Design and Implementation of Fiber Pigtailing Automation

by

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ABSTRACT

Attaching the endface of an optical fiber to an integrated optical component, a process known as "pigtailling", is currently a low-throughput and costly manual process. It is often the cost-driver in optoelectronics devices. In order to meet the forthcoming high-volume demand for commercial optoelectronic devices, pigtailling must be automated. This document describes the development of a fully automated pigtailling station which reduces the pigtailling cycle time by an order of magnitude relative to the current state-of-the-art.

Automated pigtailling is a difficult process because the attachment requires sub-micron motion resolution while the other motions of manipulating the fiber require significant range. To achieve both resolution and range, alignment modules based on a macro/micro manipulator architecture are presented. This architecture combines the range and speed of a macromanipulator with the resolution and high bandwidth of a micromanipulator.

This document describes and analyzes in detail a micromanipulator design which provides the sub-micron resolution necessary for pigtailling. This two-degree-of-freedom micromanipulator is comprised of two orthogonally mounted piezoelectric bimorph strips. The design achieves a range greater than 50 microns and a resolution finer than 100 nanometers, with a bandwidth of 189 Hertz. The micromanipulator, as part of the macro/micro alignment modules, was successfully demonstrated for production in industry. It pigtails optoelectronic devices that are within industry specifications, at much faster rates than current practice.

Thesis Supervisor: Dr. Andre Sharon
Title: Executive Officer of the Manufacturing Institute at M.I.T.
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To Scott
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Chapter 1

Introduction

1.1 Automated Fiber Pigtailing Machine (AFPM) Program and Goals

Fiber optic technology in the areas of communication, data transmission, and sensors is greatly increasing. For communication and data transmission, fiber optic signals are faster than electrical signals and are not subject to distortion from external noise and electro-magnetic interference. Fiber optics also have size and weight advantages compared to copper wire because fibers have much higher bandwidth than wire. Therefore a single fiber carries more streams of information than a single wire, so fewer fiber transmission lines are needed to carry the same amount of data as wire lines. In addition, fiber optics as sensors are increasingly common from temperature and pressure sensors to crack detection and other applications. Much of the fiber optic sensor technology has been available for years but finally the cost of fiber and related equipment is decreasing, so fiber optic sensors are now a viable option to traditional sensors.

Many applications for fiber optics require attaching the endface of a fiber to an Integrated Optoelectronic Component (IOC). This attachment is known as "pigtailing" because the fiber is commonly coiled at the attachment like the cork-screw tail of a pig. Pigtailing is a necessary operation and is the dominant cost of producing an optical device. This concentration of cost is because other processes involved in making optical devices are becoming less expensive and faster largely with technology directly borrowed from microelectronics fabrication. However, microelectronics do not have a similar process to pigtailing, so pigtailing cost and speed are not diminishing.

The optical devices which require pigtailling include applications which are increasingly for consumer markets and therefore demand high-volume production. Among these devices are transmitters and receivers for cable television and fiber optical
gyroscopes. Communication such as cable television already enjoys a vast consumer market, with continuing growth. Other applications such as fiber optic gyroscopes are shifting from high-tech applications to commercial automotive navigation⁴.

The inherent difficulty with pigtailing is that pigtailing requires sub-micron alignment tolerances. Currently, pigtailing is performed manually by highly-trained technicians with a microscope and manually adjustable positioning stages or, more recently, some computer controlled positioning stages. The average cycle time for some optical devices is over thirty minutes per pigtail due to the amount of manual fixturing and position adjustments. And many optical devices require several pigtails. The result is that pigtailing is an expensive and low-throughput process which is poorly suited to high-volume production as a manual process, but could be improved by implementing automation.

To assure that the U.S. remains a leader in optical technology and manufacturing, the AFPM Program was launched to design, build, test, and integrate an AFPM which quickly aligns and attaches optical fibers to IOCs in a queue. The AFPM aims at a cycle time of three minutes per pigtail, a cost which is conducive for use in competitive industry, as well as versatility and ease of use. As part of the effort to develop the AFPM, the Manufacturing Institute at M.I.T. designed and built alignment modules which perform the operations of carrying, positioning, and aligning the optical fibers to an IOC within the three minute target cycle time. These alignment modules are computer controlled with position and alignment feedback, and can be programmed to perform alignments on a variety of IOCs and fibers. The alignment modules are designed to meet or exceed the specifications for motion and alignment as designated by the industrial users.
1.2 Pigtailing Automation Requirements

Many types of pigtails are made to various IOCs. The pigtailing process targeted to demonstrate the performance of the alignment modules involves an IOC with "waveguides" or integral light paths diffused into the surface of a clear crystalline material. Waveguides have a similar size and function to the light transmitting core of a fiber. To automate the fiber pigtailing process, the machine must be able to manipulate a fiber, apply epoxy to the fiber endface, and align and affix the fiber to the waveguide of an IOC.

Fiber alignment involves maximizing the light which passes from the fiber to the IOC waveguide before permanently attaching the fiber to the IOC. Angular and spatial misalignments of the fiber to the waveguide will result in less light passing through the connection and therefore poorer performance of the optical device. The best feedback to improve the connection alignment is from the actual light intensity passing through the connection versus position. This feedback is established by shining laser light through the fiber while a photodetector on the other side of the IOC waveguide measures the light intensity through. An epoxy which matches the index of refraction of the fiber core is then applied to the end of the fiber, the fiber is again optimally aligned, and the epoxy is then cured in situ with strong ultra-violet light, while maintaining active alignment. The epoxy cure results in a strong, permanently aligned connection between the fiber and waveguide.

The simplest way to perform the fiber manipulation, epoxy application, and fiber alignment is to have a single automated robot, in this case the alignment module, move to precisely located fixtures which locate the fiber for pick-up, the epoxy dispenser, and the IOC to be pigtailed. Eliminating unnecessary actuation such as moving the epoxy station towards the fiber or having the IOC holder perform the alignment on a fiber which is already held in a mobile robot, simplifies the primary functions and minimizes the cost and
complexity of the AFPM. Therefore, the alignment module must have both the range to reach the fiber, epoxy, and IOC locations and have the resolution to perform the fiber to waveguide alignment.

1.3 Macro/Micro Architecture Advantages

An elegant solution which achieves large range and fine resolution at low cost is a macro/micro manipulator. A macro/micro manipulator consists of a macromanipulator which carries a micromanipulator at its endpoint. The macro/micro combines a small robot with fine resolution with the motion, speed, and range of a large robot\(^5\). The macromanipulator moves the full range of the workspace, and has a resolution suitable for the gross positioning of the fiber but too coarse for the aligning of the fiber to the waveguide. The micromanipulator has the sub-micron resolution needed to align the fiber to the waveguide, but has a limited range. Standard off-the-shelf actuators rarely have a resolution much less than three orders of magnitude smaller than their range. For the alignment modules, the required range is on the order of tens of millimeters (m\(^3\)) and the resolution is on the order of tens of nanometers (m\(^9\)) for about six orders of magnitude between the range and resolution. To achieve six order of magnitude with a single actuator with existing technology is either expensive, slow, or bulky. For the macro/micro architecture, so long as the range of the micromanipulator is greater than the resolution of the macromanipulator, the combined macro/micro manipulator can reach any point in the workspace with the desired resolution. And even though the macro/micro manipulator has twice as many actuators and controllers, the overall cost is still reduced because the macro/micro can use less accurate and lower cost actuators and encoders\(^6\).

The motion of the macro/micro manipulator is controlled by two closed-loop active feedback systems. The first, or internal loop, gives position commands based on feedback
from position sensors, such as motor encoders, which track the position of the macromanipulator. The internal loop exclusively controls the macromanipulator and is for the coarser positioning tasks of picking up the fiber, moving to an epoxy station, and moving to the vicinity of the IOC waveguide. The second, or external loop, gives position commands based on feedback from the light intensity as measured by a photodetector. The external loop finely controls the high-tolerance alignment of the fiber to the IOC which is primarily for the micromanipulator but may involve the macromanipulator if the alignment position moves out of the range of the micromanipulator. These internal and external loops are schematically shown in figure 1.1:

![Diagram of feedback loops](image)

Figure 1.1: Feedback loops
In addition to having range and resolution for low cost, the macro/micro architecture also has other advantages\(^5,6\). Several of these advantages apply directly to the functions of the AFPM alignment modules. These macro/micro advantages are realized within the critical alignment workspace, which is defined as the range during which some light intensity feedback is available. The light intensity feedback is essential because it provides position feedback at the absolute endpoint of the system and its accuracy is only limited by the resolution of the of the photodetector signal. Absolute endpoint feedback is more error-free than shaft sensors such as motor encoders. Using a motor encoder as an example, the encoder measures the position of the rotor to within some accuracy resolution but is blind to position errors which occur between the rotor and endpoint such as twist in the motor shaft, backlash, or bending in the linkages attached to the shaft. With absolute endpoint feedback, the micromanipulator can compensate for the accumulated static and dynamic position errors of the macromanipulator\(^5\). Because of this compensation, the macromanipulator does not need positioning accuracy, which is defined as the ability to reach an absolute position in space. Rather, the macromanipulator needs command resolution, such that the macromanipulator can move tiny increments to position the micromanipulator for alignment. The fact that the macromanipulator does not need to be accurate is a distinct advantage because providing accuracy over a large range is very difficult.

References 5 and 6 also outline a dynamic model of the macro/micro system which gives good physical insight into the dynamic characteristics of the alignment modules. An important conclusion from this dynamic model is that the macro/micro system gives stable response over all frequencies including those near the resonant frequency of the macromanipulator. It is further shown that if the mass of the macromanipulator is much larger than the mass of the micromanipulator, the system is stable over all frequencies, and the macro/micro transfer function actually reduces to the transfer function of the micromanipulator alone\(^5\). In the case of the AFPM alignment modules, the mass of the
prototype macromanipulator is on the order of a kilogram while the mass of the prototype micromanipulator is on the order of a few grams. The macromanipulator is discussed further in Chapter 2, and the micromanipulator is discussed further in Chapters 3 and 4. The result of the transfer function reduction is that the micromanipulator can be attached to the macromanipulator and controlled independently of the macromanipulator dynamics. Furthermore, since the macro/micro dynamics reduce to only the micromanipulator dynamics, the bandwidth of the system becomes the bandwidth of the micromanipulator alone. The micromanipulator has high bandwidth because it has low-inertia and therefore it is capable of high acceleration. A single actuator with the range and resolution of the macro/micro actuator is certainly bulkier than a microactuator alone. and therefore has higher inertia and lower bandwidth.

High bandwidth is desirable for two reasons. First, high bandwidth in the critical alignment area allows the micromanipulator to align quickly and reduce the cycle time of pigtailing. Second, it is advantageous for the micromanipulator to have a bandwidth that is higher than that of the macromanipulator such that the micromanipulator can compensate for dynamic errors of the macromanipulator as well as static errors. In this way, the micromanipulator essentially performs vibration control of the macromanipulator. In the optics industry, vibration control is very important because vibrations considered negligible in other industries can have extreme impact on the sub-micron positioning in optics. In fact, most optical alignments, including pigtailing, are performed on special vibration-isolation tables. These macro/micro advantages in cost, stability, and bandwidth make this architecture an excellent candidate for pigtailing automation.
1.4 Thesis Objectives

As part of the Macro/Micro Alignment Module for the AFPM project, this thesis presents the development of a micromanipulator which is capable of the alignment resolution required to pigtail. Having considered a spectrum of microactuators, the micromanipulator design is based on piezoelectric actuation. Chapter 3 describes a piezoelectric bimorph strip manipulator design and analytical models of both the static and dynamic behavior of the micromanipulator. Chapter 4 presents experimental data which verify the predictions of the models. Finally, Chapter 5 describes some further considerations for the next generation of micromanipulators.

In the interest of preserving proprietary information of the AFPM program and its industrial collaborators, detailed drawings of the manipulators and full information about the optical devices and manufacturing processes are not included.
2.1 Translation Range and Resolution

Having established that the automated fiber pigtailling machine will have alignment modules which pick-up and manipulate the fiber, move the fiber to an epoxy station and to the IOC, and then align the fiber to the IOC waveguide, the overall range and resolution of the alignment modules must be specified. Once the range and resolution are targeted, the alignment modules can be designed to meet those specifications. The range and resolution specifications are given in terms of Cartesian coordinates with respect to the fiber axis. These coordinates are shown in figure 2.1:

![Cartesian Coordinates](image)

**Figure 2.1: Translational Coordinates x, y, z Along Fiber Axis**

The overall range specification for the alignment module is somewhat arbitrary. The alignment module must have enough range to reach the fiber pick-up point, and epoxy station, and the IOC holder, but those locations are not constrained. Based on the experience and intuition of the design team and the industrial collaborators, a range of
25mm in each x, y, and z was specified. Therefore, the fiber and IOC holders and the epoxy dispensing tip must be within the 25mm cubic workspace.

The specifications for the resolution are more rigorously quantified. The resolution refers to the smallest increment of motion that the alignment module is able to reliably perform. Therefore, the resolution specifications are a function of the allowable misalignment of the fiber to the waveguide. Any misalignment results in a loss of optical power, so the maximum acceptable loss of optical power determines the maximum allowable resolution.

Some knowledge of how a fiber transmits light is necessary to analyze the power lost due to misalignment. A fiber consists of the jacket, the cladding, and core, as shown in figure 2.2. The cladding and core are both glass and are fused together. The jacket is a polymer and protects the glass. The jacket is stripped off much like the insulation around copper wire. The cladding is typically pure silicon which has an index of refraction of 1.4525. The index of refraction of a material is defined as the ratio of the speed of light in a vacuum to the speed of light in the material.

![Figure 2.2: Parts of an Optical Fiber](image)
n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the material}} \quad (2.1)

By comparison, the index of refraction of air is around 1.003. The core is primarily silicon which is doped with other materials to slightly raise the index of refraction. For the test optical device of the AFPM, the index of refraction of the core is 1.4574. This index varies among fibers for different applications.

The light is transmitted through the core by refracting off the core/cladding interface\(^7\). This transmission is depicted in figure 2.3. Only rays of light which enter the core at a shallow angle relative to the core/cladding interface are transmitted by refraction. The ratio of the indices of refraction of the cladding and core determine the maximum angle which refracts off the interface.

![Diagram of light transmission in the fiber core]

Figure 2.3: Light Transmission in the Fiber Core

Snell's law of optics describes the change in angle of the light due to a change in index of refraction as:

\[ n_1 \cos \theta_1 = n_2 \cos \theta_2 \quad (2.2) \]
Refraction occurs when equation 2.2 can no longer be solved for real values of $\theta_2$, as shown by rearranging equation 2.2:

$$
\theta_1 = \cos^{-1}\left\{ \frac{n_2}{n_1} \cos \theta_2 \right\}
$$

(2.3)

The value of $\theta_2$ is no longer real when $\cos \theta_2 > 1$. The maximum possible refracted angle occurs when $\cos \theta_2 = 1$, so for this fiber \( \theta_1 = \cos^{-1}\left\{ \frac{1.4525}{1.4574} (1) \right\} = 4.7^\circ \). Light traveling at angles greater than $4.7^\circ$ incident to the core/cladding interface pass through the cladding and are absorbed in the jacket.

At the endface of a fiber, when the light leaves the core into the air or another material, the beam diverges at an angle related to the refractive angle and the index of refraction of the new material. In fiber alignment, this diverging angle creates a loss of optical power proportional to the longitudinal misplacement between the fibers because the beam spreads before reaching the receiving core. Figure 2.4 depicts a fiber to fiber misalignment in the longitudinal $z$ direction.

Figure 2.4: Longitudinal Fiber-to-Fiber Misalignment
For the optical power loss calculations, fiber to waveguide losses are approximated as fiber to fiber losses because fiber to fiber losses are mathematically simpler to estimate since the cross-sectional area of both fiber cores is circular. The loss of optical power in decibels is estimated as the projected area of the light beam onto the receiving fiber core as the area grows over the distance \( z \) due to the diverging angle, by\(^8\):

\[
\text{Loss} = -10 \log_{10} \left\{ 1 - \frac{z}{2d} \left( \frac{\sqrt{n_1^2 - n_2^2}}{n_3} \right) \right\}
\] (2.4)

where \( d \) is the core diameter, \( z \) is the distance between the ends of the fibers, \( n_1, n_2 \) and \( n_3 \) are the refractive indices of the core, cladding, and medium between the fibers, respectively. Note that power loss in optics scales by a factor of 10, as opposed to the factor of 20 used in electronics.

Loss of optical power also occurs due to transverse misalignment in the \( x, y \) directions, as depicted in figure 2.5:

![Figure 2.5: Transverse Fiber-to-Fiber Misalignment](image)

Again, the loss in optical power is related to the refracting angle of the light, but transverse misalignment is also a function of the overlap of the cross-sectional areas of the misaligned cores. The loss of optical power in decibels is estimated as\(^8\):
\[
\text{Loss} = -10 \cdot \log_{10} \left\{ \frac{1}{90} \tan^{-1}\left( \frac{d}{x} \sqrt{1 - \frac{x^2}{d^2}} \right) - \left( \frac{2x}{\pi \cdot d} \sqrt{1 - \frac{x^2}{d^2}} \right) \right\}
\]  

(2.5)

where \(d\) is the diameter of the fiber core, and \(x\) is the distance between the center of the cores.

For the pigtailing application used to demonstrate the capability of the alignment modules, the total optical loss must be less than 0.5dB, or 11%, per pigtail to meet customer specifications. The total loss of optical power in the pigtail is a combination of losses due to longitudinal and transverse misalignments. But the magnitude of the power lost per nanometer of misalignment in \(z\) is different from the magnitude of the power lost per nanometer of misalignment in \(x, y\). This difference in magnitudes creates different resolution requirements in \(z\) motion than in \(x, y\) motion. To quantify this difference, figure 2.6 shows the optical loss per nanometer of misalignment for both the \(z\) direction and the \(x, y\) directions. The magnitudes are for a 5\(\mu\)m core diameter and calculated from equations 2.4 and 2.5. To be within a total of 0.5dB optical power loss, the target resolution of the alignment module in \(z\) is 500nm and in \(x, y\) is 100nm. At these resolutions, the maximum possible longitudinal and transverse misalignment are 500nm and 100nm respectively, resulting in a maximum total optical loss, as calculated from equations 2.4 and 2.5, of 0.14dB, or 3.2%.
2.2 Angular Alignment

The total optical power allowed from longitudinal and transverse misalignments is necessarily conservatively under 0.5dB because power loss occurs also due to angular misalignments. The two angular misalignments are yaw and pitch of the fiber about the x and y axes and roll about the z axis. However, adding rotational degrees of freedom to the x, y, z manipulator to actively align the angles requires additional actuators, more position feedback, and more computer interface. To keep these costs and complexities down, the angular alignments are focused on passive registration of the fibers and IOCs. The angular tolerances that these registered fixtures must hold is also a function of the optical loss due to misalignment. Angular x,y misalignment is depicted in figure 2.7:
Figure 2.7: Angular Misalignment about x or y

Similar to the loss from longitudinal z and transverse x,y, the optical loss due to angular misalignment about x,y is estimated as:

\[
\text{Loss} = -10 \cdot \log_{10} \left( 1 - \frac{\theta}{\pi} \frac{n_3}{\sqrt{n_1^2 - n_2^2}} \right)
\]  

(2.6)

where \( \theta \) is the angle between the fibers in radians, and again \( n_1, n_2 \) and \( n_3 \) are the refractive indices of the core, cladding, and medium between the fibers, respectively. Equation 2.6 shows that the passive alignment tolerances are very tight. Angular misalignment in air as small as 1° result in 0.21dB, or 4.7%, of optical power lost.

Misalignment from angular roll about the z axis causes losses of optical power due to more complex phenomena. Essentially, the light must be maintained in one axis of polarization, and angular misalignment about z allows light to enter other axes of polarization. This undesirable leaking of light into other axes is called polarization cross-talk. The manufacturer of the test optical device estimates that the amount of polarization cross-talk from roll about z is acceptable for misalignments less than 1.8°.
2.3 Micromanipulator Range and Macromanipulator Resolution

The overall range and resolution specifications of the pigtailling process are summarized in Table 2.1:

<table>
<thead>
<tr>
<th></th>
<th>range</th>
<th>resolution</th>
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<tbody>
<tr>
<td>x</td>
<td>25mm</td>
<td>100nm</td>
</tr>
<tr>
<td>y</td>
<td>25mm</td>
<td>100nm</td>
</tr>
<tr>
<td>z</td>
<td>25mm</td>
<td>500nm</td>
</tr>
</tbody>
</table>

Table 2.1: Range and Resolution Specifications

The alignment modules must meet or exceed these specifications for x, y, and z motion.

The z direction actuation does not use a macro/micro architecture for two reasons. One, the z resolution specification is larger than the x, y resolution specification and the actuator can manage both the range and resolution. Two, the dynamic alignment of the fiber to the waveguide takes place in the plane of the fiber endface which involves the x and y directions but not the z direction, so the bandwidth advantages of the macro/micro architecture do not apply to the z direction. The z actuation is accomplished with a single lead screw which moves a stage that carries the x, y macro/micro manipulator. Due to the high gear reduction of a fine-pitch lead screw with 40 threads per inch and further timing belt gear reduction, the z direction stage achieves the 500nm resolution with a low-cost motor and encoder. Per encoder tick the z direction stage moves 0.062μm. However, the controller is unlikely to be able to achieve one-tick motion consistently. The target resolution of 0.5μm corresponds conservatively to 8 encoder ticks of motion. The range of the z direction stage depends only on the length of the lead screw. By choosing a longer lead screw than necessary for the alignment modules, a z direction range of 50mm was
achieved, conveniently doubling the workspace of the alignment modules while still retaining a compact size for the z direction stage.

The actuation for the x,y axes uses is a macro/micro architecture for the advantages discussed in section 1.3. Since the overall range and resolution have been specified, the final design targets needed for x,y motion are the resolution of the macromanipulator and the range of the micromanipulator. These values are related, as discussed earlier, in that the micromanipulator range must at least equal the macromanipulator resolution for the alignment module to be able to reach every point in the workspace with the micro resolution. For the AFPM alignment module design, the resolution of the macromanipulator is determined first and this resolution specifies the minimum range of the micromanipulator.

The macromanipulator is comprised of a five-bar mechanism actuated by two DC servo motors. The mechanism has four links, where the fifth “link” is the distance between the motor shafts. The motor drives the first and fourth links, as shown in figure 2.8. The endpoint of the macromanipulator is positioned anywhere in the workspace by coordinating the angular positions of the two motors. Unlike purely Cartesian straight-line actuators, the five-bar mechanism does not require one actuator to carry the other. Many x,y positioners have x actuation mounted on y actuation or vice versa. Therefore one actuator carries a significant load and is reduced in dynamic bandwidth.

For the AFPM alignment modules, the link lengths are approximately 7cm long and were chosen so that the x,y motion exceeds the 25mm range specification for a full 90° angular range of links 1 and 4. The actuators are harmonic-drive motors with a high internal gear reduction. With 360 bit encoders, this allows for 1.2µm of motion per encoder tick. However, again the controller is unlikely to be able to achieve one-tick motion consistently, but the motion specification is met with a very conservative resolution.
of 20 ticks, or 25\mu m of motion. Given a macromanipulator range of 25\mu m, a reasonable
target resolution for the micromanipulator is double the macro resolution, or 50\mu m. In the

Figure 2.8: Macromanipulator Five-Bar Mechanism

aligning process, having a generously large micromanipulator range is useful because the
micromanipulator scans its entire workspace in approximately the same amount of time
regardless of the workspace size because the strain rate of the piezo ceramic is very high
when the voltage is applied. Since the micromanipulator may scan its entire range many times when searching for the light beam, and a large range covers more area than a small range, a large range will find the beam with fewer scans and therefore in less time.

Once the micromanipulator was fully specified with an x,y range of 50μm and an x,y resolution of 100nm, actuators had to be selected. The choice of actuators and their implementation into the micromanipulator are discussed in Chapter 3.
Chapter 3

Micromanipulator Design

3.1 Micro Actuators

Many types of actuators can achieve the range and fine resolution required for the micromanipulator. Table 3.1 shows an abridged list of potential micro actuation concepts.

<table>
<thead>
<tr>
<th>Actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Motor</td>
</tr>
<tr>
<td>2  Piezoelectric Ceramic</td>
</tr>
<tr>
<td>3  Electrostrictive Ceramic</td>
</tr>
<tr>
<td>4  Magnetostrictive Ceramic</td>
</tr>
<tr>
<td>5  Shape Memory Alloy</td>
</tr>
<tr>
<td>6  Bimetalic Strip</td>
</tr>
<tr>
<td>7  Thermal Expansion</td>
</tr>
<tr>
<td>8  Electric Field</td>
</tr>
<tr>
<td>9  Magnetic Field⁹</td>
</tr>
<tr>
<td>10 Pneumatic</td>
</tr>
<tr>
<td>11 Hydraulic</td>
</tr>
<tr>
<td>12 Superconducting Levitation</td>
</tr>
<tr>
<td>13 Surface Tension¹⁰</td>
</tr>
</tbody>
</table>

Table 3.1: Micro Actuators
For selecting a microactuator for the alignment module, the criteria, in order of importance, are:

1. resolution capability
2. speed
3. cost and availability
4. cost and availability of controllers
5. range/size

As discussed in section 2.1, the resolution capability is essential for the pigtailing process, and every actuator in table 3.1 can be controlled to meet this requirement. The second criterion, speed, is necessary because of the dynamic requirement of one pigtails every three minutes. Each pigtails may demand many cycles of scanning the 50μm range just to initiate light coupling to the photodetector, and then many more cycles of sub-micron scanning to align the fiber and hold the alignment during the epoxy curing time. Actuators 5, 6, and 7 from Table 3.1 are position controlled by temperature, so while rates of heating can be very high, the time to cycle over the range of these actuators is dominated by cooling times, which would be on the order of seconds, not milliseconds. Therefore, these actuators cannot be considered for the micromanipulator. Cost and availability of actuators and their controllers in a competitive industry are also critical and eliminate many of the more exotic actuation schemes such as 4, 8, 9, 12, 13. The last important criterion for the microactuator is the range to size ratio. Actuators which are inherently bulky or which must be large to achieve the 50μm range are unacceptable because the micromanipulator is carried by the macromanipulator, and as discussed in section 1.3, the macro/micro architecture is only well behaved over the entire range of frequencies when the mass of the macromanipulator is significantly larger than the mass of the micromanipulator. This range/size ratio eliminates actuators 1, 10, and 11. Piezoelectric ceramics and
electrostrictive ceramics are the actuators which remain as possibilities after the process of elimination. These actuators have similar characteristics and can be used interchangeably. Of the two types of actuators, piezoelectric material is more common and is available in more shapes and forms than electrostrictive material.

Piezoelectric materials (and electrostrictive materials) produce a strain when subject to an electric field. This piezoelectric property occurs naturally in some crystalline materials and can be permanently induced into some ceramic materials during a high voltage process called poling. After poling, the ceramic material will change its dimensions in response to an applied voltage. Ceramic materials are used because ceramic powders can be pressed and formed into a variety of shapes which can be poled to strain along different axes.

The strain directions depend on both the poling axis direction and the applied voltage direction. The deformation amplitude per volt depends on the type of ceramic material\textsuperscript{11}. Figure 3.1 depicts the extension/contraction of a piezoelectric ceramic block with the poling direction the same as the applied voltage direction.

![Piezoelectric Ceramic Block with Applied Voltages](image)

Figure 3.1: Piezoelectric Ceramic Block with Applied Voltages
For the parallel poling and applied voltage configuration shown in figure 2.9, the block expands and contracts along the direction of poling proportional to the applied voltage $V$ and the piezoelectric constant $d_{33}$, such that:

$$\Delta y = V \, d_{33}$$  \hspace{1cm} (3.1)

Similarly, the block expands and contracts perpendicular to the direction of poling proportional to the applied voltage $V$ and the piezoelectric constant $d_{31}$, such that:

$$\Delta x = V \, d_{31}$$  \hspace{1cm} (3.2)

Where a typical value for $d_{33}$ is 500nm/$V$ and $d_{31}$ is -250nm/$V$. Notably, $d_{31}$ is negative since the perpendicular direction contracts as the parallel direction expands in the presence of positive voltage, and vice versa for negative voltage. These piezoelectric constants determine the range and resolution capabilities of the piezoelectric micromanipulator described in chapter 3.

This piezoelectric micromanipulator attaches to the endpoint of the macromanipulator five-bar linkage. Figure 3.2 shows a sketch of the complete macro/micro actuator mounted on the $z$ direction stage.
Figure 3.2: Alignment Module with x, y and z Motion.

3.2 Bimorph\textsuperscript{p} Strips

A bimorph strip has two thin layers of a piezoelectric ceramic with a thin conductive layer in between. When an electric field is placed across the thickness of the layers, one piezoelectric layer will expand while the other layer contracts, causing bending of the strip. In this way a piezoelectric strip with electrically induced strain is similar to a bimetallic strip.

\textsuperscript{p}Bimorph is a registered trademark of Morgan Matroc, Inc. Bedford, OH
with thermally induced strain. If one end of the bimorph strip is clamped, the bending of the bimorph can be measured as a deflection of the free end. Figure 3.3 shows the deflection of a bimorph strip mounted as a cantilever before and after application of an electric field. The tip deflection of a bimorph actuator has a greater range of motion than simple expansion or contraction of a piezoelectric block of the same dimensions, so the bimorph strip is an excellent actuator for a compact micromanipulator design. The relationship between voltage and tip deflection is derived in section 3.3.1.

Bimorph strips are available with two types of electrical connections depending on the piezo ceramic poling directions. These connections are called either series or parallel connections. The cantilever mounted strip in figure 3.3 shows a series bimorph driven with an electrical connection to the top and bottom conductive surfaces of the strip. The other type of bimorph strip has a parallel connection driven with electrical connections to
the top and bottom surface electrodes as well as the center electrode. Figure 3.4 schematically shows the difference between series and parallel bimorph connections and ceramic poling directions.

![Diagram of series and parallel bimorph connections](image)

**Figure 3.4: Series and Parallel Bimorphs**

For the micromanipulator, series connection bimorph strips were chosen over parallel connection bimorph strips. Because the applied voltage is across only half the thickness in the parallel bimorph strip as compared to the series bimorph strip, the electric field induced is twice as strong, and the resulting tip deflection is doubled. While doubling the deflection is advantageous because the range of motion at the tip would be doubled, the parallel bimorph strip produces only half the force at the tip as the series bimorph strip. The actuator's ability to produce force is important because force is needed to accelerate the mass of the fiber and fiber holder at the manipulator endpoint. Furthermore, the electrical
connection to the center vane is delicate, making parallel bimorph strips less desirable for wiring and robustness in the field than series bimorph strips.

3.3 Bimorph Micromanipulator Design

The bimorph micromanipulator design is similar to the macromanipulator five-bar linkage, where the tip deflections of two bimorph strips control the endpoint position. The range of the bimorph strip tip deflections define the workspace of the micromanipulator which the endpoint can reach. Like the five-bar macromanipulator, the design for the bimorph micromanipulator does not require either the x or the y actuator to carry the other, and the two bimorph strips work with coordinated motion to position the endpoint in Cartesian coordinates. The bimorph micromanipulator is sketched in figure 3.5. The workspace size relative to the bimorph strip is exaggerated in the sketch.

![Diagram of Bimorph Micromanipulator](image)

Figure 3.5: Bimorph Micromanipulator
The bimorph strips are part of a linkage which includes two inactive plastic strips. The fiber holder is mounted on the inactive strips at the endpoint. The scale and location of the micromanipulator with respect to the macromanipulator is shown more closely in figure 3.6.

![Micromanipulator x,y (5cm high)](image)

![Macromanipulator x,y (10cm high)](image)

Figure 3.6: Complete x,y Macro/Micro Manipulator

3.3.1 Range

As discussed in section 2.3, the range of the micromanipulator is targeted at 50μm or greater, and the total tip deflection from fully deflected up to fully deflected down for
each bimorph strip defines the range in either x or y. Together, the bimorph ranges define the micromanipulator workspace size. To calculate the range of the micromanipulator, the relationship between the applied voltage and the tip deflection of the bimorph strip must be known. The range is then simply the maximum applied voltage multiplied by the deflection per volt.

The voltage to deflection relationship is found by modeling a bimorph strip as a beam undergoing Bernoulli-Euler deformations. The Bernoulli-Euler strains are uniform across the entire bimorph in extension and vary linearly across the thickness for bending as illustrated in figure 3.7\textsuperscript{12}.

![Diagram of bimorph strip with labels](image)

**extensional strain distribution**

**bending strain distribution**

Figure 3.7: Bernoulli-Euler Model Geometry and Strain Distributions
This model makes several simplifications. First, only deformation due to $d_{31}$ coupling are considered, and therefore changes in the thickness of the bimorph due to $d_{33}$ strain are neglected. Second, the bonding layer between the piezo actuators and the brass center vane is assumed to be perfectly stiff and infinitely thin, so that there are no shear losses in transferring strain from the actuators. Third, the piezoelectric coefficient $d_{31}$ is assumed to be constant in the presence of various electric fields. And lastly, the tip deflection is assumed to be linear, when the tip actually moves in a parabola. This simplification is justified since the deflection of the bimorph strip is small compared to the strip length, so the deflections are nearly linear.

The total force acting on the bimorph strip to cause extension in the $x$ direction is the sum of any external mechanical forces in the $x$ direction $P_m$, and the internal force induced in the piezo $P_p$, by the applied electric field.

$$P_{\text{total}} = P_m + P_p$$ (3.3)

Similarly, the total moment acting on the bimorph beam to cause bending about the $z$ axis, where $z$ is out of the page in figure 3.7, is the sum of any external mechanical moment about the beam axis $M_m$, and the internal moment induced in the piezo $M_p$, by the applied electric field.

$$M_{\text{total}} = M_m + M_p$$ (3.4)

Externally applied forces and moments create the resultant force $P_m$ in the $x$ direction and moment $M_m$ about the $z$ axis. These can be found by integrating the stress distribution in the beam$^{12}$.
\[ P_m = \int_y \sigma(y) \, dy \quad (3.5) \]

\[ M_m = \int_y \sigma(y) \, y \, dy \quad (3.6) \]

The internal forces and moments are induced by a voltage interacting with the piezoelectric effect, and are similarly found by integrating the stress distribution in the strip. A voltage \( V \), applied across the bimorph thickness \( t_p \), creates an electric field \( E \).

\[ E = \frac{V}{t_p} \quad (3.7) \]

The applied electric field creates a strain perpendicular to the field in the piezo electric material proportional to the piezo electric coefficient \( d_{31} \), as explained in section 3.1 and shown in figure 3.1.

\[ \varepsilon_p = d_{31} \, E = d_{31} \, \frac{V}{t_p} \quad (3.8) \]

From this induced strain \( \varepsilon_p \), and the modulus of the piezo ceramic material \( E_p \), the stress in the bimorph is determined by:

\[ \sigma_p = E_p \, \varepsilon_p \quad (3.9) \]

In the same form as equations 3.5 and 3.6, the force and moment induced in the piezo of width \( b_p \) in the z direction by the electric field is determined by\(^{12}\).
\[ P_p = \int_y E_p(y) \varepsilon_p(y) b_p(y) \, dy \quad (3.10) \]

\[ M_p = \int_y E_p(y) \varepsilon_p(y) b_p(y) y \, dy \quad (3.11) \]

Equations 3.10 and 3.11 are the generalized form for any bimorph cross section. For the bimorph with two piezo strips separated by a brass center vane all with constant width \( b_p \) like the cantilever strip shown in figure 3.3, the force induced by the electric field in one piezo strip reduces from equation 3.10 to\(^{12}\):

\[ P_p = E_p \, b_p \, t_p \, \varepsilon_p \quad (3.12) \]

and by substituting in equation 3.8 for \( \varepsilon_p \) into equation 3.12, the induced force becomes:

\[ P_p = E_p \, b_p \, d_{31} \, V \quad (3.13) \]

which is simply the force induced in one piezo layer since the brass center is not affected by the electric field. Similarly, the moment induced by the electric field in one piezo layer, reduced from equation 3.11 and with substitution from equation 3.8 for \( \varepsilon_p \), becomes:

\[ M_p = -E_p \, b_p \left( \frac{t_s}{2} + \frac{t_p}{2} \right) d_{31} \, V \quad (3.14) \]

Equation 3.14 shows that the thickness of the brass center increases the moment by holding the piezo layers away from the center axis of the strip.
For the bimorph strip, the force induced in the top piezo layer is opposite in direction to the force induced in the bottom piezo layer due to the direction of poling with respect to the direction of the electric field. This results in no net force, and therefore no net extension of the center axis of the strip:

\[ P_{p1} + P_{p2} = 0 \]  \hspace{1cm} (3.15)

However, the moments induced in the top and bottom piezo layers are in the same direction and contribute equally to the net induced moment:

\[ M_{p1} + M_{p2} = -2 \ E_p \ b_p \ \left( \frac{t_1}{2} + \frac{t_2}{2} \right) \ d_{31} \ V \]  \hspace{1cm} (3.16)

Assuming no externally applied forces \( (P_m = M_m = 0) \) the induced moment in the bimorph strip determines the magnitude of the tip deflection of the bimorph strip. And as discussed, the amount of tip deflection per volt applied determines the range of the bimorph strip. This range depends on the dimensions and piezo electric coefficient \( d_{31} \) of the bimorph and therefore determines the optimal bimorph strip size and material to use in the micromanipulator.

The bending moment \( M_p \) induces the tip deflection \( \delta \). The moment to deflection relationship is\(^{13}\):

\[ \delta = \frac{M_p \ L}{2 \ E_{total} \ I_{total}} \]  \hspace{1cm} (3.17)

where \( L \) is the length of the strip and \( I_{total} \) is the moment of inertia of the entire strip about the z axis:
\[ I_{\text{total}} = \frac{b \left( t_s + 2 t_p \right)^3}{12} \]  
(3.18)

and \( E_{\text{total}} \) is the total combined modulus of the beam calculated from percent of cross-section area for the piezo ceramic and brass material, calculated as:

\[ E_{\text{total}} = \frac{E_s A_s + 2 E_p A_p}{A_s + 2 A_p} = \frac{E_s t_s + 2 E_p t_p}{t_s + 2 t_p} \]  
(3.19)

where \( A_p \) and \( A_s \) are the cross-sectional areas of the piezo ceramic and the brass center vane, respectively. Since the width of the piezo ceramic and the brass are equal, the cross-sectional area ratios reduce to the thicknesses.

Substituting equations 3.14, 3.18, and 3.19 into equation 3.17 defines tip deflection in terms of material dimensions and properties:

\[ \delta = \frac{-3 E_p \left( t_s + t_p \right) d_{31} V L^2}{\left( E_s t_s + 2 E_p t_p \right) \left( t_s + 2 t_p \right)^2} \]  
(3.20)

In equation 3.20, the voltage \( V \) is applied over the entire thickness of the strip, as opposed to the voltage being applied over each piezo layer. The negative sign reflects that if the applied voltage is in the positive sense with the positive voltage above the negative voltage, the top piezo layer expands and the bottom piezo layer contracts and the bimorph tip deflects downward.

From equations 3.20 the deflection of the micromanipulator per applied volt is calculated. Table 3.2 lists the dimensions and material constants of the piezoelectric bimorph strips used in the calculation.
\[ d_{31} = -0.274 \frac{\text{nm}}{\text{V}} \]

\[ V_{\text{max}} = 56 \text{V} \]

\[ L = 23 \text{mm} \]

\[ E_p = 71 \frac{\text{GN}}{\text{m}^2} \]

\[ E_s = 100 \frac{\text{GN}}{\text{m}^2} \]

\[ t_p = 0.2794 \text{mm} \]

\[ t_s = 0.0508 \text{mm} \]

Table 3.2: Micromanipulator Bimorph Values

The bimorph strips are actually 25.4mm in length, but fixturing both ends of the strip into the manipulator structure leaves an effective length of 23mm. The maximum voltage \( V_{\text{max}} \) is set from the low-cost amplifiers built for the AFPM. A schematic of the amplifiers is found in Appendix A.

Calculating the maximum deflection \( \delta_{\text{max}} \) from equation 3.20 and with the values from table 3.2 results in:

\[ \delta_{\text{max}} = 34.3 \mu\text{m} \]

\[ \text{Range} = 2\delta_{\text{max}} = 68.6 \mu\text{m} \]

This \( \delta_{\text{max}} \) is for upward deflection. Reversing the electric field to the other extreme voltage of -56V results in 34.3\( \mu\)m of upward deflection for a total deflection range of 68.6\( \mu\)m.
This range exceeds the target range of 50μm, however if greater range were desired, the amplifier gain could be increased to increase $V_{\text{max}}$. This technique is fine for maximum voltages less than 110V. At voltages exceeding 110V the piezo material begins to depole and lose its piezoelectric properties.

As proof that the bimorph shape amplifies the piezoelectric strain into greater tip deflection than simple piezoelectric extension alone, the following comparison is offered. If both piezo layers were poled so that both extended or contracted together under an applied voltage, for example if the piezo strips were poled in parallel but wired in series (see figure 3.4), the extensional force would follow equation 3.13 for each strip and the total force for the bimorph strip would combine to be:

$$P_p = P_{p1} + P_{p2} = 2EP_pb_p d_{31} V$$

(3.21)

This total extensional force $P_p$ would induce the change in piezo strip length $\Delta$, as shown in figure 3.8. The relationship between force and extensional deformation for uniaxial loading is:

$$\Delta = \frac{P_p L}{E_{\text{total}} A_{\text{total}}}$$

(3.22)

where $E_{\text{total}}$ is again the combined contributions of the piezo ceramic and brass elastic moduli and $A_{\text{total}}$ is the area of the entire beam in the y-z plane. Substituting in $E_{\text{total}}$, $A_{\text{total}}$ and $P_p$, to equation 3.22, gives the extension $\Delta$ in terms of the dimensions and material properties.

53
constants of the bimorph strip. Equation 3.23 also reduces from areas to thicknesses since the width of the piezo ceramic and the width of the brass are the same:

\[
\Delta = \frac{2 E_p d_{31} V L}{(E_p t_c) + \left(2 E_p t_p\right)}
\]  

(3.23)

Calculating the maximum deflection \(\Delta_{\text{max}}\) from equation 3.23 and using the values from table 3.2 results in:

\[\Delta_{\text{max}} = 1.1\mu m\]

Range = \(2\Delta_{\text{max}} = 2.2\mu m\)
The $\Delta_{\text{max}}$ for 56V would be for extension. Reversing the electric field to the other extreme voltage of -56V would result in 1.1$\mu$m of contraction for a total deflection range of 2.2$\mu$m. This range of motion due to simple piezoelectric extension is only 3% of the range of motion due to bimorph tip deflection.

3.3.2 Resolution

The resolution of the bimorph strips is primarily limited by the resolution of the electrical signal applied. In theory, if no electrical signal noise is present in the computer D/A command voltage, and the piezo voltage amplifiers have a perfect analog gain, the resolution of the electric signal is the resolution of the computer D/A. The computer control boards used for the AFPM have 16 bit resolution. Therefore, the smallest voltage command increment of a ±5V D/A port is $(+5 - (-5))/2^{16} = 0.15\text{mV}$. this signal goes through the 11.2 amplifier gain to command a change in voltage of $(0.15\text{mV})(11.2) = 1.68\text{mV}$ across the bimorph strip. From equation 3.18, the increment of tip deflection for 1.68mV is 1.03nm, nearly two orders of magnitude below the target resolution of 100nm for the micromanipulators.

In practice, however, electrical noise dominates the resolution of the applied voltage commands. As measured on an oscilloscope, the noise in the command signal downstream of the amplifiers is within an 8mV band. From this noise, the worst case is that the micromanipulator endpoint is unsteady within 4.90nm. Of course, the amplifier instrumentation can be built to minimize noise, but not without adding complexity, and therefore cost. Since the resolution of the micromanipulator is well below the target specification despite signal noise, low cost amplifiers, like the AFPM amplifiers shown in Appendix A, are acceptable.
3.3.3 Dynamic Model

From the range and resolution experiments, the micromanipulator clearly meets the specifications for static motions. But the dynamic motion of the micromanipulator is important as well. The lowest natural frequency of vibration of the micromanipulator structure determines the practical limit to the operating bandwidth, which is the limit to the back and forth scanning cycle time, and also the limit to the compensation and vibration control frequency discussed in section 1.3. A simple beam element model of the micromanipulator structure reveals the natural frequencies of the two lowest modes of vibration and provides insight into ways to influence those structural frequencies.

Thomson\textsuperscript{14} gives a complete discussion of simple beam element models from which the micromanipulator is modeled. The dynamic model takes the micromanipulator structure to be comprised of four simple beam elements which undergo translational and rotational displacements at the endpoints of the beams. The model structure has the same physical shape as the actual micromanipulator and is shown in figure 3.9.

![Micromanipulator Beam Structure](image)

Figure 3.9: Micromanipulator Beam Structure
Each of the beam elements ab, bc, cd, and de are subject to extensional, lateral, and rotational displacements at the ends. These displacements require forces and moments to act against the stiffness of the beam structure. The displacements and the corresponding forces and moments are shown in figure 3.10.

Figure 3.10: Displacements, Forces, and Moments of Beam Elements

For each beam in the structure, the displacements are extensional or lateral in x or y depending on the orientation of that beam with respect to the coordinates shown in figure 3.9. There are no displacements in joints a or e since these joints are rigidly clamped into the micromanipulator structure. Also, the rotational displacement \( \theta_b \) is the same for beam element ab as for beam element bc because the angle between the beam elements is fixed at 90° from the corner attachments on the micromanipulator structure which are schematically
shown in figure 3.5. Similarly, \( \theta_d \) is the same for cd and de. However, this is not the case for \( \theta_e \) since the micromanipulator endpoint is a pinned joint, so that the beam element bc has rotational displacement \( \theta_{e1} \) which is independent of the rotational displacement \( \theta_{e2} \) of beam element cd. The relationship between the displacements, forces, and moments is written as the stiffness matrix [K] of the structure. The entries in the matrix are formed from the appropriate combination of the forces and/or moments corresponding to each displacement of the structure joints from figure 3.10. The full stiffness matrix of the structure is given in figure 3.11.

The mass matrix [M] of the structure is formed from the relationship between the accelerations of the displacements and the forces and moments. The mass of the beam elements is a function of the mass per unit length of the beam material \( m \) and the length of the beam \( l \). The entries of the mass matrix are found from the shape functions of the beam displacements as outlined in Thomson\(^{14}\). For the beam element structure, the mass matrix is given in figure 3.12.

To calculate a frequency of vibration of the structure from the stiffness and mass matrices, the mode of vibration must be known and imposed onto the matrices. The first mode of vibration of the structure is shown in figure 3.13:
Figure 3.11: Stiffness Matrix of Micromanipulator Beam Elements
Figure 3.12: Mass Matrix of Micromanipulator Beam Elements
In this mode, the extensional displacements of the beams are assumed to be zero because they are small compared to the lateral displacements. Therefore, beams ab and de have no displacements along their axes, such that \( y_b = 0 \) and \( x_d = 0 \). This eliminates columns and rows 2 and 8 from the stiffness and mass matrices. Similarly, since there are no extensional displacements in the beams, the length of the beams stays the same and the displacements at each end of the beam, in the direction of the beam axis, must be equal. This creates the modal conditions that \( x_c = x_e \) and \( y_c = y_d \). There is also an angular modal condition due to the symmetry of the mode. From inspection, it is clear that \( \theta_b = -\theta_d \). These modal conditions are imposed on the stiffness and mass matrices by adding columns 1 and 4, adding columns 5 and 9, and subtracting column 10 from column 3. By imposing these conditions, the extensional force components cancel out and the stiffness and mass matrices can be reduced to the stiffness and mass matrices acting at each joint. The result is the following stiffness and mass matrices corresponding to the displacements of joint c. Only the material properties and dimensions of the inactive strips influence joint c.

\[
[K]_c^{\text{mode 1}} = \frac{E_i l_i}{l_i^3} \begin{bmatrix}
12 & 0 & 0 & 6 \text{l}_i \\
0 & 12 & -6 \text{l}_i & 0 \\
0 & -6 \text{l}_i & 4 & 0 \\
6 \text{l}_i & 0 & 0 & 4
\end{bmatrix} \begin{bmatrix}
x_c \\
y_c \\
\theta_{c1} \\
\theta_{c2}
\end{bmatrix}
\]

\[
[M]_c^{\text{mode 1}} = \frac{m_i l_i}{420} \begin{bmatrix}
366 & 0 & 0 & 22 \text{l}_i \\
0 & 366 & -22 \text{l}_i & 0 \\
0 & -22 \text{l}_i & 4 \text{l}_i^2 & 0 \\
22 \text{l}_i & 0 & 0 & 4 \text{l}_i^2
\end{bmatrix} \begin{bmatrix}
x_c \\
y_c \\
\theta_{c1} \\
\theta_{c2}
\end{bmatrix}
\]
The natural frequency is found by solving the relationship for $\omega$:

$$ - \omega^2 [M]_c + [K]_c = 0 $$

(3.24)

where $\omega$ is the natural frequency of the structure. The lowest solution to equation 3.24 gives the root:

$$ \omega = 2.02 \frac{E_i I_i}{m_i l_i^4} $$

(3.25)

The higher solution is inaccurate since a higher order mode has a more complex shape which cannot be modeled with endpoint displacements only. To calculate the natural frequency, the material constants and dimensions of the inactive strips are given in table 3.3.

$$ E_i = 2 \frac{GN}{m^2} $$

$$ I_i = 2.65 \times 10^{-13} m^4 $$

$$ l_i = 23.4 mm $$

$$ m_i = 0.0056 \frac{kg}{m} $$

**Table 3.3: Material Constants and Dimensions of Inactive Strips.**

Calculating the natural frequency $\omega$ from equation 3.25 with the values in table 3.3 gives

$$ \omega = 1134.9 \frac{rad}{s} = 180.7 Hz $$

for the first mode of vibration.
The second mode of vibration of the structure is shown in figure 3.14. The second mode has the same translational constraints of the first mode where \( y_b \) and \( x_d \) are assumed to be zero, such that \( x_b = x_c \) and \( y_d = y_c \). So again, columns and rows 2 and 8 are eliminated, 1 and 4 are added, and 5 and 9 are added. However, the rotational displacement constraints are different from the rotational constraints in the first mode. In the second mode, the angular modal condition is that \( \theta_b = \theta_{c1} = \theta_{c2} = \theta_d \) which is imposed by adding columns 3, 6, 7, 10, and 1, since \( \theta_{c1} = \theta_{c2} \), rows 6 and 7 are added.

Figure 3.14: Second Mode of Vibration

The result is the following matrices for stiffness and mass at joint c.

\[
[K]_c = \frac{E I}{l^3} \begin{bmatrix}
12 & 0 & 12 & 0 \\
0 & 12 & -12 & 0 \\
6 & -6 & 12 & 0 \\
6 & -6 & 12 & 0
\end{bmatrix}
\begin{bmatrix}
x_c \\
y_c \\
\theta_c \\
\end{bmatrix}
\]

\[
[M]_c = \frac{m l_i l_i}{420} \begin{bmatrix}
366 & 0 & 9 & m_i l_i \\
0 & 366 & -9 & m_i l_i \\
22 & -22 & l_i & 0 \\
22 & -22 & l_i & 0
\end{bmatrix}
\begin{bmatrix}
x_c \\
y_c \\
\theta_c \\
\end{bmatrix}
\]
Again solving for equation 3.24, the lowest solution gives the root:

\[ \omega = 3.71 \sqrt{\frac{E_l l}{m_l l_t^4}} \]  

(3.26)

Calculating the natural frequency \( \omega \) from equation 3.26 with the values in table 3.3 gives

\[ \omega = 2084.4 \frac{\text{rad}}{s} = 331.9 \text{Hz} \] for the second mode of vibration.

The first mode of vibration limits the micromanipulator bandwidth to 180.7Hz. However, this bandwidth is still high enough to compensate for the dynamic errors in the macromanipulator and to align the fibers quickly.

3.3.4 Load Carrying Capacity

The load carrying capacity defines the limits to the amount of mass at the endpoint which the micromanipulator can align. This mass consists of the slight weight of the fiber and the more substantial weight of the fiber holder. The load carrying capacity depends on the force produced by the bimorph strips, and the possible brittle fracture of the piezoelectric ceramic.

Piezoelectric actuators have a free deflection to blocked force performance curve which is similar to the no load frequency to stall torque performance curve of a motor. The free deflection of the bimorph strips is the amount of deflection per volt with no force load, or no mass, at the tip. The blocked force is the force exerted by the bimorph at the tip, or the external force needed to prevent deflection of the tip. The graph in figure 3.15 depicts
the free deflection to blocked force relationship. Each diagonal line represents a line of constant voltage.

![Diagram showing the relationship between free deflection and blocked force with increasing voltage.](image)

Figure 3.15: Free Deflection versus Blocked Force

Figure 3.15 shows that as the external force increases, the amount of deflection per volt along any given line of constant voltage decreases linearly proportional to that force. The practical implication is that the range of the micromanipulator decreases as the fiber holder weight increases. In all the previous deflection/range calculations the external force at the tip, or weight of the fiber holder, was assumed to be zero such that the bimorph strips are operating in free deflection and achieving the largest deflection per volt.

However, the fiber holder has mass, and therefore has weight in gravity, and the blocked force shows the limit of the weight which prevents deflection. The blocked force is calculated from\textsuperscript{15}:

$$F_b = \frac{N C_e V}{C_m} \quad (3.27)$$
where $N$ is the ratio of voltage produced when force is applied to the piezoelectric ceramic, $C_e$ is the static capacity of the material, $V$ is the applied voltage, and $C_m$ is the beam relationship between tip deflection to applied force at the tip. The values of $N$, $C_e$, and $C_m$ are calculated as follows:

$$N = \frac{3}{2} g_{31} \frac{1}{b t} \quad (3.28)$$

where $g_{31}$ is a piezoelectric constant relating the electrical field induced by applied stress, and $l$, $b$, and $t$ are the length, width and thickness, respectively, of the bimorph strip.

$$C_e = K \varepsilon_0 \frac{1}{2} \frac{b}{t_p} \quad (3.29)$$

where $\varepsilon_0$ is the permittivity of free space, $t_p$ is the thickness of one piezoelectric layer of the bimorph strip, and $K$ is the relative dielectric constant of the material such that:

$$K = \frac{\text{permittivity of the material}}{\text{permittivity of free space}} \quad (3.30)$$

and

$$C_m = \frac{l^3}{3EI} = \frac{4}{E} \frac{l^3}{b t^3} \quad (3.31)$$

where $E$ is the modulus of the material, and $I$ is the moment of inertia of the bimorph strip.

Substituting equations 3.28, 3.29, and 3.30 into equation 3.27 and making the approximation that $t_p \approx \frac{1}{2} t$, results in:

$$F_b = 6 E K \varepsilon_0 g_{31} \frac{b t}{l} V \quad (3.32)$$
From equation 3.32, the blocked force per applied \( v \) or 
the dimensions and material constants of the bimorph:

\[
\varepsilon_0 = 8.85 \times 10^{-12}
\]

\[\text{K} = 3400\]

\[g_{31} = 9.1 \times 10^{-3} \text{ m} \]

\[E = \frac{71 \text{ GN}}{\text{m}^2}\]

\[b = 6.35 \text{mm}\]

\[t = 0.6096 \text{mm}\]

\[L = 23 \text{mm}\]

\[V_{\text{max}} = 56 \text{V}\]

Table 3.4: Bimorph Strip Values

Calculating from equation 3.32 with the bimorph strip
force, or 11.2g of weight in gravity of \( 9.81 \frac{\text{m}}{\text{s}^2} \). This
of a horizontally mounted bimorph strip prevents def

However, the micromanipulator structure is c
the cantilevered bimorph strip since the structure has
mounted at 45° to the direction of gravity. As showi
can be lifted against gravity g is the contribution of b
so for a blocked force of
31.7g.

Since the block deflection decreases by
fiber holder weight can
from section 3.3.1 and
meet the target range
linear relationship:

where \( x \) is the maxin
8.6g. Therefore, the
The theoretical calculations and the determination of the carrying capacity are all experiments conducted in Chapter 4.
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4.2 Freque

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difficult to disadvent ceramic material y position (0.001")
bimorph strip must be handled with care. The design describes a piezoelectric compressive strain micromanipulator. Micromanipulators are used in precision applications.
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5.2.2 Dynamic Analysis

The model used the steel structure, which is stiffer than pinned joint vibration in a pinned joint. Equation 3 shows the structure equation:

bimorph s
provide a consideration. It would mean automating the industry.

functions normally complete reduced enormous
To turn amplifiers, the document suggests an approach through an initial example of a circuit diagram, depicted as a figure. The circuit contains elements with opposite polarities, highlighting the importance of understanding potential, and the impact on tip deflection.

The diagram, labeled as figure A, illustrates the configuration of the amplifiers as described.
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