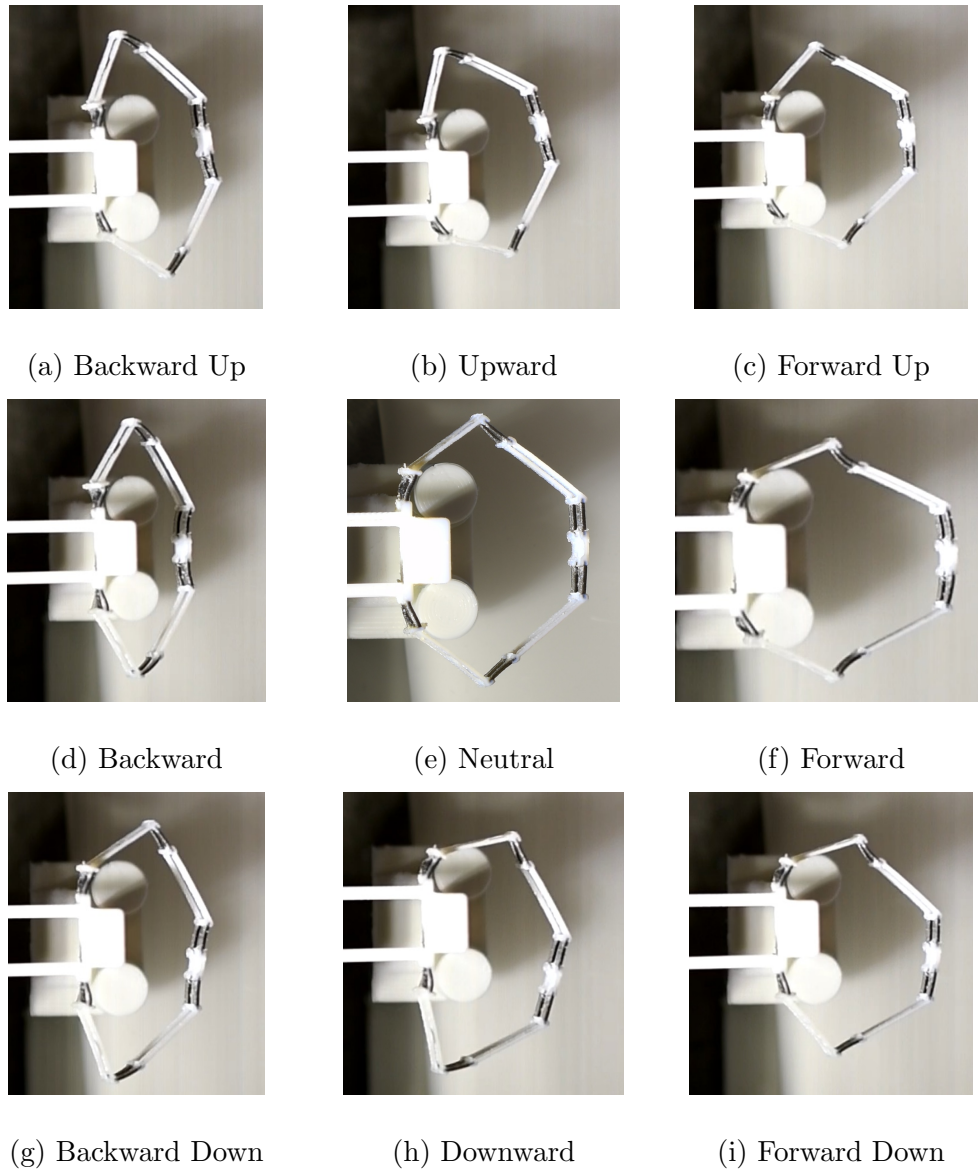


Fig. 4.17 Basic movements of the parallel robot

As the micrometer stage is controlled by hand, only the basic movements and workspace trace trajectory are tested. Examining the initial results (shown in

Fig. 4.18 and Table. 4.4), there is a significant decrease in peak displacement for all basic movements, in particular the forward and backward movements, whereas the upward and downward movements are somewhat close to the peak results. Due to the manual turning of the micrometers, the forward and backward movements aren't linear, as these movements require both micrometers to be turned in opposing directions simultaneously. The diagonal movements, however, only require one micrometer to be controlled at a time and thus are more precise. A hysteresis loop is clearly visible in the diagonal movements, as the trajectory differs when the end effector moves back and forth from the peak diagonal displacements. The diagonal movements follow a slightly different trajectory than predicted, as the arcs do not follow the same paths as predicted. There is a horizontal workspace of 12.14 millimeters, a vertical workspace of 16.31 millimeters, and the area of the workspace is 105.65 square millimeters.

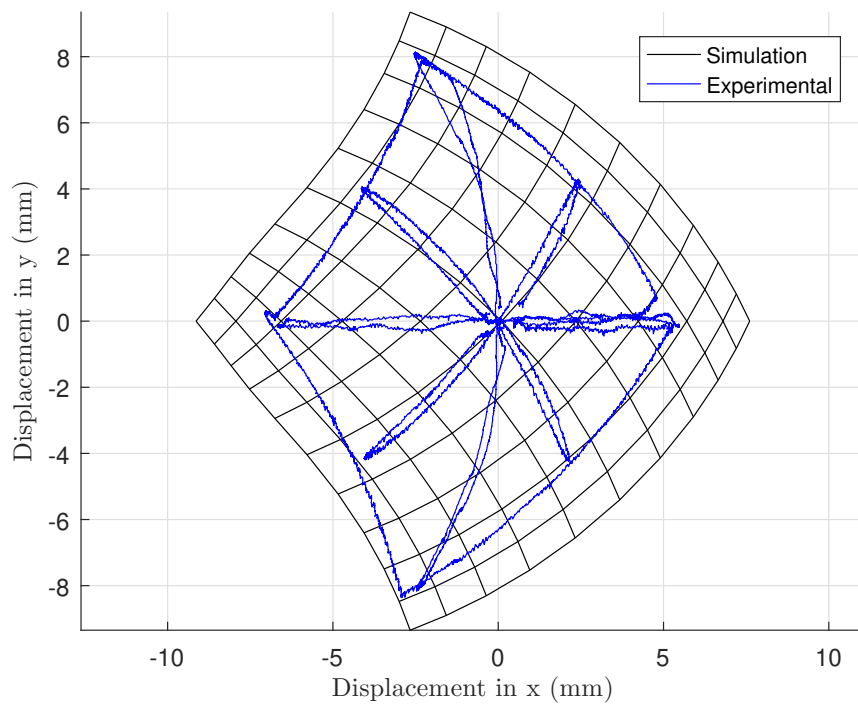


Fig. 4.18 Micrometer test of the parallel robot

Movement	δy_{b1} (mm)	δy_{b2} (mm)	δx (mm)	δy (mm)	θ (deg)
Forward (+X)	0.45	-0.45	5.47	-0.183	-1.7
Backward (-X)	-0.45	0.45	-6.67	-0.176	2.0
Down (-Y)	0.45	0.45	-2.47	-8.18	-19.8
Up (+Y)	-0.45	-0.45	-2.52	8.13	20.4
Forward Down	0.45	0	2.13	-4.25	-7.7
Backward Up	-0.45	0	-4.14	4.02	12.4
Backward Down	0	0.45	-4.06	-4.18	-11.0
Forward Up	0	-0.45	2.44	4.26	7.1

Table 4.4 Basic movements for the parallel robot, actuated by micrometer stage

Due to the small size of the parallel robot, integrating the parallel robot with the bimorphs has many challenges, largely due to the precision required. Aligning the surfaces between the bimorph and the parallel robot before bonding them together with glue is done visually and by hand, likely leading to alignment errors. The micrometer stages are also turned manually when moving the bimorphs to their initial positions, without any indicator of when the proper position is achieved. When actuated manually with a micrometer stage, the parallel robot can be controlled as predicted in two degrees of freedom. However, the workspace of the experimental

model was smaller than predicted, while some deflection of the end effector due to gravity was larger than expected. Hysteresis was also seen for the first time during experimental testing, which was expected but not accounted for as the finite element analysis uses an elastic material model for Agilus30, a rubber-like material.

4.4 Final parallel robot

After the micrometer actuated tests, the design is revised to address issues identified during initial experimental testing to improve the performance of the robot. To reduce the deflection due to gravity, the design was optimized manually, with the intention of reducing the deflection due to gravity to less than 5% of the horizontal workspace of the robot, while maintaining a horizontal workspace of at least 15 millimeters (resulting in a maximum deflection due to gravity of 0.75 millimeters).

4.4.1 Design changes

The final design of the parallel robot (shown in Fig. 4.20 and Fig. 4.21) encases the ends of all flexures and increases the thickness of the rigid arms, which were the most common feature to break while cleaning. The base has an increased thickness and width to reduce motion when testing the robot at higher frequencies, and the mechanically grounded flexures are connected at a different angle to improve clearance near the driven flexures for the bimorphs. The flexures in the transmission

mechanism have an increased thickness of 504 microns to reduce the deflection due to gravity that was seen at the end effector. The width of the mechanically grounded flexures is doubled as well. By increasing these two parameters, the deflection due to gravity should be reduced, which is explained by the area moment of inertia

$$I = \frac{bh^3}{12} \quad (4.1)$$

where b is the width of the flexures, and h is the thickness of the flexures. The mechanically grounded flexures area moment of inertia increases by a factor of 9, while the driven flexures area moment of inertia increases by a factor of 4.5. The predicted deflection (shown in Fig. 4.19) due to gravity is 0.192 millimeters, a significant reduction despite an increase in the mass of the rigid bars.

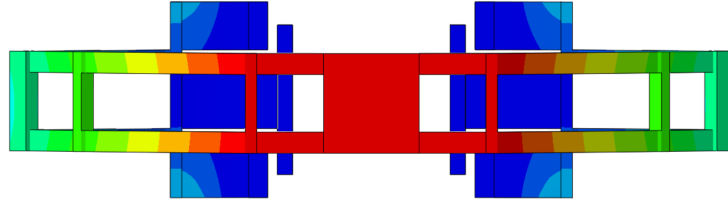


Fig. 4.19 Deflection under gravity for the final parallel robot design.

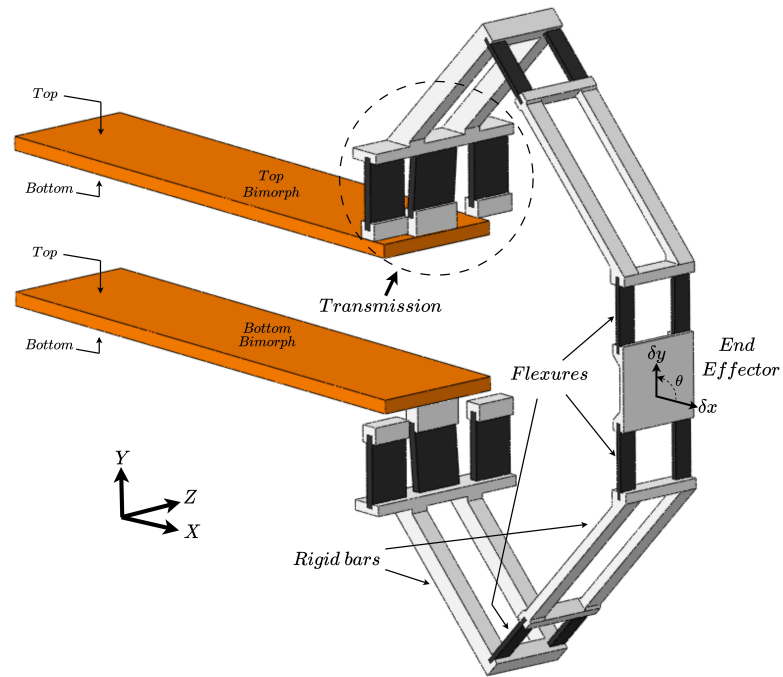


Fig. 4.20 Final parallel robot with the piezoelectric bimorphs highlighted in orange, flexures highlighted in black, and the rigid material highlighted in white.

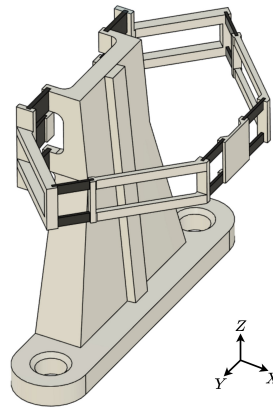


Fig. 4.21 CAD model of the final parallel robot

4.4.2 Finite element model

The finite element model for the final parallel robot is implemented in ABAQUS similarly to the previous model. Simulations are performed to predict performance at high frequencies and near resonance.

4.4.2.1 Static deflection

The displacements for the basic movements for the final parallel robot (shown in Fig. 4.22, values in Table. 4.6) are similar to the previous parallel robot. The final parallel robot has a less square workspace (shown in Fig. 4.23a). There is a larger horizontal workspace, increasing from 16.75 mm to 19.0 mm, while the vertical workspace decreases from 18.70 mm to 15.54 mm. The area of the workspace is 145.53 square millimeters.

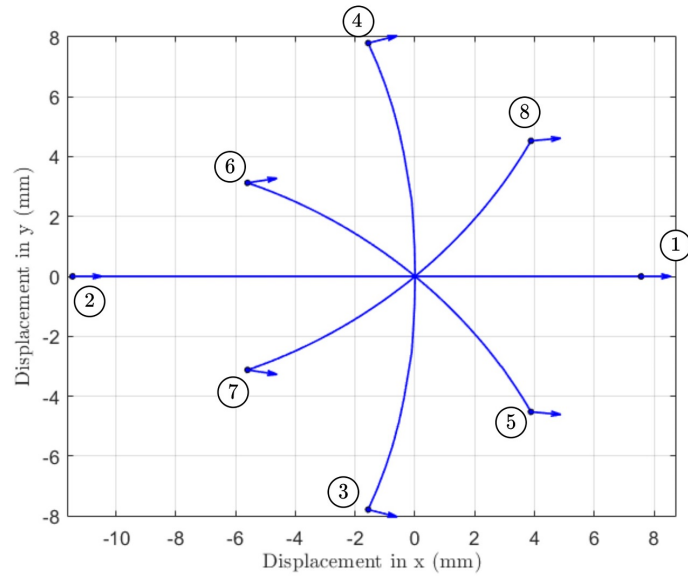
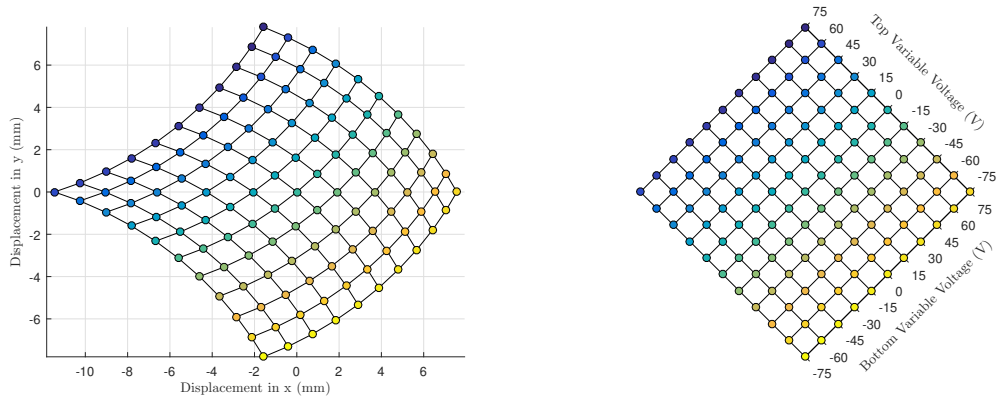


Fig. 4.22 End effector displacement for 8 basic movements, arrows denote end effector orientation



(a) Displacement in the XY plane (b) Variable voltages for both bimorphs

Fig. 4.23 Workspace grid

Case	Movement	$V_{\sim\text{top}}$	$V_{\sim\text{bot}}$	δx (mm)	δy (mm)	θ (deg)
1	Forward (+X)	-75	75	7.56	0	0
2	Backward (-X)	75	-75	-11.44	0	0
3	Down (-Y)	-75	-75	-1.56	-7.77	-14.1
4	Up (+Y)	75	75	-1.56	7.77	14.1
5	Forward Down	-75	0	3.88	-4.52	-5.03
6	Backward Up	75	0	-5.60	3.12	8.62
7	Backward Down	0	-75	-5.60	-3.12	-8.62
8	Forward Up	0	75	3.88	4.52	5.03

Table 4.6 Basic movement cases and results for the parallel robot

4.4.2.2 Resonance frequencies

The resonance frequencies (shown in Fig. 4.24) are determined in ABAQUS, using the same method for the bimorph resonance frequencies. The first and third modes (shown in Fig. 4.24a and Fig. 4.24c, respectively) occur as the end effector moves up or down, along the Y -axis. The second and fourth modes (shown in Fig. 4.24b and Fig. 4.24d, respectively) correspond to movement along the X -axis, where the end effector moves forward or backward.

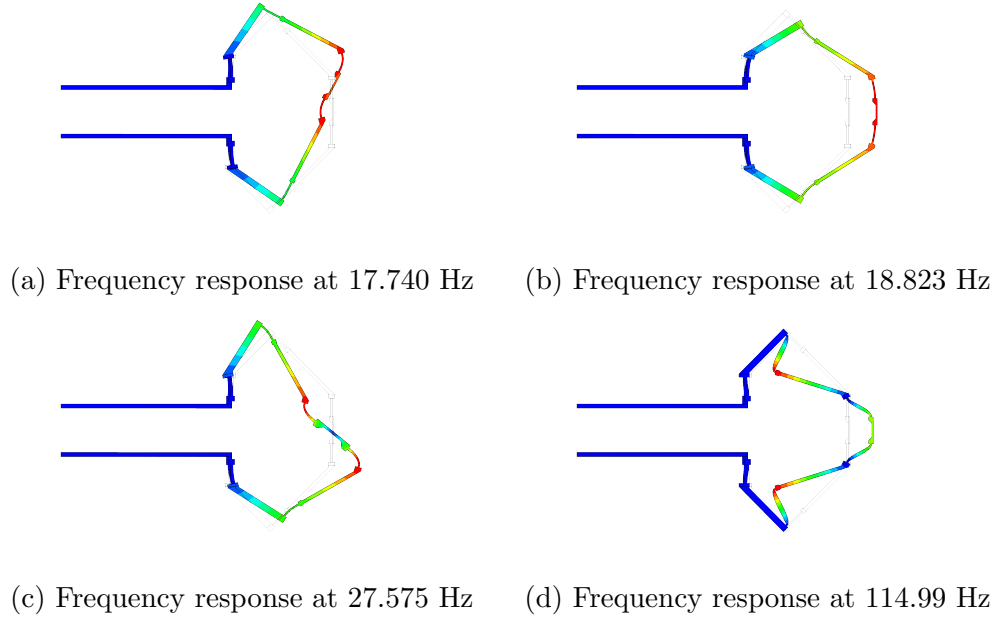


Fig. 4.24 Resonant frequencies of the final parallel robot

4.4.2.3 Dynamic analysis

Trajectories are generated to determine if the parallel robot can be controlled within its workspace. Three different trajectories are simulated at 0.5, 2, 5, and 10 Hz. To estimate the Rayleigh damping parameters for the Agilus30 and VeroWhite, the parallel robot is made to retract rapidly, and the displacement of the end-effector along the x -axis is taken. The damping parameters are then tweaked until critical damping behavior is observed. This results in a mass-proportional damping coefficient of 100 for Agilus30 and VeroWhite.

4.4.2.4 Trajectory 1: Workspace trace

To trace out the workspace of the parallel robot (shown in Fig. 4.25a), the robot first extends slowly outward to the forward state. At this point the trace begins, moving to the upward state, followed by the backward and downward states. Next, it returns to the forward state, then slowly returns to the origin. The input voltages for this trajectory are simple (shown in Fig. 4.25b), as the transition for most segments (such as from the forward state to the upward state) requires only one bimorph voltage input to change at a time.

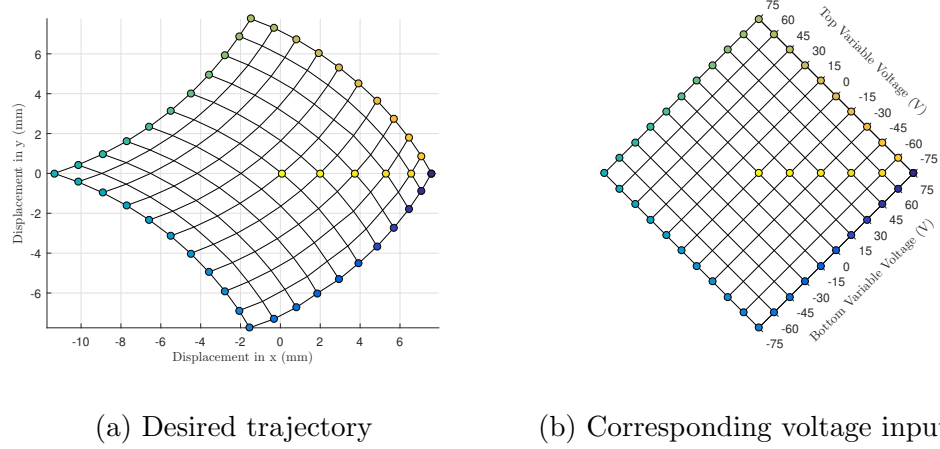


Fig. 4.25 Workspace Grid Trace

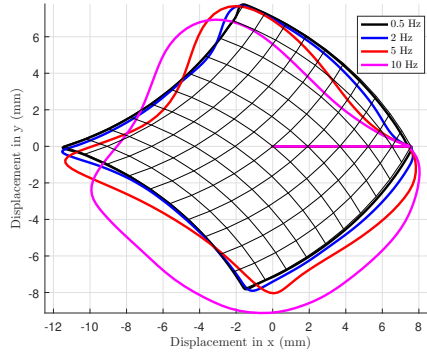


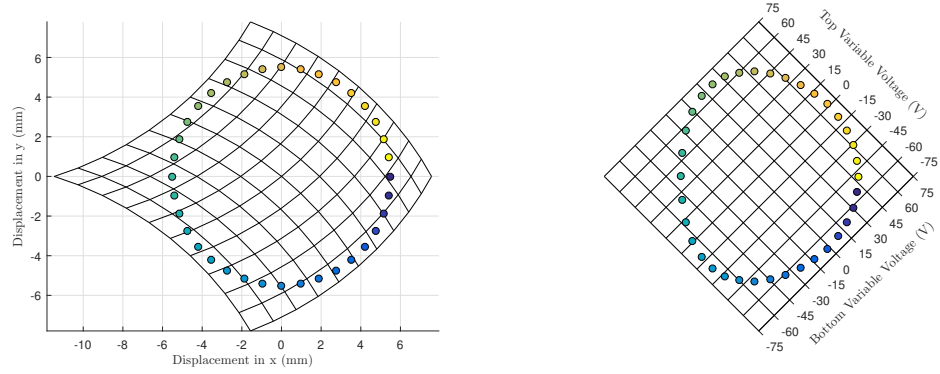
Fig. 4.26 High-frequency results for the workspace trace

Above 5 Hz, the performance of the robot is poor (shown in Fig. 4.26), as the workspace trace moves further and further outward.

4.4.2.5 Trajectory 2: Circle

For a given point within the workspace of the parallel robot, there should be a corresponding combination of input voltages. To plot a circular trajectory within the workspace of the parallel robot (shown in Fig. 4.27a), the required input voltages for that trajectory must be determined. Using the *fitgeotrans()* function in MATLAB a geometric transformation is defined between the input voltages of the system and corresponding displacements. With this transformation, a circular pattern of points with a radius of 5.5 millimeters is converted to the input voltages (shown in Fig. 4.27b). To generate a circular trajectory, the parallel robot first extends to the start of the circle, then a linear path is generated between each of the points in the

circle. Finally, the robot returns to the origin once the circle is completed.



(a) Desired trajectory within workspace (b) Corresponding voltage inputs

Fig. 4.27 Workspace Grid Circle

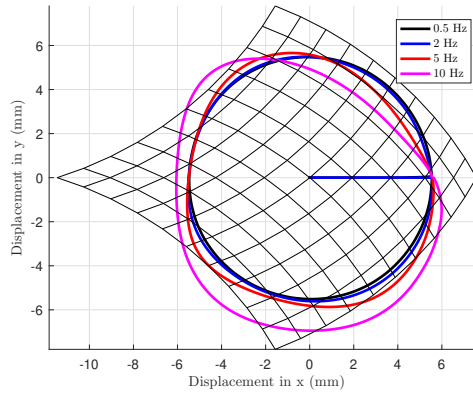
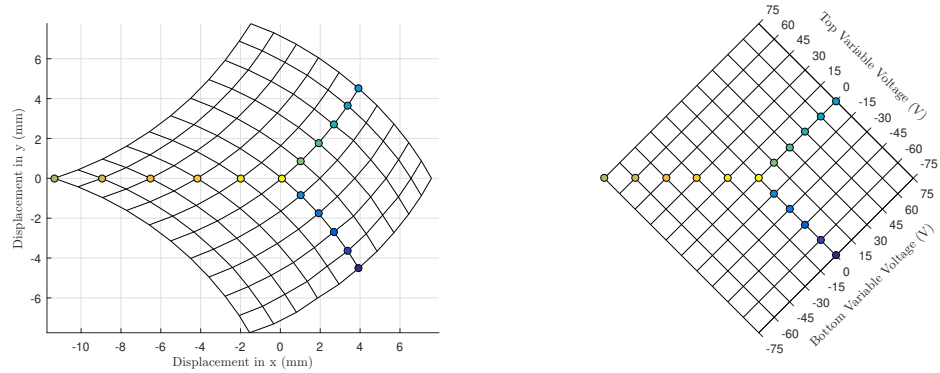


Fig. 4.28 High-frequency results for a circle

Above 2 Hz the displacement is no longer circular, with the displacement taking on an increasingly deformed shape.

4.4.2.6 Trajectory 3: The letter Y

Similar to the first trajectory, tracing the letter Y (shown in Fig. 4.29a) is simple, as the movements required are all basic movements of the robot. The robot moves from the origin to the retracted state, then returns to the origin. Next, it moves to the forward-up diagonal state and returns to the origin once again. Finally, it moves to the forward-down diagonal state and then returns to the origin.



(a) Desired trajectory within workspace (b) Corresponding voltage inputs

Fig. 4.29 Workspace Grid Letter Y

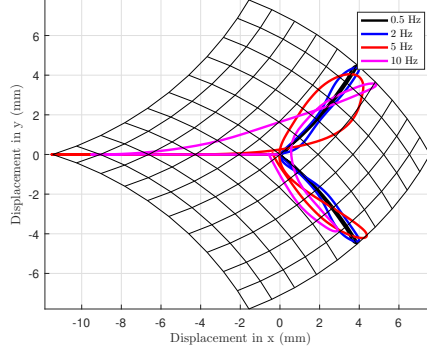


Fig. 4.30 High-frequency results for the letter Y

Above 2 Hz, the trajectory moves off course as it retracts from the diagonal directions (shown in Fig. 4.30), with significant drift at 5 and 10 Hz.

The finite element results for the final parallel robot model suggest the parallel robot is capable of tracing various trajectories using the end effector. Simulations suggest the robot has difficulty controlling the end effector position at frequencies above 5 Hz. To validate these simulations, the final parallel robot is tested experimentally with the piezoelectric bimorphs.

4.4.3 Experimental setup

The process to integrate the piezoelectric bimorphs with the parallel robot is similar to the previous setup. Each Thorlabs PB4NB2W bimorph is mounted on a micrometer stage (shown in Fig. 4.31), while the robot is mounted to a 3D printed mount, which is itself mounted to the optical table. A rectangular section of non-

conductive material is glued to the end of each bimorph, which is then glued to a connector for the parallel robot (which is shaped to cover the driven flexure cap of the transmission). The micrometer stage is used to adjust the position of the bimorphs as the bimorph connectors are glued to the robot transmissions. The bimorphs are then positioned so that the parallel robot is in a neutral position.

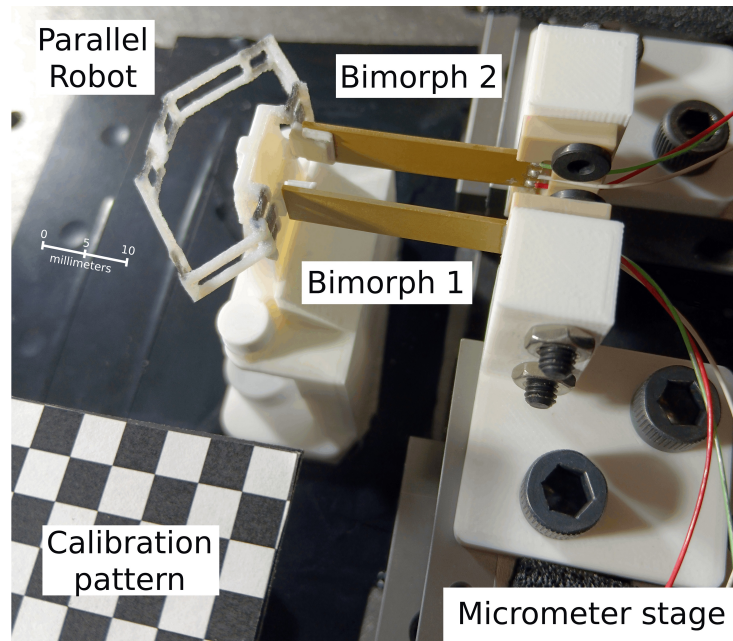


Fig. 4.31 Experimental setup for the parallel robot and piezoelectric bimorphs

To actuate the bimorphs, the wiring is similar to the experimental testing of the bimorphs. The low-bias and high-bias voltage inputs for each bimorph are connected to the ground and high-voltage outputs of the amplifier (as shown in Fig. 4.32. The first output of the amplifier is connected to the variable voltage of

the first bimorph, and the second output is connected to the variable voltage of the second bimorph. Both of these outputs from the amplifier are controlled by the signal from Simulink using a Speedgoat Performance Real-Time machine IO133 module. A Chronos 2.1 high-speed camera is positioned above the parallel robot to record the movement and ProAnalyst was used to perform motion tracking to determine the displacement of the end effector.

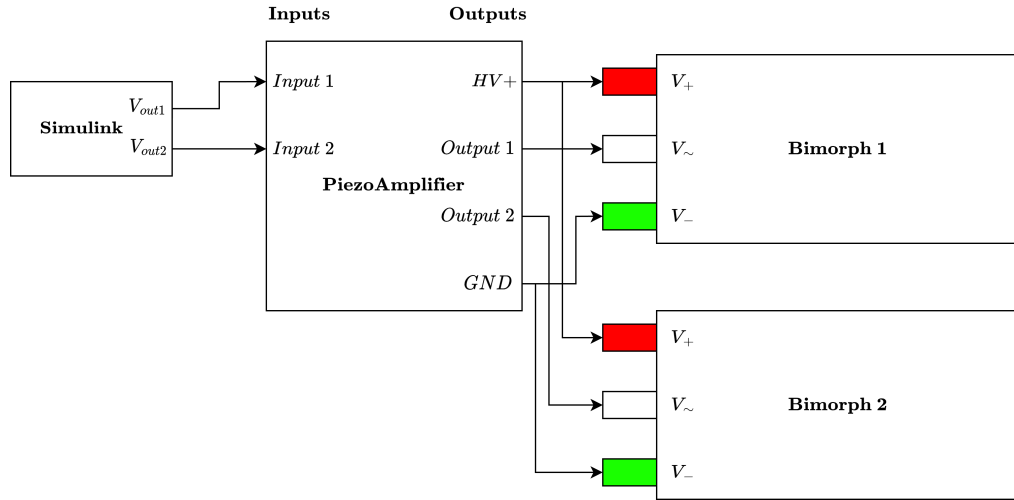


Fig. 4.32 Wiring Diagram for actuating the parallel robot

4.4.4 Experimental results

Similar to before, the parallel robot can be controlled using bimorphs to achieve eight basic movements (shown in Fig. 4.33).

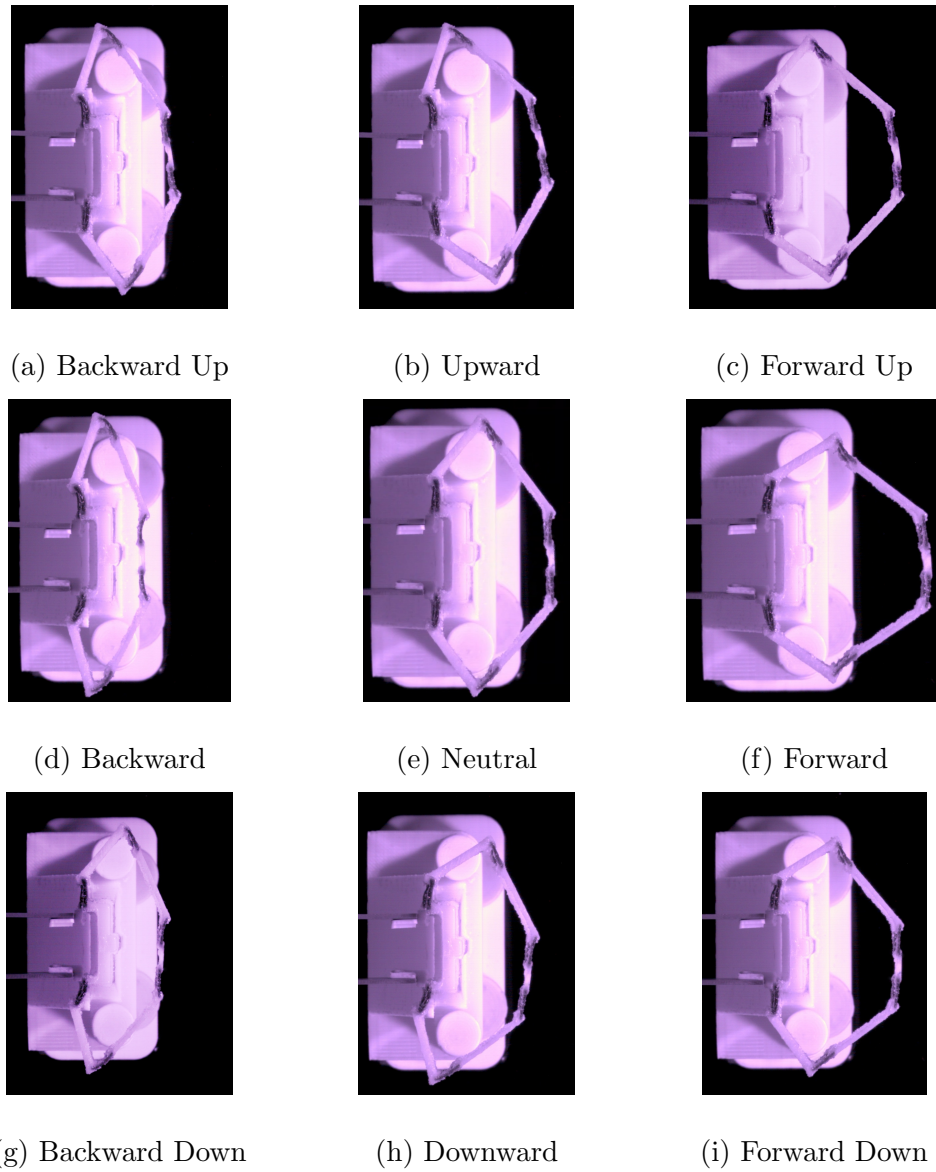


Fig. 4.33 Basic movements of the parallel robot

The results for the piezoelectric bimorph actuated parallel robot (shown in Fig. 4.33, values in Table. 4.8) are similar to the simulated predictions, but have a smaller

workspace, in particular along the y -axis.

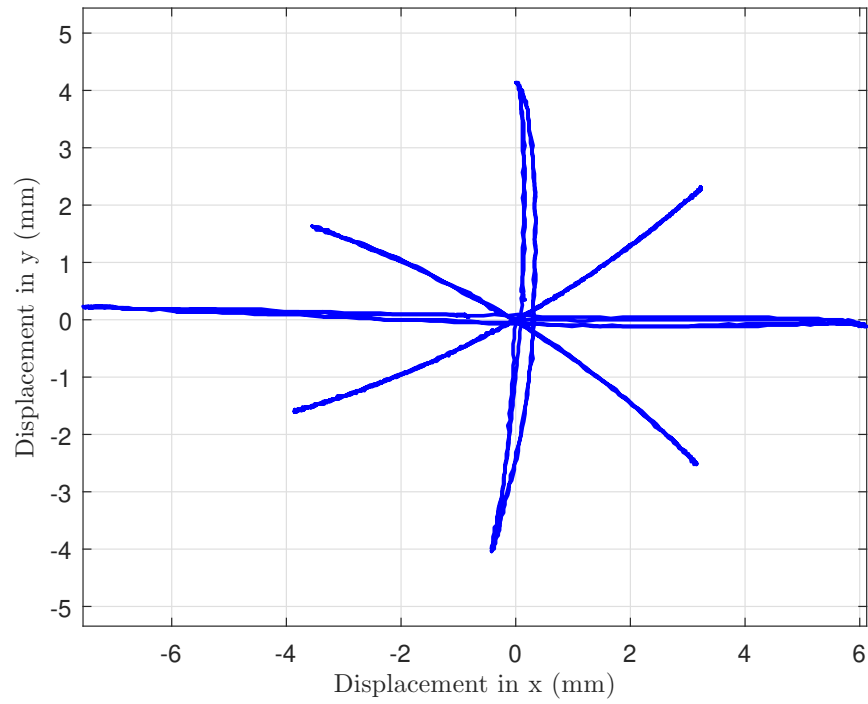


Fig. 4.34 Basic movements of the parallel robot (bimorph actuated)

Case	Movement	$V_{\sim 1}$	$V_{\sim 2}$	δx (mm)	δy (mm)	θ (deg)
1	Forward (+X)	148	0	6.542	-0.076	-1.2
2	Backward (-X)	0	148	-7.815	0.216	-0.6
3	Down (-Y)	148	148	-0.7886	-4.258	-10.6
4	Up (+Y)	0	0	-0.4206	-4.404	10.7
5	Forward Down	148	74	3.271	-2.704	-4.2
6	Backward Up	0	74	-4.159	1.852	4.7
7	Backward Down	74	148	-4.147	-1.624	-6.7
8	Forward Up	74	0	3.563	2.588	4.9

Table 4.8 Basic movements for the parallel robot (bimorph actuated)

4.4.5 Workspace grid

Due to the hysteresis in both the piezoelectrics bimorphs and the materials in the flexures, the relationship between the input voltages of the bimorphs and the resulting displacements in the parallel robot varies depending on the previous inputs. To account for this, the workspace is traced with alternating start positions, trace directions, and peak voltages. To start, the end effector is positioned to either the positive or negative maximum along the x -axis over half a second. Next, the

workspace is traced by moving to the first point in the clockwise (CW) or counter-clockwise (CCW) direction (shown in Fig. 4.35) over half a second. Once the point is reached, the robot waits half a second before repeating the process for all the remaining points. This process is repeated with different peak voltages to acquire results within the workspace (shown in Fig. 4.36).

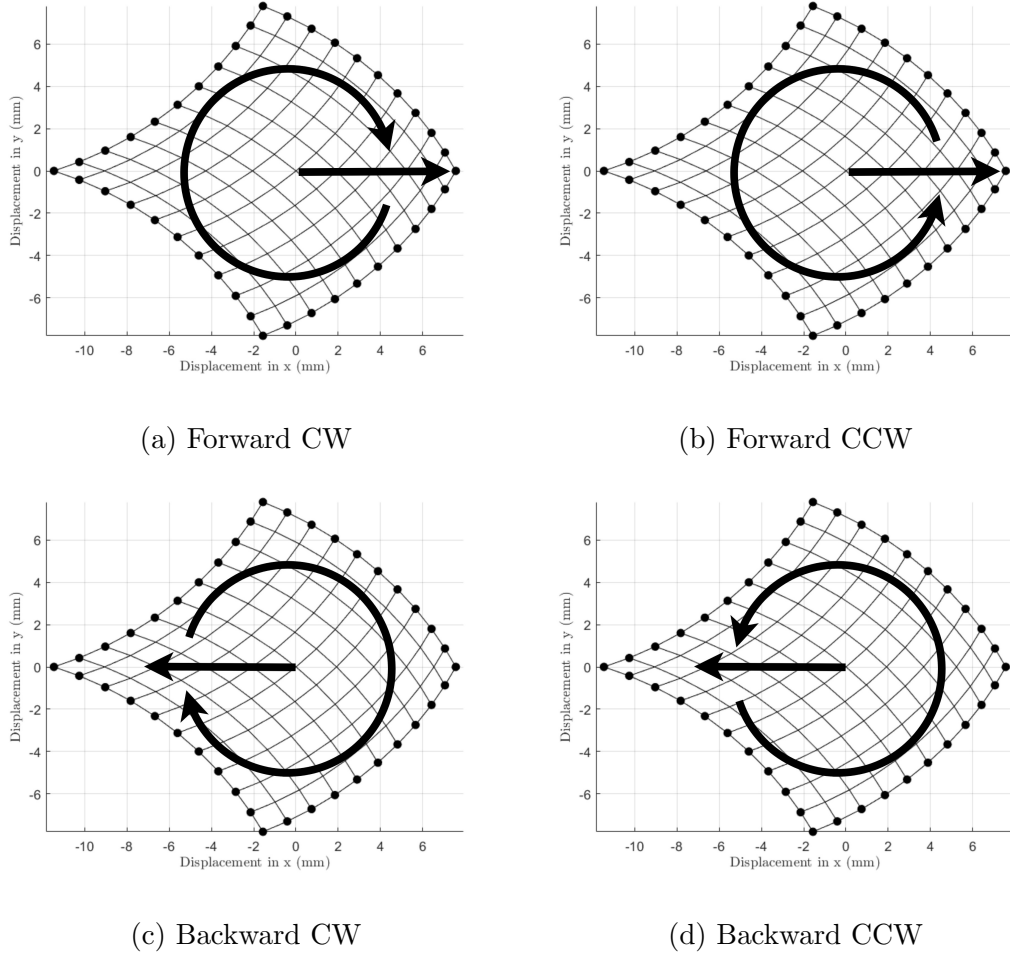
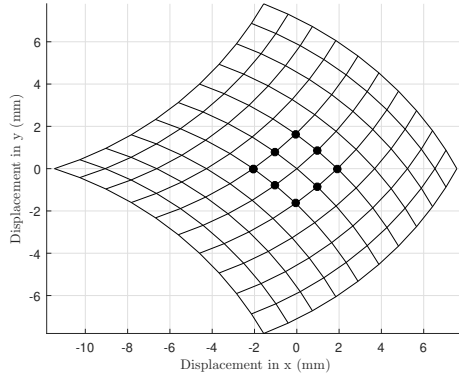
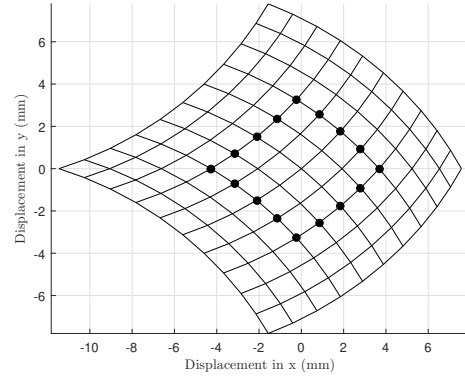


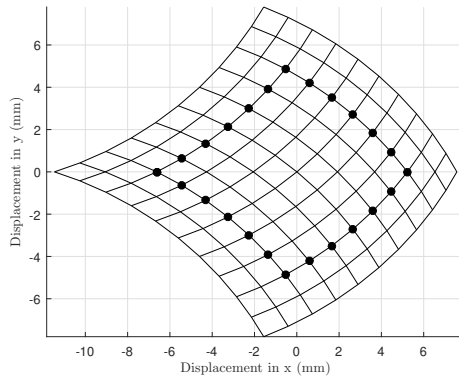
Fig. 4.35 Varying workspace trace directions and initial positions



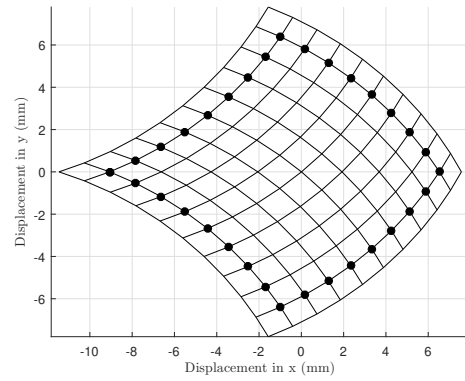
(a) Inner ring 1



(b) Inner ring 2



(c) Inner ring 3

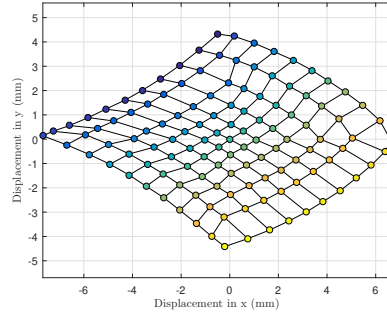


(d) Inner ring 4

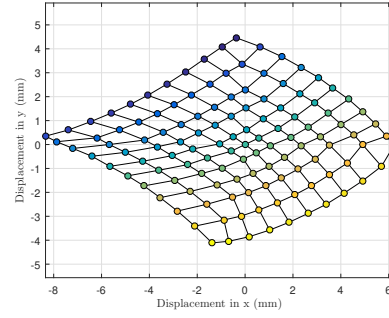
Fig. 4.36 Different inner traces used for workspace determination

Examining the results for the workspace traces (shown in Fig. 4.37), there are clear variations between the different tests. The peak results vary depending on the direction of movement, and the clockwise traces are skewed in a clockwise direction, while the counter-clockwise traces are skewed in a counter-clockwise direction. If all the workspace traces are averaged (shown in Fig. 4.38a), the relationship between

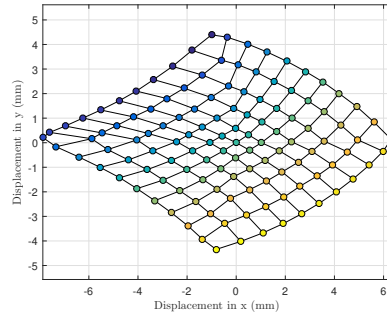
the input voltages (shown in Fig.4.38b) and the displacements is clearly visible. Compared to the expected displacement, the workspace is more diamond-shaped due to a reduction in movement along the y -axis. There is a horizontal workspace of 14.36 millimeters, a vertical workspace of 8.66 millimeters, and the total area of the workspace is 65.6144 square millimeters. The smaller workspace is partly due to the piezoelectric bimorphs, which have a lower displacement than expected.



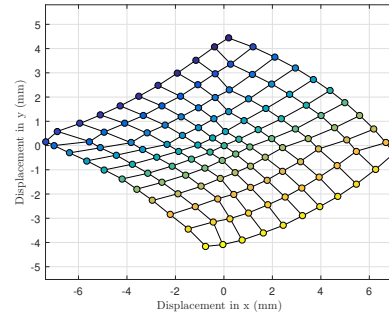
(a) Forward CW results



(b) Forward CCW results

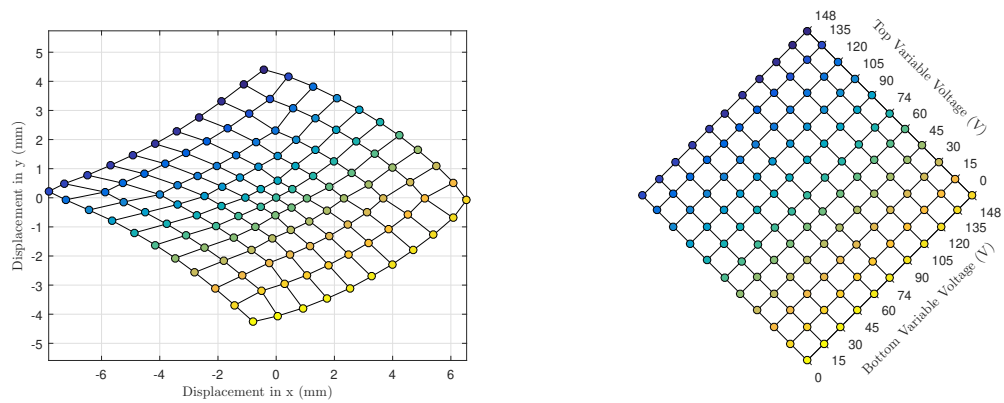


(c) Backward CW results



(d) Backward CCW results

Fig. 4.37 Workspace trace results for different directions and initial positions

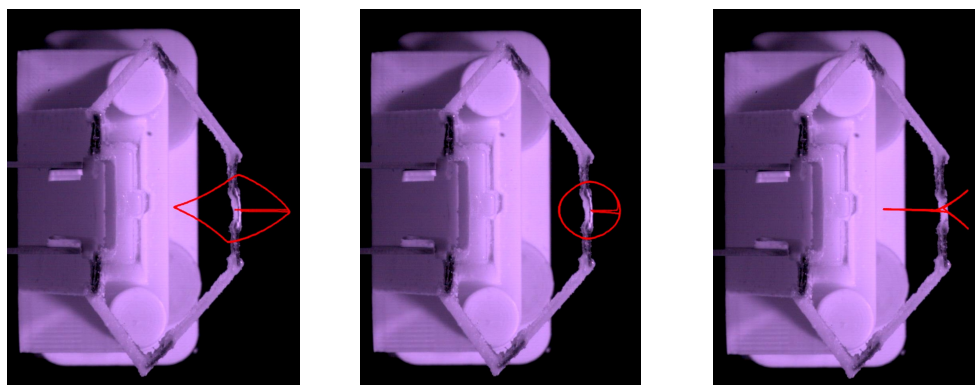


(a) Average of all workspace grids (b) Variable voltages for both bimorphs

Fig. 4.38 Workspace grid

4.4.6 Trajectories

All three trajectories are tested for 3 cycles to determine if the trajectories are stable across multiple cycles, and to see if the same path is followed in each cycle.



(a) Workspace trace (b) Circle (c) The letter Y

Fig. 4.39 Overlay of trajectory results

4.4.6.1 Trajectory 1: Workspace trace

The workspace trace trajectory (shown in Fig. 4.40a) follows a path similar close to the grid of points found earlier. There are slight differences in the results (quantifying the performance is shown in Appendix A) that are visible near the lower half of the trace, which is later in the trajectory. Hysteresis may be the source of this error, as the first half of the trajectory is more aligned with the grid of points found earlier.

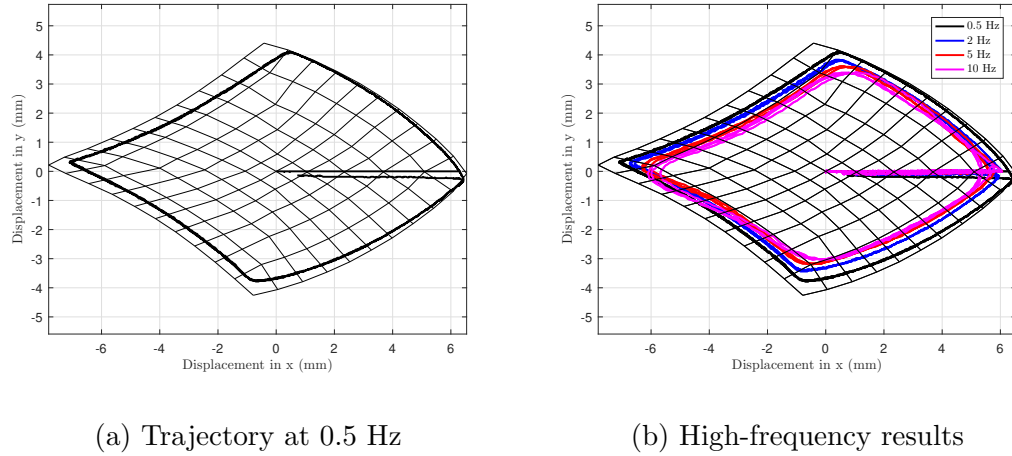


Fig. 4.40 Trajectory 1 Experimental Results

4.4.6.2 Trajectory 2: Circle

To test the circular trajectory, the input trajectory used in the finite element analysis was tested on the parallel robot. The circular trajectory results (shown in

Fig. 4.41) show an elliptical shape. This is to be expected, as the simulated performance of the parallel robot has a larger workspace, in particular along the y -axis. The robot is capable of maintaining the trajectory at 10 Hz, however with a reduced area.

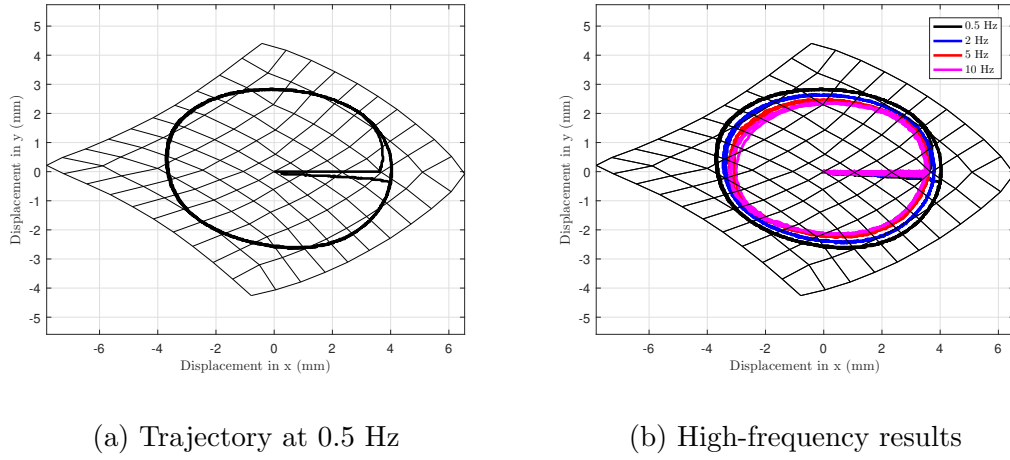
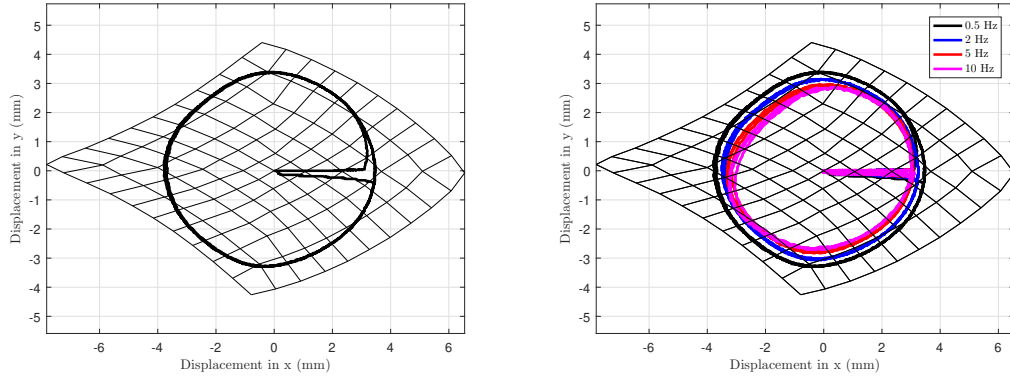


Fig. 4.41 Trajectory 2 Experimental Results

To improve upon the previous trajectory, the workspace grid obtained experimentally was used to generate a new set of input voltages for the circular trajectory, to trace out a circle with a radius of 3.5 millimeters. When this trajectory is used, the results (shown in Fig. 4.42) improve drastically. A circular shape is clearly visible with a radius of 3.5 millimeters, and the trajectory is stable at 10 Hz with only a slightly smaller workspace.



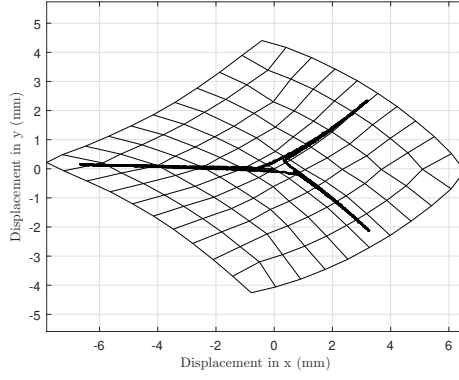
(a) Trajectory at 0.5 Hz

(b) High-frequency results

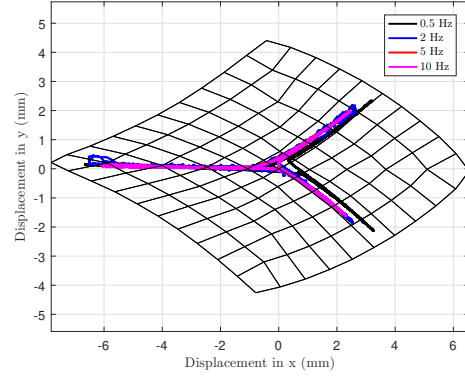
Fig. 4.42 Trajectory 2 Experimental Results, revised transformation data

4.4.6.3 Trajectory 3: The letter Y

Hysteresis is clearly visible in the results for the third trajectory (shown in Fig. 4.43a). As the upper segment of the letter is traced, it does not return fully to the origin before beginning the lower segment of the letter and has a different origin when returning to rest at the end. At higher frequencies (shown in Fig. 4.43b) the trajectory is clear, but peak displacements are closer to the origin.



(a) Trajectory at 0.5 Hz

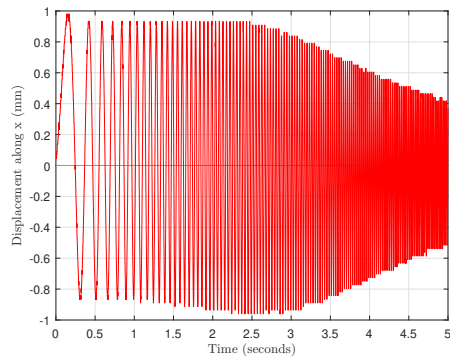


(b) High-frequency results

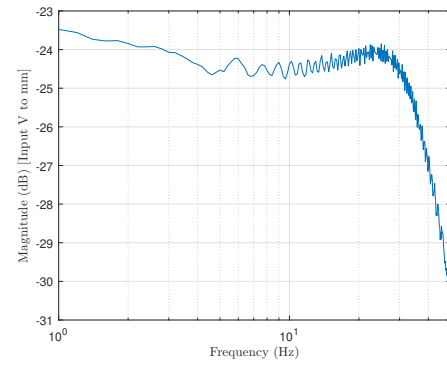
Fig. 4.43 Trajectory 3 Experimental Results

4.4.6.4 Chirp signals

To determine the frequency response of the parallel robot, a chirp signal with a magnitude of 15V is applied to the bimorphs. Two tests are completed with the same chirp signal. The first test applies the chirp signal to both bimorphs at once, driving the parallel robot forward and backward. The second test inverts one of the chirp signals, driving the parallel robot up and down. The chirp signal lasts for five seconds, sweeping from 1 to 50 Hz.

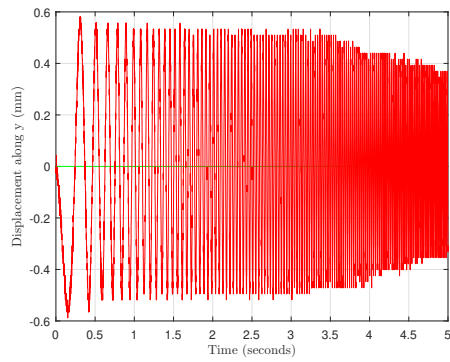


(a) Displacement results

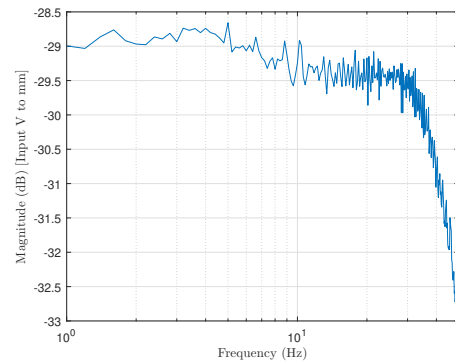


(b) Frequency Results

Fig. 4.44 Chirp signal results for horizontal motion



(a) Displacement results



(b) Frequency Results

Fig. 4.45 Chirp signal results for vertical motion

For the horizontal motion (shown in Fig. 4.44), there is a decrease in the response of the system as it increases from 1 to 5 Hz. It slowly begins, peaking around 25 Hz, before dropping rapidly as the system moves towards 50 Hz. The predicted

horizontal resonance frequencies were 18.823 and 114.99 Hz. For the vertical motion (shown in Fig. 4.45), the system response does not change significantly from 1 to 5 Hz, but then begins to drop without reaching another peak. Unlike the horizontal response, the vertical frequency response does not have a peak near the predicted resonance frequencies of 17.740 and 27.575 Hz, but rolls off after 25 Hz.

4.4.6.5 Fatigue testing

To determine the response of the parallel robot to cyclic loading, it was actuated forward and backward at 10 Hz for 10000 cycles. The horizontal workspace of the parallel robot was 11.916 millimeters when actuated at 10 Hz before the fatigue testing. After fatigue testing, the horizontal workspace of the parallel robot when actuated at 10 Hz is 12.01 millimeters. The difference between these results (shown in Fig. 4.46) is 0.8 percent, well within the error due to measurement or hysteresis, suggesting that there is no noticeable change for the parallel robot after 10000 cycles.

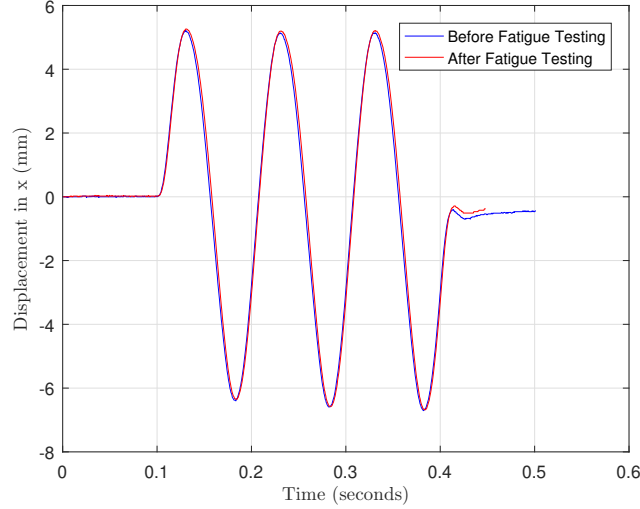
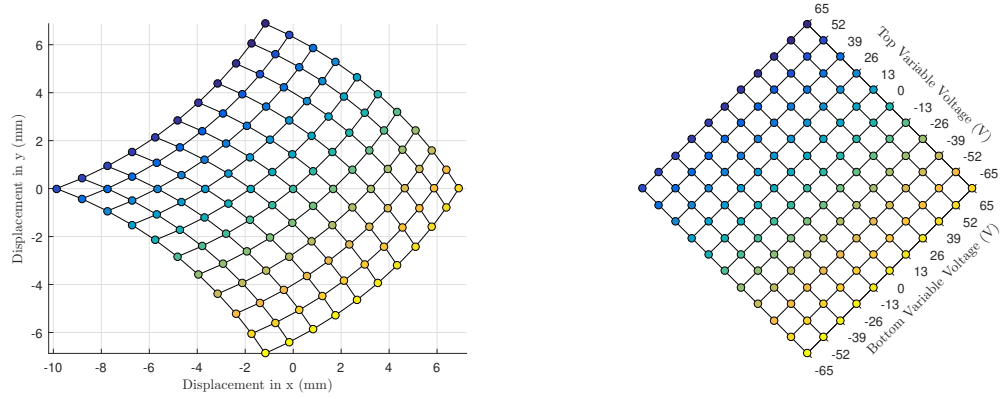


Fig. 4.46 Comparison of parallel robot performance before and after fatigue testing

4.4.7 Updating simulations with experimental bimorph performance

The piezoelectric bimorphs used for the parallel robot have lower displacement than expected, with peak results between 375 – 400 microns instead of 450 microns. To compare the experimental results further, an updated simulation is performed where the displacement at peak for the piezoelectrics is limited to 400 microns by lowering the peak voltage from 75 volts to 65 volts. The workspace grid for this setup (shown in Fig. 4.47a) is similar to previous results but has a reduced workspace. There is a horizontal workspace of 16.78 millimeters, a vertical workspace of 13.75 millimeters, and the area of the workspace is 113.53 square millimeters. Compared to the experimental results, the horizontal workspace is slightly larger, while the

vertical workspace is significantly larger.



(a) Displacement in the XY plane (b) Variable voltages for both bimorphs

Fig. 4.47 Workspace Grid

Case	Movement	$V_{\sim\text{top}}$	$V_{\sim\text{bot}}$	δx (mm)	δy (mm)	θ (deg)
1	Forward (+X)	-75	75	6.908	0	0
2	Backward (-X)	75	-75	-9.871	0	0
3	Down (-Y)	-75	-75	-1.167	-6.873	-12.2
4	Up (+Y)	75	75	-1.167	6.873	12.2
5	Forward Down	-75	0	3.527	-3.944	-4.6
6	Backward Up	75	0	-4.825	2.84	7.3
7	Backward Down	0	-75	-4.825	-2.84	-7.3
8	Forward Up	0	75	3.527	3.944	4.6

Table 4.10 Basic movement cases and results for the parallel robot, reduced voltage

As with the transmission mechanism alone, the experimental testing of the parallel robot was difficult due to the small-scale design and difficulties of manual support removal. These difficulties likely contributed to the reduction in the vertical workspace for the final parallel robot tests.

5 Conclusions and Future Work

In this work, a mesoscale parallel robot was designed using piezoelectric bimorphs for actuation, compliant joints for the active joints and passive joints, and additive manufacturing for fabrication.

To start, Chapter 2 covered the characterization of piezoelectric bimorphs. Finite element models were developed to compare the performance of commercially available piezoelectric benders with manufacturer specifications and experimental results. Using a laser displacement sensor the displacement and resonance frequency were verified, and bimorphs were selected for the actuation of a transmission mechanism and robot.

The development of a compliant transmission mechanism that converts a small linear displacement into a large rotational motion was the focus of Chapter 3. Using a planar finite element model, followed by a three-dimensional finite element model, the critical design parameters for the conversion and amplification of motion were identified. These parameters were revealed to be the thickness of the flexure

elements, followed by the length and angle between flexure members. Experimental testing of the mechanism demonstrated the transmission behaved as expected, converting and amplifying a small linear motion to a large rotational motion, with the thickness of the flexures impacting the performance of the transmission.

In Chapter 4, the integration of the piezoelectric bimorphs and transmission mechanism to form a six-bar mesoscale parallel robot that can be controlled in two degrees of freedom was presented. A simplified kinematic model was developed to understand the expected motion of the parallel robot while identifying critical parameters to increase the workspace of the system. A finite element model was developed based on the simplified kinematic model that incorporated the piezoelectric bimorph and transmission mechanism models. By testing combinations of input voltages to the bimorphs, the basic movements for the parallel robot along the X and Y axes were identified. The workspace of the parallel robot was mapped by testing a grid of input voltages, mapping the relationship between the input voltages and end effector displacement. With a transformation function, a set of desired displacements were converted to a set of input voltages, allowing for trajectories to be generated within the workspace, such as a circular trajectory. The robot was built and integrated based on this design, and experimental testing demonstrated the relationship between input voltages and displacement is close to the simulated performance. The parallel robot has a horizontal and vertical workspace of 14.36

and 8.66 millimeters, respectively, and is capable of maintaining a horizontal and vertical workspace of 12.06 and 6.80 millimeters, respectively, at 10 Hz. Trajectories spanning the entire workspace can be maintained at 10 Hz, performing better than expected in simulation, while fatigue tests indicated no change in performance after 10,000 cycles. The end effector of the parallel robot can be controlled as expected, with slight deviations due to hysteresis in both the piezoelectric actuator and flexible material. The parallel robot covers an area of 557.6 millimeters squared. With a workspace area of 65.6 millimeters squared, the robot has a workspace area to manipulator area ratio of $\frac{1}{8.5}$.

5.1 Future Work

To improve the design of the transmission mechanism and the parallel robot, the causes for the gap between the predicted and experimental results must be investigated. The experimental displacements of the bimorphs can be used for the transmission mechanism simulations to provide a more accurate actuation distance. Capturing the mechanical behavior of flexible materials such as Agilus30 at different strain rates (possibly modeling viscoelastic behavior) would give insight into the performance of the transmission mechanism. This would also improve the understanding of the system at high frequencies and at resonance.

An ongoing challenge is the integration of the bimorphs and transmission mech-

anisms of the parallel robot, primarily due to the small scale of the components and the flexible regions. Misalignment when bonding the surfaces of the transmission and bimorph results in a decreased workspace of the parallel robot. Alternate materials and printing methods can be investigated for multi-material printing of flexible and rigid sections. Testing composite materials of varying hardness using photopolymer blends would allow for the material properties of the flexible sections to be tuned, leading to further optimization of the transmission mechanism. Using soluble support material during fabrication would reduce the post-processing time significantly, shortening the design cycle for the robot.

The robot presented in this work does not have a controller to improve performance at higher frequencies or to account for hysteresis effects. Adding sensors such as accelerometers to the end effector would allow for feedback control of the system, ideally improving control of the end effector position at higher frequencies. To account for the hysteresis behavior of the bimorphs and flexible material in the transmission, it may be possible to use the expected and resultant positions for various movements and trajectories for the end effector and use those results to improve estimations of the end effector position.

The transmission mechanism used for the parallel robot can be expanded to other designs, such as a $3RRR$ planar robot, allowing for control of the position and orientation of an end effector, or spatial robots that can control the position

and/or orientation of an end effector in three-dimensional space. Testing the flexible transmission in conditions such as extreme heat, cold, or in a vacuum would help narrow down future applications such as micro-assembly or micro-positioning tasks either in terrestrial or space environments. As additive manufacturing methods mature and expand into new material types, it could be possible to fabricate the entire mechanism, including the actuators and transmission, in one step. These robots could be immediately ready for use after fabrication, leading the way for an easily modifiable mass manufacturing process for robots of various sizes.

A Performance of experimental trajectories

To quantify the performance of the experimental results of the parallel robot for different trajectories, the position error between the expected trajectory within the experimental workspace and the actual performance was compared. Specifically, the position of the end effector is compared to the expected performance along the x-direction, y-direction, and the magnitude, for a given trajectory.

A.1 Trajectory 1: Workspace Trace

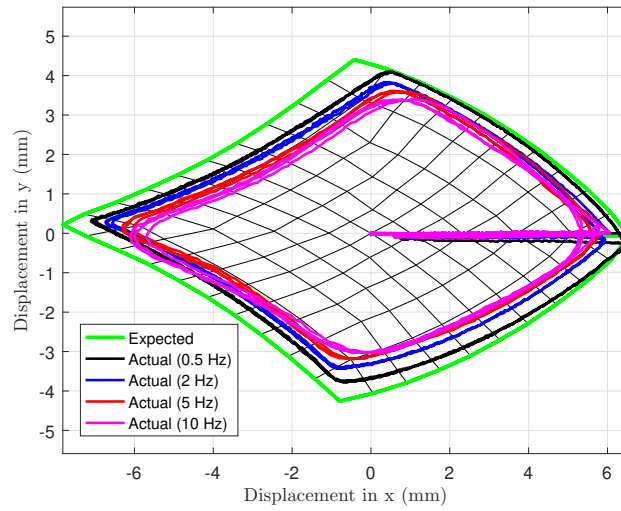


Fig. A.1 Expected and actual performance for Trajectory 1

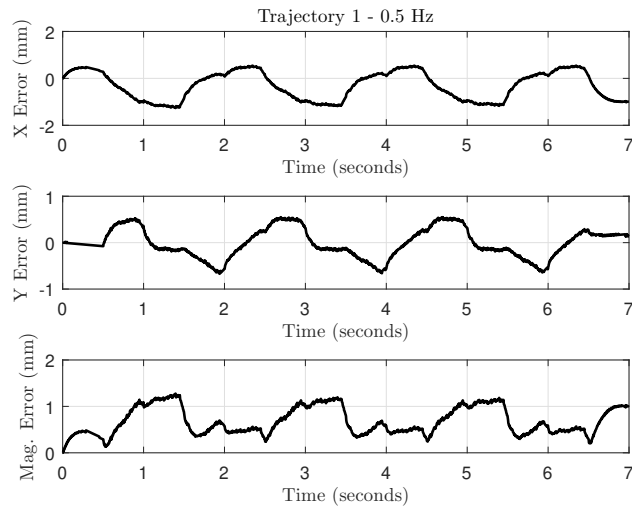


Fig. A.2 Position error for Trajectory 1: 0.5 Hz

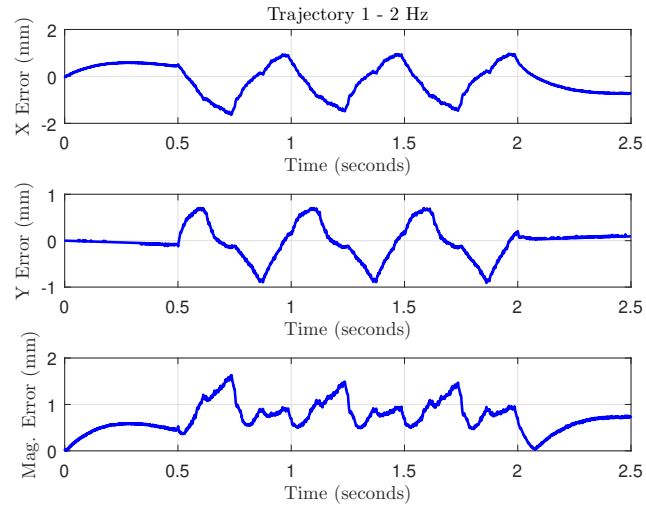


Fig. A.3 Positon error for Trajectory 1: 2 Hz

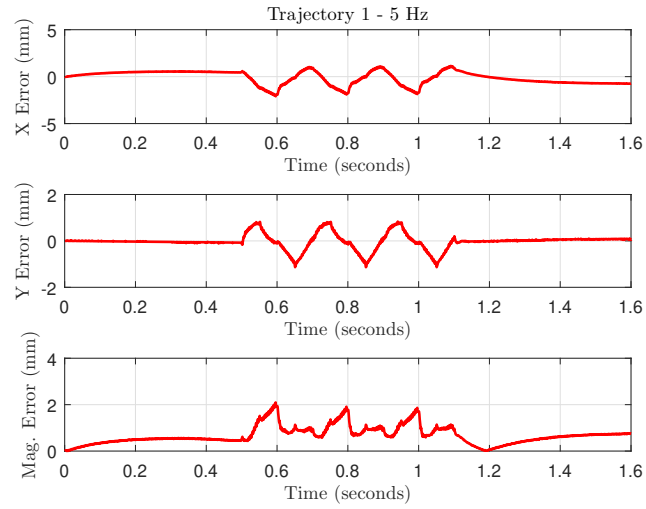


Fig. A.4 Positon error for Trajectory 1: 5 Hz

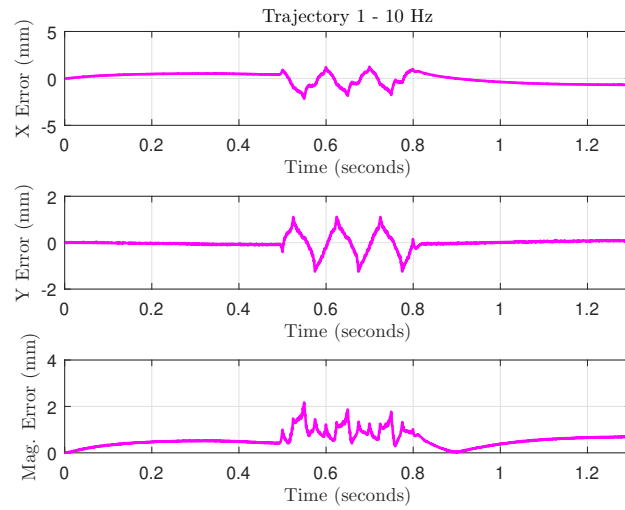


Fig. A.5 Positon error for Trajectory 1: 10 Hz

A.2 Trajectory 2: Circle

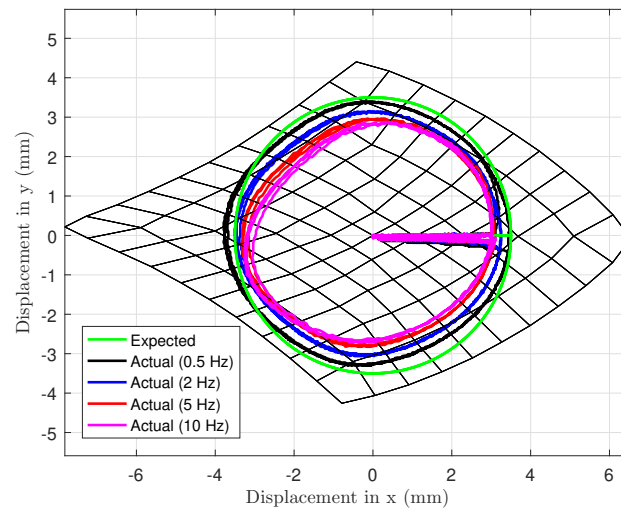


Fig. A.6 Expected and actual performance for Trajectory 2

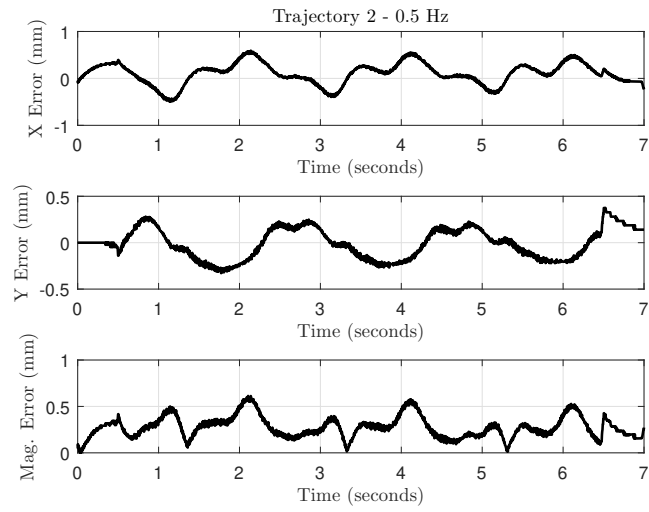


Fig. A.7 Positonal error for Trajectory 2: 0.5 Hz

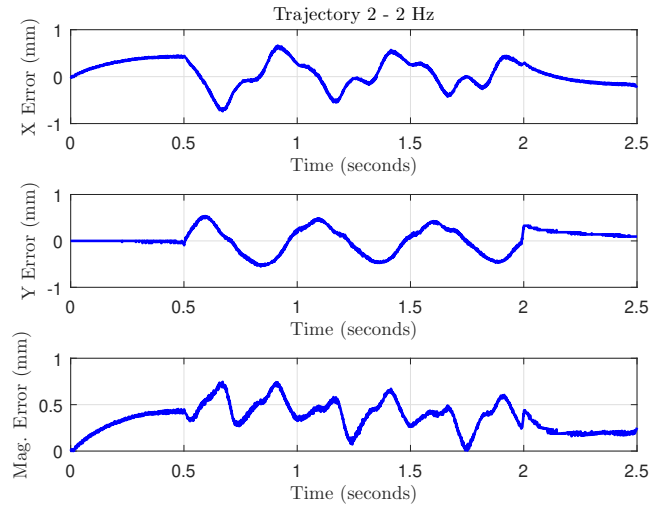


Fig. A.8 Positon error for Trajectory 2: 2 Hz

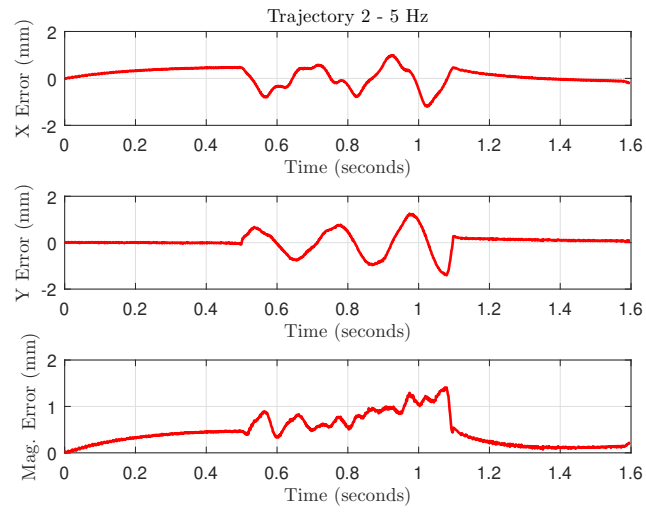


Fig. A.9 Positon error for Trajectory 2: 5 Hz

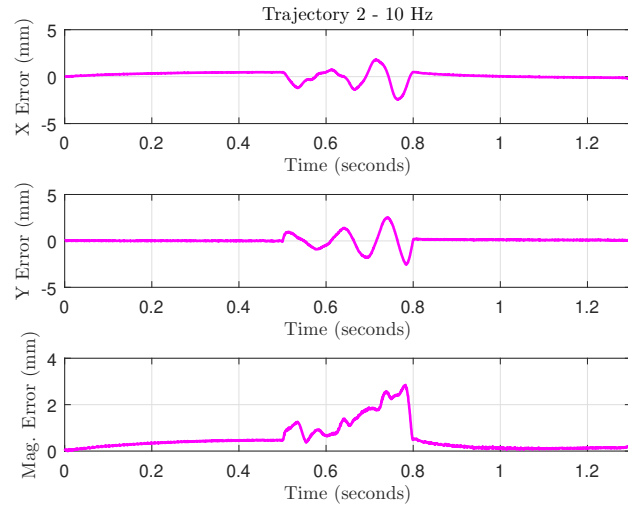


Fig. A.10 Positon error for Trajectory 2: 10 Hz

A.3 Trajectory 3: The letter Y

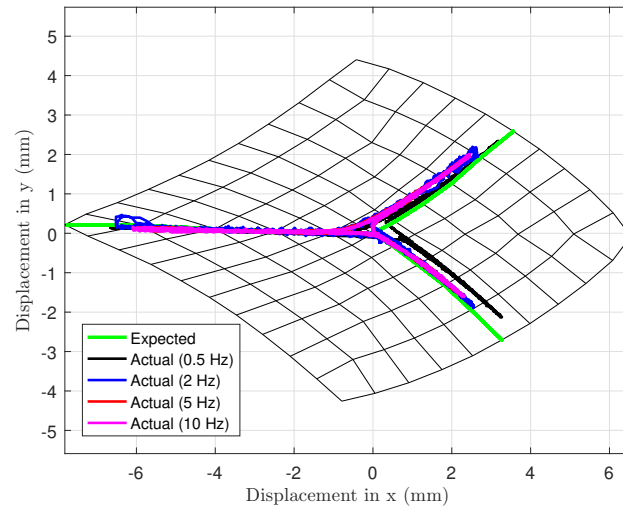


Fig. A.11 Expected and actual performance for Trajectory 3

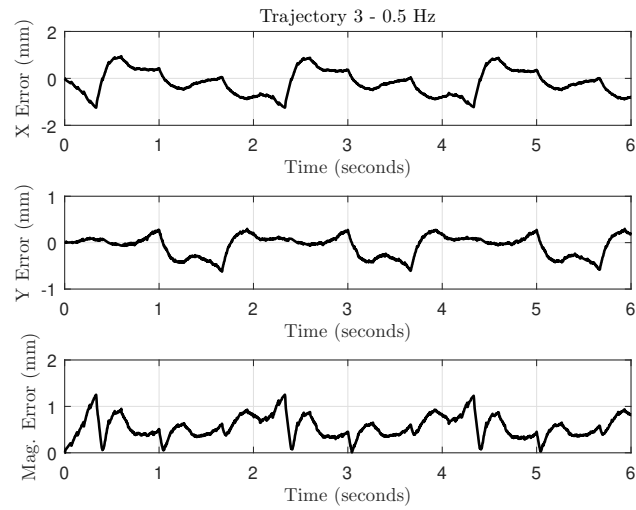


Fig. A.12 Position error for Trajectory 3: 0.5 Hz

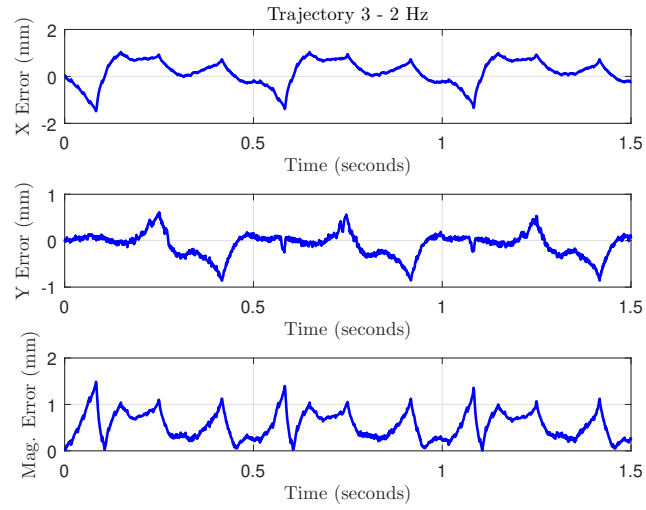


Fig. A.13 Positon error for Trajectory 3: 2 Hz

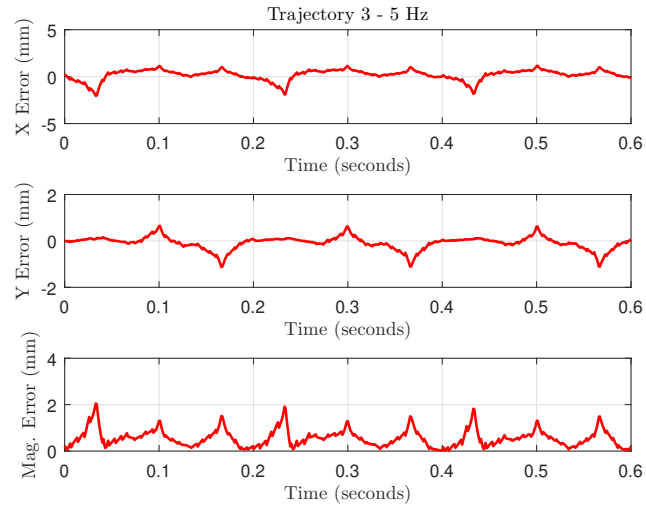


Fig. A.14 Positon error for Trajectory 3: 5 Hz

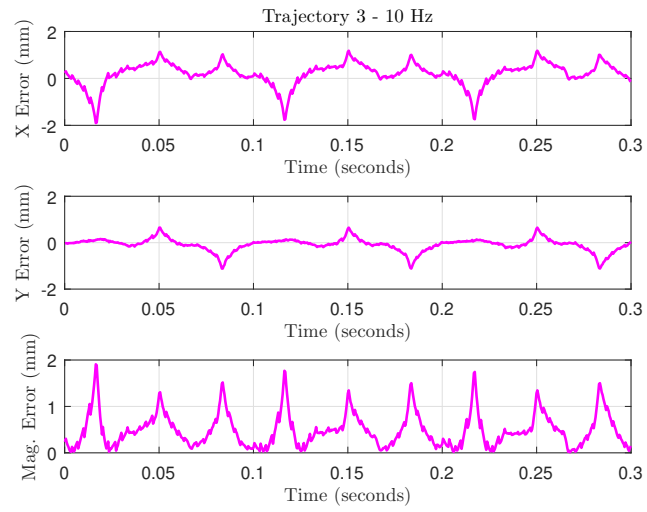


Fig. A.15 Positon error for Trajectory 3: 10 Hz

B Complete List of Publications

B.1 Conference Papers

A. Tabak and R. Orszulik, “A monolithic flexible transmission for piezoelectric actuators,” in *2022 IEEE/ASME International Conference on Advanced Intelligent Machines (AIM)*, IEEE, 2022, pp. 138-143.

B.2 Abstracts

A. Tabak and R. Orszulik, “Additively manufactured transmission design for mesoscale mechanisms,” in *Proceedings of the Canadian Society for Mechanical Engineering International Congress 2022*, 2022.

Bibliography

- [1] I. Paprotny and S. Bergbreiter, “Small-scale robotics: An introduction,” in *Workshop at the IEEE International Conference on Robotics and Automation*, Springer, 2013, pp. 1–15.
- [2] P. S. Sreetharan, J. P. Whitney, M. D. Strauss, and R. J. Wood, “Monolithic fabrication of millimeter-scale machines,” *Journal of Micromechanics and Microengineering*, vol. 22, no. 5, pp. 055–027, 2012.
- [3] E. Pernette, S. Henein, I. Magnani, and R. Clavel, “Design of parallel robots in microrobotics,” *Robotica*, vol. 15, no. 4, pp. 417–420, 1997.
- [4] B. Goldberg, M. Karpelson, O. Ozcan, and R. J. Wood, “Planar fabrication of a mesoscale voice coil actuator,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, 2014, pp. 6319–6325.
- [5] T. Dow and R. Scattergood, “Mesoscale and microscale manufacturing processes: Challenges for materials, fabrication and metrology,” in *Proceedings of the ASPE winter topical meeting*, Citeseer, vol. 28, 2003, pp. 14–19.

- [6] D. O. Popa and H. E. Stephanou, “Micro and mesoscale robotic assembly,” *Journal of Manufacturing Processes*, vol. 6, no. 1, pp. 52–71, 2004.
- [7] C. D. Near, “Piezoelectric actuator technology,” in *Smart Structures and Materials 1996: Smart Structures and Integrated Systems*, International Society for Optics and Photonics, vol. 2717, 1996, pp. 246–258.
- [8] K. Y. Ma, P. Chirarattananon, S. B. Fuller, and R. J. Wood, “Controlled flight of a biologically inspired, insect-scale robot,” *Science*, vol. 340, no. 6132, pp. 603–607, 2013.
- [9] H. McClintock, F. Z. Temel, N. Doshi, J.-s. Koh, and R. J. Wood, “The millidelta: A high-bandwidth, high-precision, millimeter-scale delta robot,” *Science Robotics*, vol. 3, no. 14, 2018.
- [10] P. Mannam, O. Kroemer, and F. Z. Temel, “Characterization of compliant parallelogram links for 3D-printed delta manipulators,” in *International Symposium on Experimental Robotics*, Springer, 2020, pp. 75–84.
- [11] M. Attaran, “The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing,” *Business Horizons*, vol. 60, no. 5, pp. 677–688, 2017.

- [12] S. Ford and M. Despeisse, “Additive manufacturing and sustainability: An exploratory study of the advantages and challenges,” *Journal of Cleaner Production*, vol. 137, pp. 1573–1587, 2016.
- [13] T. Xu, J. Zhang, M. Salehizadeh, O. Onaizah, and E. Diller, “Millimeter-scale flexible robots with programmable three-dimensional magnetization and motions,” *Science Robotics*, vol. 4, no. 29, 2019.
- [14] L. Lu, P. Guo, and Y. Pan, “Magnetic-field-assisted projection stereolithography for three-dimensional printing of smart structures,” *Journal of Manufacturing Science and Engineering*, vol. 139, no. 7, 2017.
- [15] K. R. Ryan, M. P. Down, and C. E. Banks, “Future of additive manufacturing: Overview of 4d and 3d printed smart and advanced materials and their applications,” *Chemical Engineering Journal*, vol. 403, pp. 126–162, 2021.
- [16] R. Mutlu, G. Alici, M. in het Panhuis, and G. M. Spinks, “3d printed flexure hinges for soft monolithic prosthetic fingers,” *Soft Robotics*, vol. 3, no. 3, pp. 120–133, 2016.
- [17] R. S. Pierre, N. Paul, and S. Bergbreiter, “3dflex: A rapid prototyping approach for multi-material compliant mechanisms in millirobots,” in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, 2017, pp. 3068–3073.

- [18] T.-W. Na, D.-H. Kang, J.-Y. Jung, J.-H. Han, and I.-K. Oh, “Linear-to-rotary motion converter using asymmetric compliant mechanics and single-crystal PMN-PT stack actuator,” *Journal of Intelligent Material Systems and Structures*, vol. 25, no. 18, pp. 2221–2227, 2014.
- [19] J. S. Cuellar, G. Smit, D. Plettenburg, and A. Zadpoor, “Additive manufacturing of non-assembly mechanisms,” *Additive Manufacturing*, vol. 21, pp. 150–158, 2018.
- [20] W. P. Mason, “Piezoelectricity, its history and applications,” *The Journal of the Acoustical Society of America*, vol. 70, no. 6, pp. 1561–1566, 1981.
- [21] G. Lippmann, “Principe de la conservation de l’électricité, ou second principe de la théorie des phénomènes électriques,” *Journal de Physique Théorique et Appliquée*, vol. 10, no. 1, pp. 381–394, 1881.
- [22] T. Tanaka, “Piezoelectric devices in japan,” *Ferroelectrics*, vol. 40, no. 1, pp. 167–187, 1982.
- [23] G. Gautschi, “Piezoelectric sensors,” in *Piezoelectric Sensorics*, Springer, 2002, pp. 73–91.
- [24] K. Uchino, *Piezoelectric Actuators and Ultrasonic Motors*. Springer Science & Business Media, 1996, vol. 1.

- [25] S. R. Moheimani and A. J. Fleming, *Piezoelectric Transducers for Vibration Control and Damping*. Springer Science & Business Media, 2006.
- [26] S. Trolier-McKinstry, S. Zhang, A. J. Bell, and X. Tan, “High-performance piezoelectric crystals, ceramics, and films,” *Annual Review of Materials Research*, vol. 48, pp. 191–217, 2018.
- [27] R. Calìò, U. B. Rongala, D. Camboni, *et al.*, “Piezoelectric energy harvesting solutions,” *Sensors*, vol. 14, no. 3, pp. 4755–4790, 2014.
- [28] “IEEE standard on piezoelectricity,” *ANSI/IEEE Std 176-1987*, 1988. DOI: 10.1109/IEEESTD.1988.79638.
- [29] D. Damjanovic, “Hysteresis in piezoelectric and ferroelectric materials,” Academic Press, Tech. Rep., 2006.
- [30] *Piezoelectric constants*, <https://www.americanpiezo.com/knowledge-center/piezo-theory/piezoelectric-constants.html>, Accessed: 2022-01-12.
- [31] M. Jong, W. Chen, H. Geerlings, M. Asta, and K. Persson, “A database to enable discovery and design of piezoelectric materials,” *Scientific Data*, vol. 2, Sep. 2015. DOI: 10.1038/sdata.2015.53.

- [32] V. V. Varadan, J.-H. Jeng, and V. K. Varadan, “Form invariant constitutive relations for transversely isotropic piezoelectric materials,” *The Journal of the Acoustical Society of America*, vol. 82, no. 1, pp. 337–341, 1987.
- [33] K. Uchino, “The development of piezoelectric materials and the new perspective,” in *Advanced Piezoelectric Materials*, Elsevier, 2017, pp. 1–92.
- [34] G. Busch, “Early history of ferroelectricity,” *Ferroelectrics*, vol. 74, no. 1, pp. 267–284, 1987. DOI: 10.1080/00150198708201307.
- [35] C. H. Sherman and J. L. Butler, *Transducers and Arrays for Underwater Sound*. Springer, 2007, vol. 4, pp. 6–9.
- [36] C. Randall, R. Newnham, and L. Cross, “History of the first ferroelectric oxide, BaTiO₃,” *Materials Research Institute, The Pennsylvania State University, University Park, Pa, USA*, vol. 1, 2004.
- [37] H. Jaffe, “Piezoelectric ceramics,” *Journal of the American Ceramic Society*, vol. 41, no. 11, pp. 494–498, 1958.
- [38] D. Berlincourt, “Piezoelectric ceramics: Characteristics and applications,” *The Journal of the Acoustical Society of America*, vol. 70, no. 6, pp. 1586–1595, 1981.

- [39] J. F. Tressler, S. Alkoy, and R. E. Newnham, "Piezoelectric sensors and sensor materials," *Journal of Electroceramics*, vol. 2, no. 4, pp. 257–272, 1998.
- [40] P. Panda and B. Sahoo, "PZT to lead free piezo ceramics: A review," *Ferroelectrics*, vol. 474, no. 1, pp. 128–143, 2015.
- [41] T. R. Shrout and S. J. Zhang, "Lead-free piezoelectric ceramics: Alternatives for PZT?" *Journal of Electroceramics*, vol. 19, no. 1, pp. 113–126, 2007.
- [42] *NAVY TYPE PZT CLASSIFICATIONS*, <https://sensortechcanada.com/2021/07/03/navy-type-pzt-classifications/>, Accessed: 2021-11-13.
- [43] *Equivalent Ceramic Materials*, https://www.bostonpiezooptics.com/assets/pdf/Equiv_Ceramic_Matls.pdf, Accessed: 2021-11-13.
- [44] *Boston Piezo Optics Inc., Ceramic Materials*, <https://www.bostonpiezooptics.com/ceramic-materials-pzt>, Accessed: 2021-09-29.
- [45] A. Arnau *et al.*, *Piezoelectric transducers and applications*. Springer, 2004, vol. 2004.
- [46] E. Steinhaus and S. Lipson, "Bimorph piezoelectric flexible mirror," *JOSA*, vol. 69, no. 3, pp. 478–481, 1979.

- [47] A. Michael and C. Kwok, “Piezoelectric micro-lens actuator,” *Sensors and Actuators A: Physical*, vol. 236, pp. 116–129, 2015.
- [48] T. King, M. Preston, B. Murphy, and D. Cannell, “Piezoelectric ceramic actuators: A review of machinery applications,” *Precision Engineering*, vol. 12, no. 3, pp. 131–136, 1990.
- [49] J. Feenstra, J. Granstrom, and H. Sodano, “Energy harvesting through a backpack employing a mechanically amplified piezoelectric stack,” *Mechanical Systems and Signal Processing*, vol. 22, no. 3, pp. 721–734, 2008.
- [50] R. C. Simoes, V. Steffen Jr, J. Der Hagopian, and J. Mahfoud, “Modal active vibration control of a rotor using piezoelectric stack actuators,” *Journal of Vibration and Control*, vol. 13, no. 1, pp. 45–64, 2007.
- [51] S. S. Aphale, B. Bhikkaji, and S. R. Moheimani, “Minimizing scanning errors in piezoelectric stack-actuated nanopositioning platforms,” *IEEE Transactions on Nanotechnology*, vol. 7, no. 1, pp. 79–90, 2008.
- [52] *Piezoelectric actuators*, CAT128E R3, Physik Instrumente (PI) GmbH I& Co. KG, 2016. [Online]. Available: https://static.piceramic.com/fileadmin/user_upload/pi_ceramic/files/catalog_CAT/PI_CAT128E_R3_Piezoelectric_Actuators.pdf.

- [53] C. Germano, “Flexure mode piezoelectric transducers,” *IEEE Transactions on Audio and Electroacoustics*, vol. 19, no. 1, pp. 6–12, 1971.
- [54] Q.-M. Wang and L. E. Cross, “Performance analysis of piezoelectric cantilever bending actuators,” *Ferroelectrics*, vol. 215, no. 1, pp. 187–213, 1998.
- [55] V. Kugel, S. Chandran, and L. Cross, “Caterpillar-type piezoelectric d33 bimorph transducer,” *Applied Physics Letters*, vol. 69, no. 14, pp. 2021–2023, 1996.
- [56] K. Yao, W. Zhu, E. Uchino, Z. Zhang, and L. C. Lim, “Design and fabrication of a high performance multilayer piezoelectric actuator with bending deformation,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 46, no. 4, pp. 1020–1027, 1999.
- [57] J. W. Judy, D. L. Polla, and W. P. Robbins, “A linear piezoelectric stepper motor with submicrometer step size and centimeter travel range,” *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 37, no. 5, pp. 428–437, 1990.
- [58] S. Yun, K. Lee, H. Kim, and H. So, “Development of the pneumatic valve with bimorph type pzt actuator,” *Materials Chemistry and Physics*, vol. 97, no. 1, pp. 1–4, 2006.

- [59] *Unimorph*, <https://en.wikipedia.org/wiki/Unimorph>, Accessed: 2021-11-13.
- [60] L. L. Howell, *Compliant Mechanisms*. John Wiley & Sons, 2001.
- [61] B. Zhu, X. Zhang, H. Zhang, *et al.*, “Design of compliant mechanisms using continuum topology optimization: A review,” *Mechanism and Machine Theory*, vol. 143, 2020.
- [62] B. P. Trease, Y.-M. Moon, and S. Kota, “Design of large-displacement compliant joints,” 2005.
- [63] S. Perai, “Methodology of compliant mechanisms and its current developments in applications: A review,” *American Journal of Applied Sciences*, vol. 4, no. 3, pp. 160–167, 2007.
- [64] W. Bachta, P. Renaud, E. Laroche, and J. Gangloff, “The cardiolock project: Design of an active stabilizer for cardiac surgery,” *Journal of Mechanical Design*, vol. 133, no. 7, Jul. 2011.
- [65] *Compliant Mechanisms Explained*, <https://www.compliantmechanisms.byu.edu/about-compliant-mechanisms>, Accessed: 2023-05-26.
- [66] J. O. Jacobsen, B. G. Winder, L. L. Howell, and S. P. Magleby, “Lamina emergent mechanisms and their basic elements,” 2010.

- [67] C. Balletti, M. Ballarin, and F. Guerra, “3D printing: State of the art and future perspectives,” *Journal of Cultural Heritage*, vol. 26, pp. 172–182, 2017.
- [68] T. Pereira, J. V. Kennedy, and J. Potgieter, “A comparison of traditional manufacturing vs additive manufacturing, the best method for the job,” *Procedia Manufacturing*, vol. 30, pp. 11–18, 2019.
- [69] B. Bhushan and M. Caspers, “An overview of additive manufacturing (3d printing) for microfabrication,” *Microsystem Technologies*, vol. 23, pp. 1117–1124, 2017.
- [70] W. Oropallo and L. A. Piegler, “Ten challenges in 3D printing,” *Engineering with Computers*, vol. 32, no. 1, pp. 135–148, 2016.
- [71] C. Buchanan and L. Gardner, “Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges,” *Engineering Structures*, vol. 180, pp. 332–348, 2019.
- [72] B. Vayre, F. Vignat, and F. Villeneuve, “Designing for additive manufacturing,” *Procedia CIRP*, vol. 3, pp. 632–637, 2012.
- [73] M. Szilvsi-Nagy and G. Matyasi, “Analysis of STL files,” *Mathematical and Computer Modelling*, vol. 38, no. 7-9, pp. 945–960, 2003.

- [74] S. Nayar, S. Bhuminathan, and W. M. Bhat, “Rapid prototyping and stereolithography in dentistry,” *Journal of Pharmacy & Bioallied Sciences*, vol. 7, no. Suppl 1, S216, 2015.
- [75] T. J. Horn and O. L. Harrysson, “Overview of current additive manufacturing technologies and selected applications,” *Science Progress*, vol. 95, no. 3, pp. 255–282, 2012.
- [76] A. Su and S. J. Al’Aref, “History of 3D printing,” in *3D Printing Applications in Cardiovascular Medicine*, Elsevier, 2018, pp. 1–10.
- [77] S. Singh, G. Singh, C. Prakash, and S. Ramakrishna, “Current status and future directions of fused filament fabrication,” *Journal of Manufacturing Processes*, vol. 55, pp. 288–306, 2020.
- [78] A. R. Torrado and D. A. Roberson, “Failure analysis and anisotropy evaluation of 3D-printed tensile test specimens of different geometries and print raster patterns,” *Journal of Failure Analysis and Prevention*, vol. 16, no. 1, pp. 154–164, 2016.
- [79] S. Sun, M. Brandt, and M. Easton, “Powder bed fusion processes: An overview,” *Laser Additive Manufacturing*, pp. 55–77, 2017.
- [80] I. Gibson, D. Rosen, and B. Stucker, “Powder bed fusion processes,” in *Additive Manufacturing Technologies*, Springer, 2015, pp. 107–145.

- [81] *Agilus 30 For Rubber-Like Parts*, <https://www.stratasys.com/materials/search/agilus30>, Accessed: 2021-11-11.
- [82] A. Gasparetto and L. Scalera, “From the unimate to the delta robot: The early decades of industrial robotics,” in *Explorations in the History and Heritage of Machines and Mechanisms*, Springer, 2019, pp. 284–295.
- [83] B. Siciliano, O. Khatib, and T. Kröger, *Springer Handbook of Robotics*. Springer, 2008, vol. 200.
- [84] L.-W. Tsai, *Robot analysis: the mechanics of serial and parallel manipulators*. John Wiley & Sons, 1999.
- [85] *How Are Industrial Robots Built? A Guide on the Components and the Movement of Robot Arms*, <https://robotics.kawasaki.com/ja1/xyz/en/1804-03/>, Accessed: 2021-11-11.
- [86] A. Ghosal, *Robotics: fundamental concepts and analysis*. Oxford university press, 2006.
- [87] Y. Patel, P. George, *et al.*, “Parallel manipulators applications—a survey,” *Modern Mechanical Engineering*, vol. 2, no. 03, p. 57, 2012.
- [88] C. Dumas, S. Caro, S. Garnier, and B. Furet, “Joint stiffness identification of six-revolute industrial serial robots,” *Robotics and Computer-Integrated Manufacturing*, vol. 27, no. 4, pp. 881–888, 2011.

- [89] E. Abele, M. Weigold, and S. Rothenbücher, “Modeling and identification of an industrial robot for machining applications,” *CIRP Annals*, vol. 56, no. 1, pp. 387–390, 2007.
- [90] Z. Pandilov and V. Dukovski, “Comparison of the characteristics between serial and parallel robots,” *Acta Technica Corvininesis-Bulletin of Engineering*, vol. 7, no. 1, 2014.
- [91] *Robot welding*, <https://rime.de/en/welding/robot-welding/>, Accessed: 2021-11-12.
- [92] D. Stewart, “A platform with six degrees of freedom,” *Proceedings of the Institution of Mechanical Engineers*, vol. 180, no. 1, pp. 371–386, 1965.
- [93] B. Dasgupta and T. Mruthyunjaya, “The stewart platform manipulator: A review,” *Mechanism and Machine Theory*, vol. 35, no. 1, pp. 15–40, 2000.
- [94] V. Gough, “Contribution to discussion of papers on research in automobile stability, control and tyre performance,” *Proc. of Auto Div. Inst. Mech. Eng.*, vol. 171, pp. 392–395, 1957.
- [95] *Hexapod Robot Applications in Automotive Assembly*, <https://www.pi-usa.us/en/tech-blog/hexapod-robots-in-automotive-applications/>, Accessed: 2021-11-12.

- [96] C. Georgiades, M. Nahon, and M. Buehler, “Simulation of an underwater hexapod robot,” *Ocean Engineering*, vol. 36, no. 1, pp. 39–47, 2009.
- [97] J.-P. Merlet, *Parallel robots*. Springer Science & Business Media, 2005, vol. 128.
- [98] F. Pierrot, C. Reynaud, and A. Fournier, “Delta: A simple and efficient parallel robot,” *Robotica*, vol. 8, no. 2, pp. 105–109, 1990.
- [99] *H-840 6-Axis Hexapod*, <https://www.pi-usa.us/en/products/6-axis-hexapods-parallel-positioners/h-840-6-axis-hexapod-700810/>, Accessed: 2021-11-12.
- [100] R. Clavel, *Device for the movement and positioning of an element in space*, US Patent 4,976,582, 1990.
- [101] L. Rey and R. Clavel, “The delta parallel robot,” in *Parallel Kinematic Machines*, Springer, 1999, pp. 401–417.
- [102] C. Connolly, “Abb high-speed picking robots establish themselves in food packaging,” *Industrial Robot: An International Journal*, 2007.
- [103] *Delta robot*, https://en.wikipedia.org/wiki/Delta_robot, Accessed: 2021-11-11.
- [104] H. Makino, “Development of the SCARA,” *Journal of Robotics and Mechatronics*, vol. 26, no. 1, pp. 5–8, 2014.

- [105] S. Krut, M. Benoit, H. Ota, and F. Pierrot, “I4: A new parallel mechanism for scara motions,” in *2003 IEEE International Conference on Robotics and Automation (Cat. No. 03CH37422)*, IEEE, vol. 2, 2003, pp. 1875–1880.
- [106] A. Burisch, S. Soetebier, J. Wrege, and R. Slatter, “Design of a parallel hybrid micro-scara robot for high precision assembly,” in *International IEEE Conference Mechatronics & Robotics*, Citeseer, 2004, pp. 1370–1380.
- [107] *Medium type SCARA robots YK-XG*, <https://global.yamaha-motor.com/business/robot/lineup/ykxg/middle/>, Accessed: 2022-01-13.
- [108] J. E. Correa, J. Toombs, N. Toombs, and P. M. Ferreira, “Laminated micro-machine: Design and fabrication of a flexure-based delta robot,” *Journal of Manufacturing Processes*, vol. 24, pp. 370–375, 2016.
- [109] T. Tanikawa, M. Ukiana, K. Morita, *et al.*, “Design of 3-DOF parallel mechanism with thin plate for micro finger module in micro manipulation,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, IEEE, vol. 2, 2002, pp. 1778–1783.
- [110] S. Y. Chin, V. Dikshit, B. Meera Priyadarshini, and Y. Zhang, “Powder-based 3D printing for the fabrication of device with micro and mesoscale features,” *Micromachines*, vol. 11, no. 7, p. 658, 2020.

- [111] M. A. Kalafat, H. Sevinç, S. Samankan, A. Altinkaynak, and Z. Temel, “A novel origami-inspired delta mechanism with flat parallelogram joints,” *Journal of Mechanisms and Robotics*, vol. 13, no. 2, pp. 1–22, 2021.
- [112] H. Li, X. Lai, C. Li, Z. Lin, J. Miao, and J. Ni, “Development of meso-scale milling machine tool and its performance analysis,” *Frontiers of Mechanical Engineering in China*, vol. 3, no. 1, pp. 59–65, 2008.
- [113] C. D. Onal, R. J. Wood, and D. Rus, “Towards printable robotics: Origami-inspired planar fabrication of three-dimensional mechanisms,” in *2011 IEEE International Conference on Robotics and Automation*, IEEE, 2011, pp. 4608–4613.
- [114] Z. Zhakypov and J. Paik, “Design methodology for constructing multimate-rial origami robots and machines,” *IEEE Transactions on Robotics*, vol. 34, no. 1, pp. 151–165, 2018.
- [115] J. P. Whitney, P. S. Sreetharan, K. Y. Ma, and R. J. Wood, “Pop-up book mems,” *Journal of Micromechanics and Microengineering*, vol. 21, no. 11, 2011.
- [116] *milliDelta: Millimeter-Scale Delta Robot*, <https://wyss.harvard.edu/technology/millimeter-scale-delta-robot-millidelta/>, Accessed: 2021-11-13.

- [117] *PL112 - PL140 PICMA Bender*, <https://www.piceramic.com/en/products/piezoceramic-actuators/bender-actuators/pl112-pl140-picma-bender-103000>, Accessed: 2022-10-31.
- [118] *Piezoelectric Benders*, https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=10958&pn=PB4NB2W, Accessed: 2022-10-31.
- [119] *Picma bender*, Physik Instrumente (PI) GmbH I& Co. KG, 2020. [Online]. Available: https://www.piceramic.com/fileadmin/user_upload/physik_instrumente/files/datasheets/PL112-PL140-Datasheet.pdf.
- [120] *Piezoelectric bimorph*, CTN010296-S01, Rev C, Thorlabs, 2020. [Online]. Available: <https://www.thorlabs.com/drawings/2228daa77ab7ede9-D5CCFD91-96DD-BA6A-ABE7B7EA38BBC5E5/PB4NB2W-SpecSheet.pdf>.
- [121] *Piezoelectric actuators*, V22-1, Thorlabs. [Online]. Available: https://www.thorlabs.com/images/Brochures/Thorlabs_Piezo_Brochure.pdf.
- [122] *Piezoelectric ceramic products*, CAT125E R3, Physik Instrumente (PI) GmbH I& Co. KG, 2016. [Online]. Available: https://static.piceramic.com/fileadmin/user_upload/pi_ceramic/files/catalog_CAT/PI_CAT125E_R3_Piezoelectric_Ceramic_Products.pdf.
- [123] D. M. Dykstra, J. Busink, B. Ennis, and C. Coulais, “Viscoelastic snapping metamaterials,” *Journal of Applied Mechanics*, vol. 86, no. 11, 2019.

- [124] C. Wu, T. T. Do, and P. Tran, “Mechanical properties of polyjet 3d-printed composites inspired by space-filling peano curves,” *Polymers*, vol. 13, no. 20, p. 3516, 2021.