Design of An Automated Fiber Pigtail Preparation Machine

by

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B.S., Middle East Technical University (1995)

Submitted to the Department of Mechanical Engineering
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Abstract

Gyroscopes are inertial guidance devices. The first gyroscopes were mechanical and because of there excessive weight and cost, were used only in military and civilian aircraft. As technology improved, gyroscopes found wider applications, not only on aviation, but in submarines and even ground vehicles such as tanks, jeeps, and agricultural machines. Fiber–optic gyroscopes are advantageous over other gyroscope architectures in that they require less maintenance and are **potentially** much less costly to manufacture. Using current labor–intensive manufacturing technologies, however, they are expensive to produce and hence have not found wide–spread applications. By improving the associated manufacturing technologies, the cost of the fiber–optic gyroscopes could be dramatically reduced, enabling them to achieve tremendous market infiltration.

As part of a DARPA initiative to reduce the cost of fiber optic gyroscopes, the MIT Manufacturing Institute developed an automated fiber pigtail preparation machine. This thesis describes the design, developement, and fabrication of this machine and summarizes performance.

Thesis Supervisor: Dr. Andre Sharon
Title: Executive Officer, Manufacturing Institute

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Chapter 1

Introduction

A gyroscope (gyro) is a sensor that is used to measure rotation. It finds use in a wide range of applications but it is most frequently used in navigation. From submarines to single-engine planes to satellites, gyroscopes make it possible for vehicles to accurately and reliably chart out their courses, either automatically or with the aid of an operator. Gyroscopes perform operations as simple as telling a plane which way is up or as complex as telling a satellite in near-zero gravity if it has deviated a thousandth of a degree off course.

One of the most recent applications of the gyroscope is associated with the Global Positioning System or GPS [1]. Cars and other vehicles can use GPS to find their position on the globe. With the aid of a computer, the location information from GPS can be used to track a cars progress and help a driver chart a course. Communication with satellites is not without problems: it is expensive and does not work well when obscured by obstacles, such as mountains or tall buildings. By using a gyroscope and a simple computer instead of satellite communication for location information, a vehicle can navigate in almost any set of conditions. The problem to date has been that gyroscopes have been too expensive to find use in consumer automobiles. New technology has made it possible to reduce cost of gyroscopes, enabling their use in GPS. A gyro would sense any turns made by the vehicle and a computer would keep track of the distances and directions traveled. By referencing this information to known maps and knowing the reference starting position, the computer can locate the vehicle on a map contained in memory.

Traditionally, gyroscopes have been mechanically based devices consisting of a rapidly spinning wheel set in a framework that permits it to tilt freely in any direction, i.e., to rotate about any axis. A working three-axis gyro is comprised of many precision parts. Exactly how these parts turn inside the sensor is well defined by modern dynamic theory. Essentially all mechanical gyroscopes operate on the same basic principle; conservation of angular momentum of a spinning mass [2]. By measuring torques and forces generated as certain internal parts of a gyroscope move, the rotational motion of the entire gyroscope can be deduced. Different gyroscopes accomplish these measurements in different ways, depending on the application and accuracy grade of the sensor, but all give a measurement of the rotation of the sensor.

There are two significant disadvantages to using mechanical gyros. The first is that they are relatively expensive to produce, especially the highest accuracy varieties. The high precision components and accurately machined parts used inside these gyros are inherently expensive to produce. Though great effort has been expended to cost-reduce these parts, the parts are still difficult to manufacture and remain an impedance to cost-reducing mechanical gyros. In addition, the electronics and sensors in the gyros add expense due to their high accuracy and low noise requirements. All parties interested would like to see a less expensive gyroscope, but the current cost of the components of the mechanical sensor make this virtually impossible.

The second disadvantage of mechanical gyros is that they contain moving parts which are particularly subject to failure over time. Eventually, a bearing may wear out, a part of the structure may fatigue and break, or something could shift out of alignment. Either way, the gyroscope would become useless and would have to be replaced. On vehicles such as satellites, this is not easy and could lead to the destruction of the satellite. If moving parts could be eliminated altogether, these problems could obviously be avoided.

Optical solid state technology has been shown in the last few years to be a viable substitute to the traditional mechanical technology used in gyroscopes. These solid state gyros incorporate no moving parts, relying on light traveling through an optical pathway to detect rotation. There are several ways that the optical pathway can be created. Ring Laser Gyros (RLGs) and Fiber Optic Gyros (FOGs) use two of the possible methods [3], [4]. As suggested by its name, the RLG uses a set of accurate mirrors arranged in a ring around which the light can travel. The FOG uses optical fiber to define the light path. For reasons of greater possible accuracy and lower cost, the FOG seems to be the most promising alternative.

FOGs can reach, and possibly exceed the precision of current mechanical gyros and can operate under equal, or even harsher environmental conditions. The drawback to date has been the cost of manufacturing these solid state gyros. Only recently has the state of technology begun to progress enough to bring the cost of manufacturing the gyros down to competitive levels. Optical fiber has become less expensive and methods of interfacing the fiber with other components in the gyro have become well defined. Likewise, the lasers, which act as the light source for the sensor, have recently become far more affordable. These are very attractive features for many users of commercial gyros [5], [6].

The main factor currently driving the price of manufacturing solid state gyroscopes is assembly time [7]. It can take one person up to three weeks to assemble a working, three-axis gyroscope. If this assembly time can be reduced, through automation and other techniques, the cost of a solid state gyro can be brought significantly below that of a mechanical one Given that they have no moving parts and could be made inexpensively, the solid state gyroscope could prove to be a superior alternative to its mechanical cousin.

This thesis describes the design and development of a optical fiber pigtail preparation machine. In the rest of this chapter the details of how a FOG works and the building blocks of a FOG are presented. Chapter 2 will introduce the fiber optic pigtail and an overview of the entire current manufacturing process will be given. From the current manufacturing process we will also discuss the drive to automation in Chapter 2. In

Chapter 3 we will explain the overall system design and details the concept generation. The selection process that was used to determine the overall workstation configuration and process flow is also discussed in Chapter 3. In Chapter 4 the detail design and development of some of the subsystems of the machine are presented. Chapter 5 deals with some of the special issues relating to the fiber pigtailing process that were important to automation. Finally, a discussion of the success of the machine and future recommendations will be presented in chapter 6.

1.1 How A Fiber Optic Gyro Works

The basic theory behind the FOG is fairly simple. Consider a long strand of optical fiber that is wrapped into a coil (Figure 1-1).The fiber is wound from its midpoint outwards so that half the fiber is wound counterclockwise around the coil and the other clockwise. The two ends of the fiber will then be located on the outside of the coil as shown in the figure. Light that is in phase is passed through both ends of the fiber coil. If the coil remains stationary, light coming out of the two ends will be in phase. However, if the coil turns along its axis, as indicated in Figure 1-1, light traveling through the coil in the direction of the rotation will take longer to travel the fiber length than the light traveling against the direction of rotation [8].

A physical example may prove useful in understanding this concept. Consider two balls that are rolled along a plank of a given length from opposite ends, towards each other at equal velocities, i.e. $V_1 = V_2$, as shown in Figure 1-2.

The balls are rolled along the two edges of the plank so that they do not collide. If the plank is held stationary, the balls will take the same amount of time to reach the ends of the plank. If, on the other hand, the plank is moved towards one of its ends while the balls are moving, the ball traveling in that direction will take longer to reach the end than the ball traveling in the opposing direction. The time difference between when the two balls reach the ends of the plank is related to the velocity of the plank. This is a similar

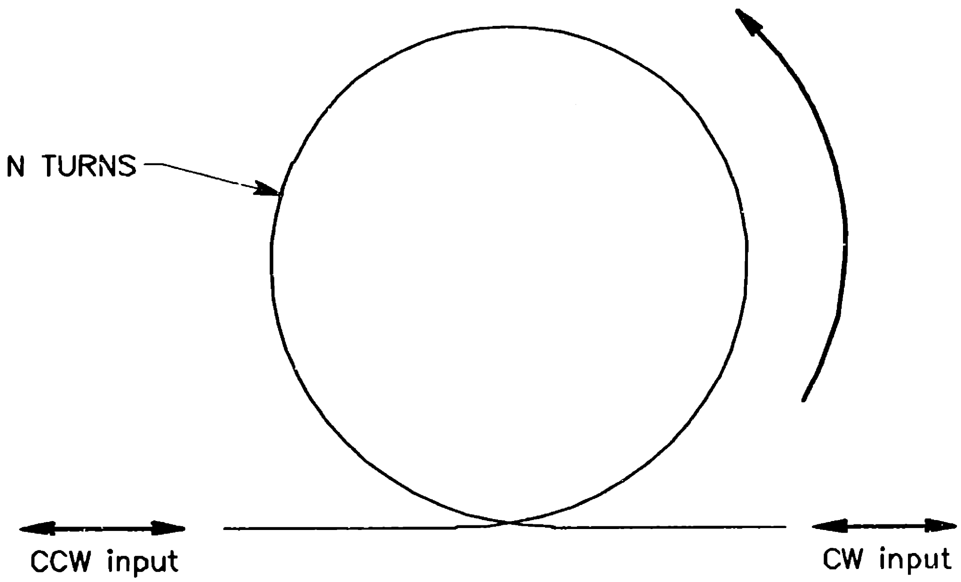

Figure 1-1: A simple representation of a FOG sensing coil.

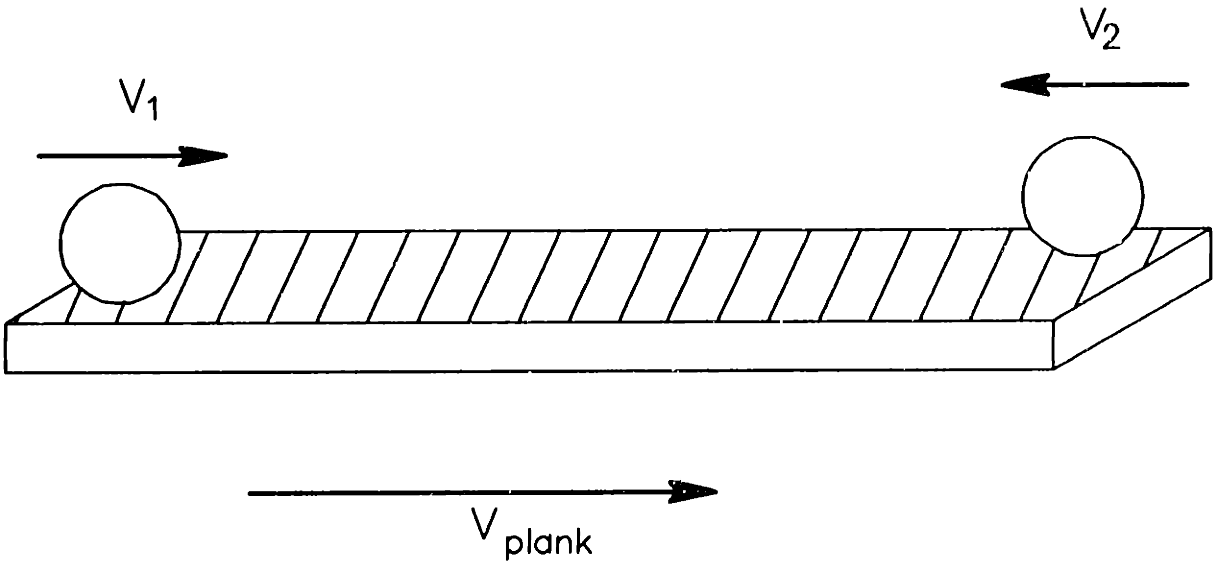

Figure 1-2: Balls rolling relative to a plank

concept to that employed in the fiber optic gyroscope except that light takes the place of the balls and optical fiber takes the place of the plank. The primary conceptual difference is that the fiber is wound into a coil so that rotation rather than translation is measured. The light emerging from opposite ends of the coil can be recombined and measured for phase shift. If the coil has experienced rotation, the light traveling in opposite direction will take different times to traverse the length of the coil and will be shifted in phase when they emerge. This shift is directly related to the rotation rate of the coil.

In 1914, a French researcher by the name of Sagnac first proposed using this concept of phase shift for measurement [9]. He created a simple device consisting of bright light, a 45° beam splitter, and a ring of mirror. With this device, he was able to successfully prove the above described concept, which is now commonly known as the Sagnac Effect. His device, called a Sagnac interferometer is shown in Figure 1-3. The entire device was rotated at an angular velocity Ω and the combined light was shown onto a screen. A fringe pattern was seen on the screen which corresponded directly to the rotation Ω. About sixty years later, in 1976, Vali and Shorthill proposed and implemented the first optical fiber gyroscope [10]. Since then, the technology has grown to the point where FOGs are as viable as their mechanical counterparts.

A few, simple mathematical relations are enough to entirely describe the Sagnac effect and relate the relative phase shift of the light to the rotation rate of the coil. When the light beams emerging from the coil are recombined, the beams will interfere, and there will be a power loss corresponding to the degree of phase shift between the beams. This relationship is described by the following equation:

$$P = \frac{1}{2}P_0\left(1 + \cos\Delta\Phi\right)^6 \tag{1.1}$$

where P is the detected output power, P_0 is the power input to the coil, and Φ is the phase difference. By measuring the power output with a photodetector, and knowing the power input, the phase shift can be deduced. The rotation rate is related to the phase

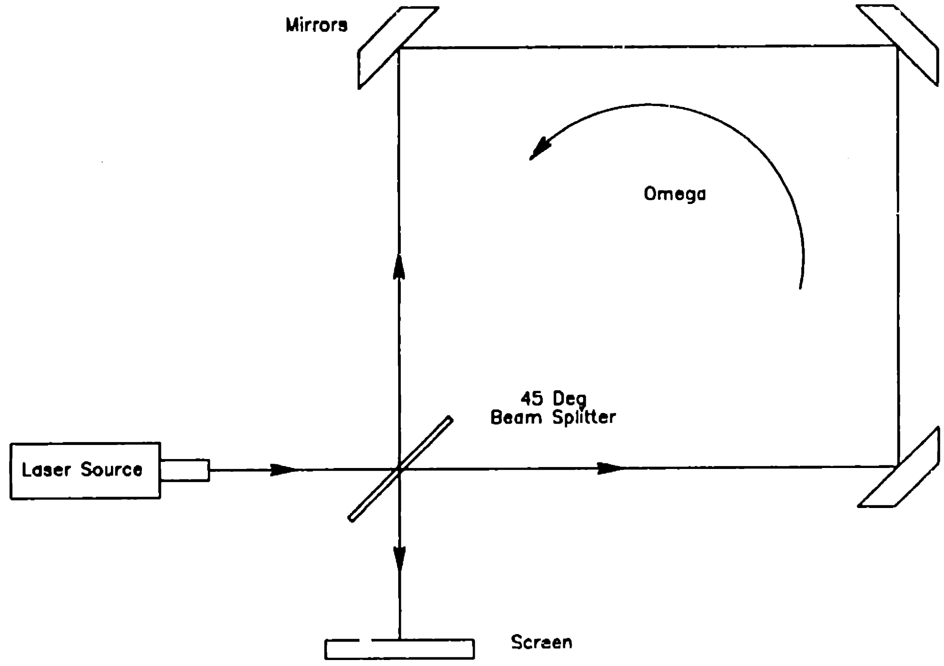

Figure 1-3: The Sagnac Interferometer

shift of the coil through the following relation:

$$\Delta\Phi = \frac{2\pi LD}{\lambda_0 c_0}\Omega \tag{1.2}$$

where λ_0 and c_0 are the wavelength and velocity of light in vacuum, respectively, L is the length of fiber, and D is the diameter of the coil. $\Delta\Phi$ is the phase shift, as per equation 1.1, and Ω is the rotation rate of the coil. Thus, by measuring the power output from the recombined beams that have passed through the sensing coil, a measure of the rate of rotation of the coil can be made. The majority of fiber optic gyroscopes use this basic concept in sensing rotation.

1.2 Building Blocks of A FOG

The fiber optic gyro consists of the following components:

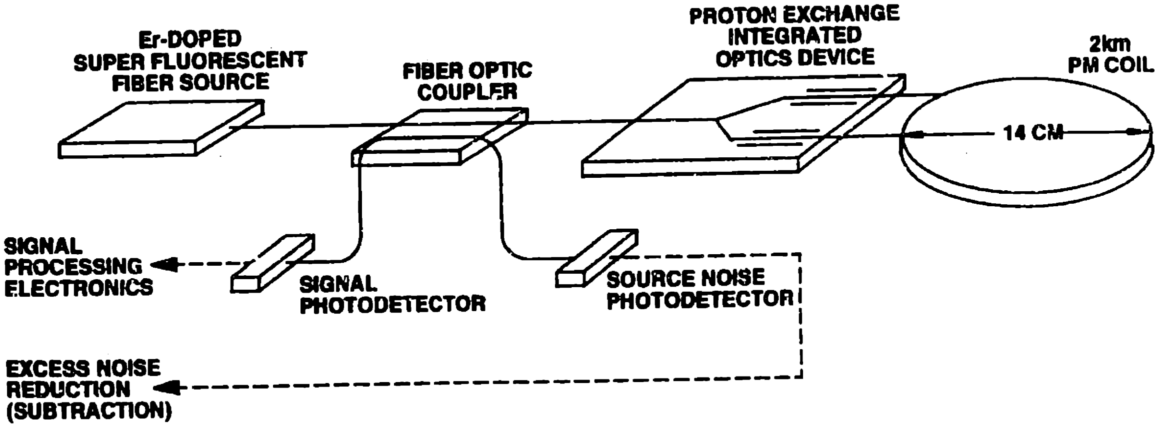

Figure 1-4: Integrated fiber optic gyroscope components.

- Light Source
- Source Coupler
- Integrated Optical Chip (IOC)
- Photodetector
- Sensing Coil
- Optical Fiber

Each of the major components of the gyro can be seen in Figure 1-4. Each of these components will be discussed in the following sections.

1.2.1 Light Source

The laser is the light source for the gyro. It provides a constant, coherent beam of light that drives the Sagnac Effect. Laser Diodes are commonly used in FOGs as they are small and exhibit adequate performance. To meet power requirements, these diodes are coupled with a rare-earth doped fiber that acts to amplify the beam. Together, the diode and doped fiber act to generate the light beam for the gyro.

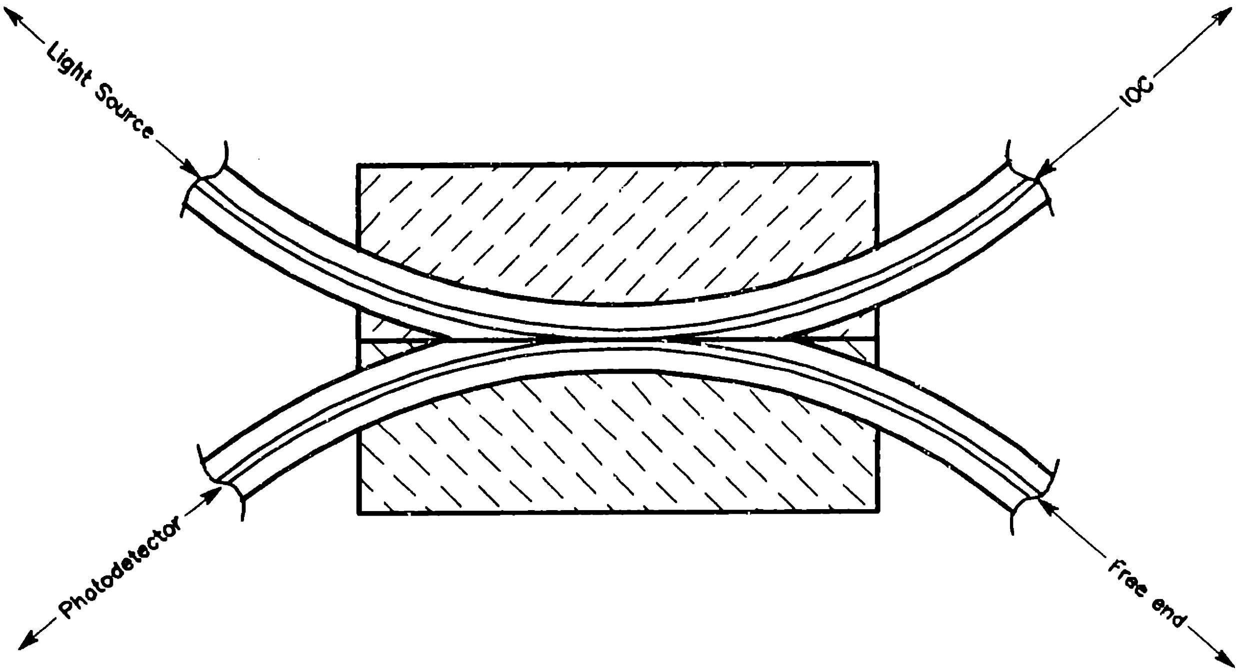

Figure 1-5: Assembled optical fiber coupler

1.2.2 Source Coupler

The source coupler serves the basic function of routing the returning light beam from the coil to the photodetector. The coupler also allows for light to travel from the light source towards the coil. In order to accomplish this, two fibers are fused together along their sides and are reinforced for durability [11]. A fiber lead coming from the laser attaches to the end of one of the fibers and the lead from the coil is attached to the other end of the same fiber. The photodetector lead is attached to the end of the other fiber in the coupler. Finally, the last coupler fiber end is left unattached (Figure 1-5 and Figure 1-4).

1.2.3 Integrated Optical Chip (IOC)

The FOG measures the rotation by detecting the phase shift induced by the rotation of the sensing coil. That means that beam combiners, dividers, lenses and some active devices such as phase modulators, switches or frequency shifters are needed. All these

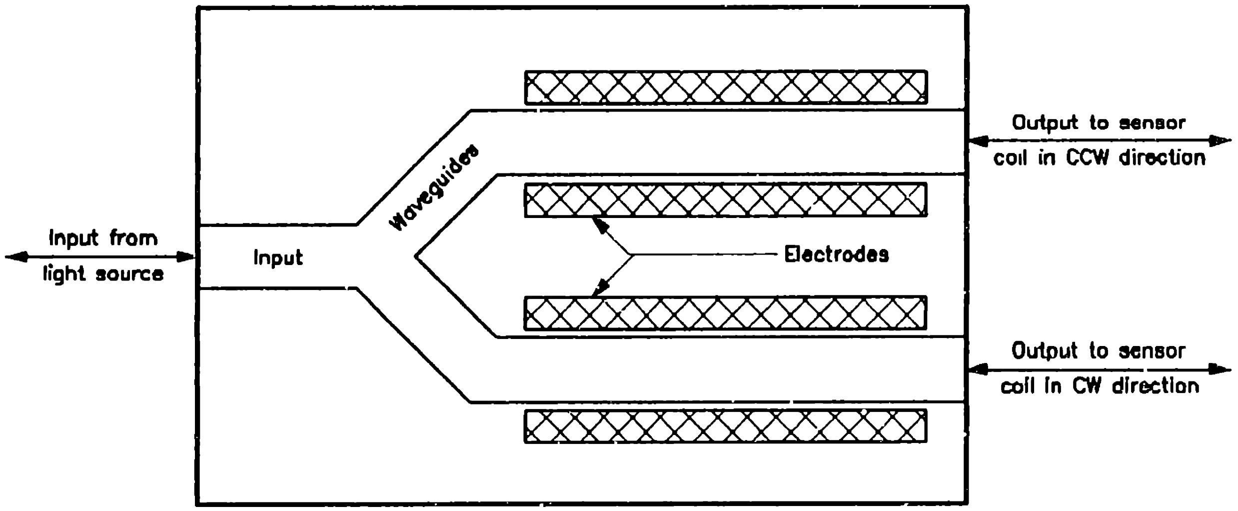

Figure 1-6: Integrated Optic Waveguide Chip (IOC)

types of optical devices can be realized in a compact way using integrated optic technology thus leading to a very small but stable heart of the FOG [12]. This is particularly true for the optical gyroscope using passive Sagnac interferometers where the phase shifts induced by the rotation onto the two counter–propagating waves are very small.

While there are various forms of integrated optics available, a special type called an Integrated Optics Chip (IOC) is commonly used in fiber optic gyroscopes. Light pathways are formed within a specially designed chip to efficiently guide the light between the single fiber and the two coil fiber ends. The IOC looks much like a rectangular piece of glass with the fibers attaching to the shorter ends of the rectangle.

The IOC becomes unique from other beam splitters in the phase modulator contained within the IOC. The modulator acts to modulate the frequency of the light beam which aids in the operation of the gyro and significantly increases their accuracy. The IOC also acts to polarize the light beams which also increases operating efficiency.

1.2.4 Photodetector

In order to detect the phase shift in the light emerging from the coil, two different types of photodetectors are commonly used. Both the PIN and Avalanche Photodiodes operate on the principle of photons of light creating free electrons upon contact with a specially designed surface. The surface is connected to an electrical circuit and the current is measured. By the nature of the interaction, current is proportional to light intensity; thus, providing a measure of the phase shift in the light beams. The PIN variety is the most common in FOGs.

1.2.5 Sensing Coil

The FOG senses rotation due to the Sagnac Effect. The Sagnac Effect states that the shift in the phase of the light beams is due solely to the rotation of the coil. Then from the phase shift the angular rotation can be calculated. The fiber is first wound in a special pattern. This winding pattern is very important in the performance of the FOG [13], [14]. The two free ends that come off of the coil are then attached to the IOC.

1.2.6 Optical Fiber

The optical fiber is the element that carries the light to its destination. A fiber consists of three layers (Figure 1-7):

1. The protective outer jacket.

2. Cladding

3. Core.

The light beam travels through the core and follows the path of the fiber by reflecting from the inner walls of the cladding (Figure 1-7). The refractive index between the core and the cladding is designed so there will be maximum reflection of the light beam.

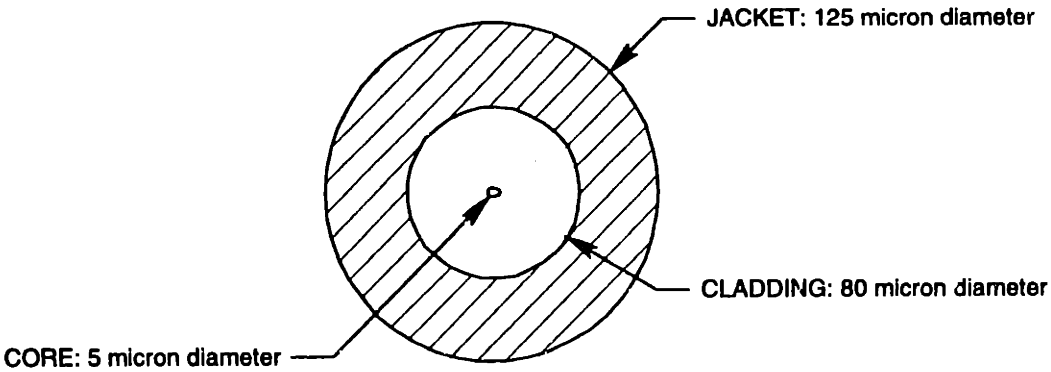

Figure 1-7: Optical fiber crossection.

Fiber performance is measured from the attenuation of the travelling light. Attenuation or loss is defined by the following equation:

$$A = -10 \log \left(\frac{P_i}{P_o} \right) \tag{1.3}$$

where A is the attenuation and P_i and P_o are the input power and output power, respectively. Attenuation is measured in decibels (dB) per unit length, typically dB/km.

Loss can vary from 1 to 1000 dB/km in useful fibers with the various causes of loss often being wavelength dependent. The causes for loss are absorption, scattering, micro–bending and end loss due to reflection [15].

Chapter 2

Fiber Pigtails

The fiber optic pigtails have the most bearing on this thesis of all the FOG components, as the goal of the project was to build a fiber pigtail preparation machine. Therefore, the many unique features of the fiber pigtails will be covered in much more detail than the other components. Many of the references cited in Chapter 1 thoroughly discuss the other FOG components.

FOGs use a lot of optical fiber. The components in the FOG are linked to each other via the fiber. The fiber must be attached to each of these components with maximum durability, minimum attenuation and in the least time. Two fibers are attached to each other via special splicing techniques [16], [17], [18]. There are also places in the FOG where the fiber must be attached to other optical components. These are the light source, photodetector and IOC. The fiber attachment to the light source and photodetector is discussed in references [17], [18].

At the IOC, in order to ensure that the light enters the IOC with minimum attenuation the alignment between the fiber and the chip has to be within micrometers[1] of each other. In addition, once aligned, the fiber must be attached to the chip in a ruggedized manner that will allow the completed unit to withstand the environment it is used in.

The end of the fiber is attached to a block which is then attached to the IOC. The

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[1] $1\mu m = 10^{-6}m$

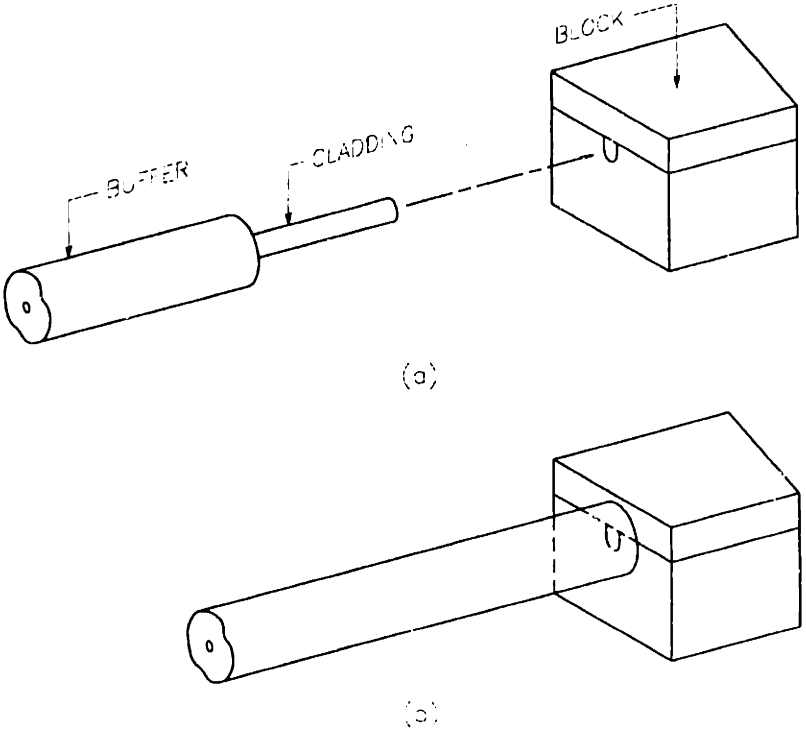

Figure 2-1: (a) Fiber insertion into a glass block, (b) finished product: fiber pigtail.

finished product of fiber plus block is called the fiber optic pigtail (Figure 2-1).

2.1 The Manual Pigtail Manufacturing Process

The manual fiber optic pigtail production consists of several semi–automated procedures along with a series of time consuming, repetitive tasks that are manually completed by trained operators. Several different workstations are utilized in the process and the same process is used regardless of the type of pigtails that are being produced.

The pigtail preparation process can be subdivided into four distinct phases. These phases are block preparation, fiber preparation, pigtail assembly, and final block dicing and polishing. A flowchart for the current pigtail preparation station is shown in Figure 2-3.

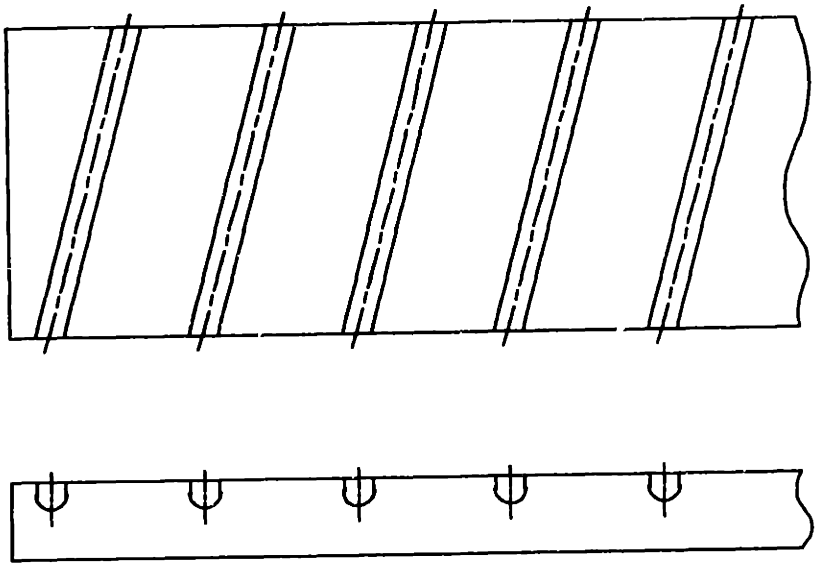

Figure 2-2: Carrier block used in manual process.

2.1.1 Block Preparation

Fiber pigtail production begins with a wafer of block material. The wafer is mounted in an automated workstation and small slots are then machined in the wafer at constant intervals. After all the slots are machined, the wafer is then cut into strips that are a few millimeters wide. The strip length allows upwards of 40 pigtails to be made from each strip.

2.1.2 Fiber Preparation

While the carrier strips are being fabricated, technicians usually begin preparing the next batch of fibers to be used in the pigtail production process. Fiber typically arrives from manufacturers on a spool that is about a foot in diameter and between four to six inches wide. Each spool may contain anywhere from several hundred meters of fiber to several kilometers of fiber. To begin preparing the fiber for production, the fiber is unwound from the supply spool and cut to the appropriate length. Once a fiber is cut to the correct length, it is wound on a card and then the fiber type and batch number are recorded on the card.

2.1.3 Pigtail Assembly

Pigtail assembly begins with the technician stripping the fiber end. Stripping is done manually, as are all the other steps in assembly, and is performed using a hand held pair of fiber strippers. The stripped portion of the fiber is then cleaned using cotton. Once clean, the fiber is cleaved with a manual diamond wheel cleaver.

At this point, the operator places the fiber into a vacuum chuck that is mounted on a manual XYZ stage. A microscope is used to aid the visual alignment of the fiber with respect to the slot in the carrier strip and the fiber is partially inserted using the Z-axis of the micro-positioning stage. A dab of epoxy is applied to the fiber before the final insertion takes place. Polarization maintaining fibers require the additional process step of having their polarization axes aligned with the carrier strip geometry. Vision equipment is used to provide the operator with a clear picture of the fibers end face. This allows the polarization axes to be aligned to the geometry of the strip. This is not sufficiently accurate to achieve the required extinction ratios for pigtailing thus the actual pigtailing process usually requires additional polarization alignment [19]. The inserted and aligned fiber is usually left in the vacuum chuck while the operator strips and cleaves the next lead, allowing adequate time for the epoxy to cure.

2.1.4 Dicing and Polishing

After loading all the fibers in a carrier strip, the carrier strip is cut into separate blocks which have a fiber lead on each one of them (Figure 2-1(b) on page 23).Once diced the finished pigtails are removed from the affixing devices, soaked in a cleaning bath, and inspected before they are sent to the pigtailing station.

2.2 Process Evaluation

It was imperative that the manual manufacturing process was thoroughly understood and evaluated before an automated workstation could be developed to produce fiber optic pigtails. By evaluating the manual process, bottlenecks and process improvements could be easily identified. Additionally, realistic goals and requirements for the automated station could then be based on this process evaluation.

Several important issues in this evaluation warrant comments at this point. The evaluation of the process concentrated only on the fiber preparation and pigtail assembly areas. Block preparation as well as dicing and polishing processes were deemed acceptable and therefore were not evaluated.

In order to properly conduct the evaluation detailed timing records of each step in the process were prepared. A flow chart of the process currently in use at one manufacturer is shown in Figure 2-3.

Two different timing methods were used to evaluate manual fiber pigtail preparation. The first was a bottom–up approach that the MIT Manufacturing Institute measured. During observations of the process, detailed timing sheets were kept as ten fiber leads were produced. Both the total time per lead as well as the individual process step times were recorded.

The second timing method used was carried out by the manufacturer and consisted of a top–down approach to timing. This method simply took the total number of fiber pigtails produced per week and divided by the total amount of labor time making pigtails. While not as detailed as the bottom–up approach, this method is much more accurate when detailed cost models and pricing data is needed. The normalized results of both timing methods are shown in Table 2.1. For proprietary reasons the timing was normalized to the total time measured in the bottom–up approach. In other words the time tabulated for every process is actually a percentage of the total time calculated with the bottom–up approach.

The first thing to notice about these timing methods is the large discrepancy between

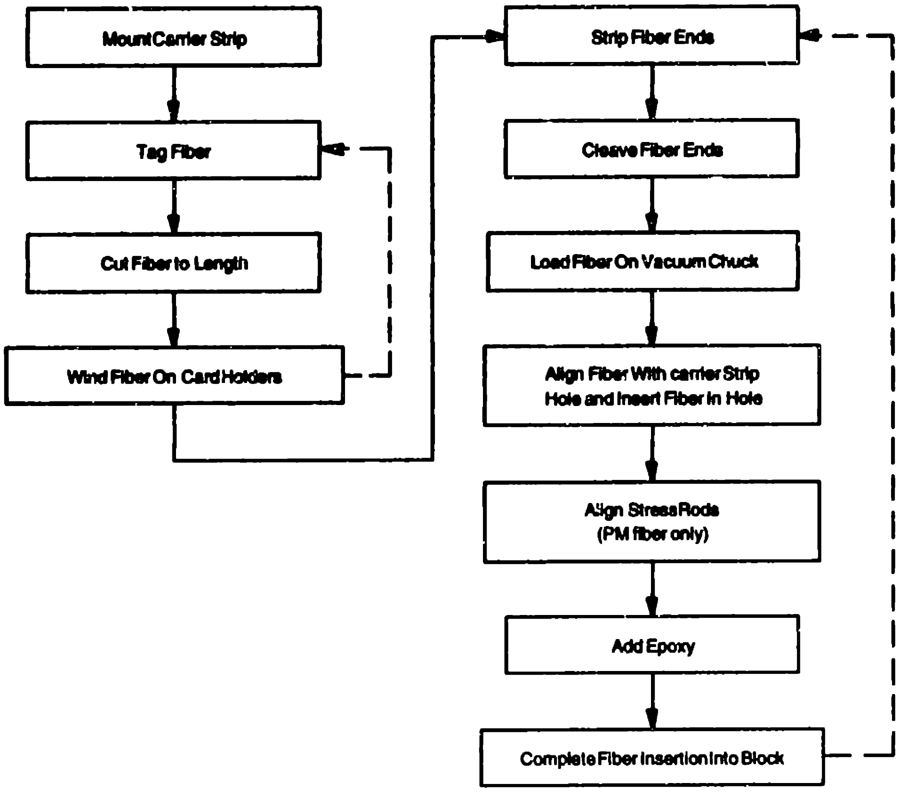

Figure 2-3: Manual pigtail preparation process flowchart.

Timing Evaluation	
Process Step	**Average Time**
Tag fiber	0.06
Cut fiber to length	0.07
Wind fiber on card holder	0.29
Strip fiber end	0.08
Cleave fiber end	0.07
Load fiber into insertion chuck	0.18
Align and insert fiber into strip	0.09
Rotationally align fiber	0.09
Apply epoxy	0.07
Bottom–Up Timing Approach	1.00
Top–Down Timing Approach	3.13

Table 2.1: Timing results for the current fiber pigtail production process

the top–down and bottom–up approach. The discrepancy is due to several factors; the most fundamental one being that the operator cannot perform such a tedious task at the same rate all day long. In addition, washroom, coffee and telephone breaks are not included in bottom–up timing. Nor are any distractions by fellow workers or equipment that needs attention. Based on this information, the bottom–up observed times should be thought of as best obtainable times and not as the average time for each fiber pigtail. These times are still very useful, however, as they show the relative times between process steps, which enables the bottlenecks in the process to be easily identified.

The most visible bottleneck is wrapping the fiber lead on the paper card holder. This single step consumes 30 percent of the total process time. The next major bottleneck, with 18 percent, is loading the fiber into the insertion chuck. The problem with this step occurs because the previous fiber that has been inserted cannot be removed from the chuck until the epoxy holding it in the strip has fully cured. Cure time for the epoxy is dependent on several factors, the most important one being the temperature of the strip. The remainder of the process steps take approximately the same time to complete and do not seem to hinder the process in any significant manner.

Several important observations were also made during the process evaluation. To begin with, the fixtures that were used to aid in cutting the fiber leads to length, hold and heat the carrier strip, and hold the fiber as it is being aligned and inserted into the hole were very good. They were easy to use and manipulate, and were very repeatable. The methods used to transport the fiber between work areas was less than optimal and considered a bottleneck.

2.2.1 The Drive to Automation

At present it is widely believed that the production future of fiber optic gyros depends on the development of the integrated optic circuit [20] to replace the various bulk components and labor intensive components presently utilized. Before this can become practical, the fabrication of low-loss integrated optical circuits and the low-loss coupling of fibers must be achieved. The component that greatly affects the cost and performance of the coupling is the fiber optic pigtail.

Currently The Defense Advanced Research Projects Agency (DARPA) is working with the industry in an effort to achieve cost reduction of FOGs [7], [21]. The MIT Manufacturing Institute was selected to develop the machines that will automate some aspects of the production process of a FOG. One of these machines is a workstation to automate the production of fiber optic pigtails.

Based on the observations and the gathered timing data presented in the process evaluation, the following conclusions were drawn about the current manufacturing process:

- While preparing pigtails is not a complicated or especially difficult task, it is very strenuous due to the fragile and miniature nature of the parts being used.
- The entire process has a low throughput because of the strenuous and tedious nature of the production process.
- There are several bottlenecks which definitely need to be addressed if production is to be increased in an efficient manner.
- Finally, the most important observation which needs attention is simply that the entire process is 100% dependent on manual touch labor.

From the preceding evaluation of the current process, it was quite apparent that automation of at least some of the fiber pigtail preparation process, along with a few simple process changes would be very advantageous in order to both decrease cost and improve production volume.

There is a definite opportunity in the industry for improvement of the fiber optic pigtail production process. If FOGs are to become competitive, the cost of fiber pigtails must be reduced without sacrificing quality. To accomplish this goal, production times must be decreased and rejection rates lowered. This implies that operator intervention must be removed from the process, or at least minimized. In the past, that was not feasible. Over the last few years the state of technology has greatly improved, facilitating the development of automation. Given that the process and technology are in place, and the opportunity is present, there is a definite drive towards automation. It is now possible to design and build a machine that can automatically manufacture fiber optic pigtails and, therefore, reduce the cost per IOC and consequently the cost of FOG's.

Chapter 3

Conceptual Design

In this Chapter we will set the fiber preparation automation goals for the station and come up with a detailed conceptual design. To set the automation goal the current process was assessed and bottlenecks pinpointed as explained in Chapter 2. MIT and the customer agreed on a preliminary set of automation goals. The agreed automation goals were as follows:

- The working supply of fiber would be manually loaded into the proposed station and according to the lead length, the fiber lead ends would be either manually or automatically affixed for pickup by the fiber manipulator.
- The machine would fully automate stripping.
- Cleaving would be fully automated.
- The cleaning of the fiber end after stripping would be automated.
- The station would automatically insert the fibers into the carrier strip slots, align the optical axis of the fibers with the blocks, and glue them to the carrier strip.

It was unknown in the beginning of the project how long of a fiber lead would be necessary. Also, the length of the carrier strip was expanded to hold more fibers, thus requiring the automated machine to be able to handle more fibers. The automation goals were chosen in order to increase the production rate of the fiber pigtails, and to enhance the polarization alignment of the fiber with the block, thereby easing the pigtailing alignment requirements.

Initially two different concepts for the proposed station were developed. One was a fully automated station while the other was a semi-automatic workstation. The semi-automatic workstation concepts were based on requirements for the long fiber leads.

The fully automated machine would handle the shorter lead length fibers. The operator's activities would be limited to loading the carrier strip and fiber spool onto the machine and affixing the fiber ends for automated pickup by the station. The automatic station's activities were envisioned to consist of the following process steps.

- The machine would strip and clean the fiber end for the next insertion.
- The fiber transport system would pick the fiber end that will be already stripped, cleaned and cleaved and would insert the fiber into the carrier strip.
- The epoxy would be applied and the polarization axes of the fiber would be aligned.
- The stripped fiber end for the next insertion would be brought to the cleaver and cleaved while the epoxy is curing.
- The inserted fiber would then be stowed away to prevent fiber entanglement...

From the distinct process steps proposed in the automated machine, a process flowchart was constructed for the automated pigtail preparation station (Figure 3-1).

The semi–automated machine would handle the longer lead length fibers. The station would require the operator to load spool holders into the machine and cut the continuously wound fiber. At this point, the operator takes one of the fiber ends and inserts it into an enclosed tooling device above the machine's work surface. There, the fiber is stripped and cleaved (if necessary). The operator then takes the fiber and places it in an insertion jig. Using a vision enhancing system to watch the fiber and carrier strip slot,

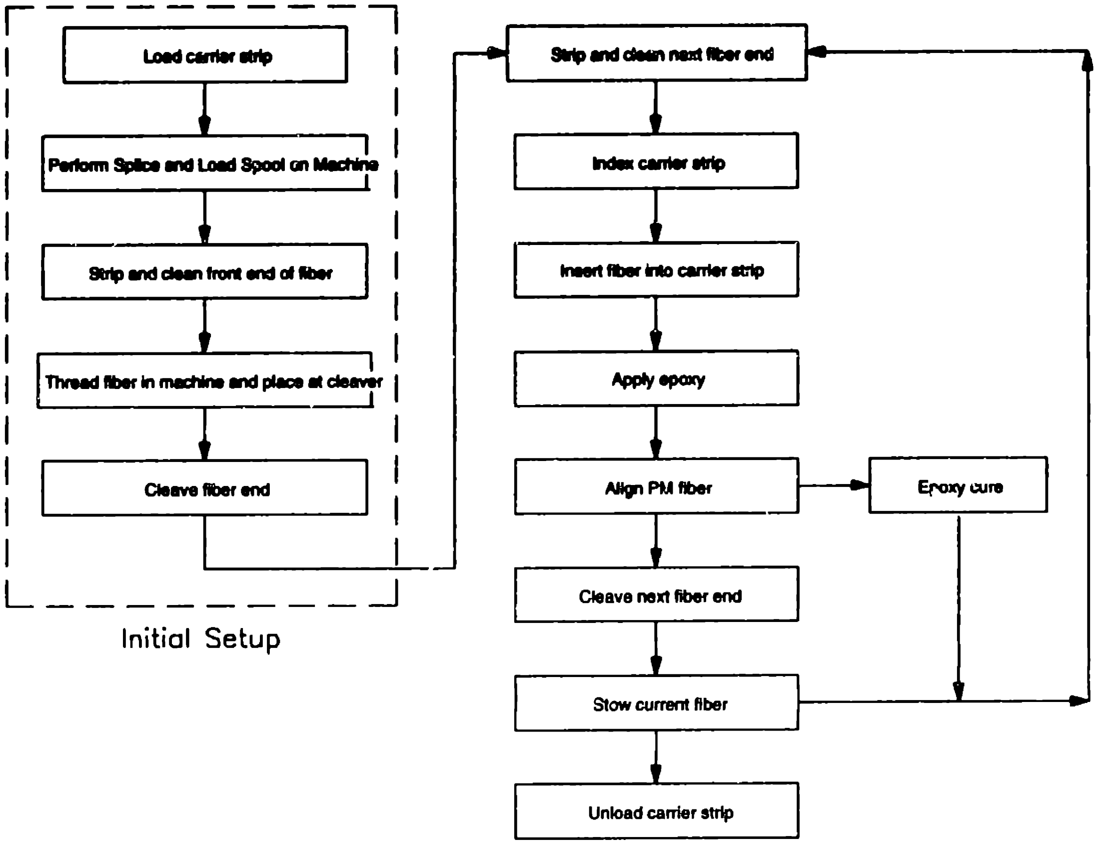

Figure 3-1: Automated fiber pigtailing process.

the operator maneuvers the chuck, into position, using a keyboard, and inserts the fiber into the slot. Once in place, the fiber is automatically aligned rotationally with respect to the carrier strip and glued.

The semi-automated and fully automated machine concepts were used to divide the machine into the following functional areas:

- Spool holding
- Fiber end affixing
- Fiber manipulation
- Fiber stripping
- Cleaving
- Fiber clamping at stripping and cleaving
- Fiber insertion into the carrier strip
- Alignment of the stress rods
- Clamping and gluing

3.1 Conceptual Design Alternatives

We will continue this section by explaining the conceptual design alternatives for each functional area listed in the previous paragraphs. After the design alternatives are introduced the advantages and disadvantages of the conceptual design will be discussed. For some of the conceptual designs feasibility experiments were conducted to validate the concepts and solidify them. The description of the experiments that were conducted, the results obtained from them, and their impact on the conceptual designs will be discussed. Finally a conceptual design will be selected.

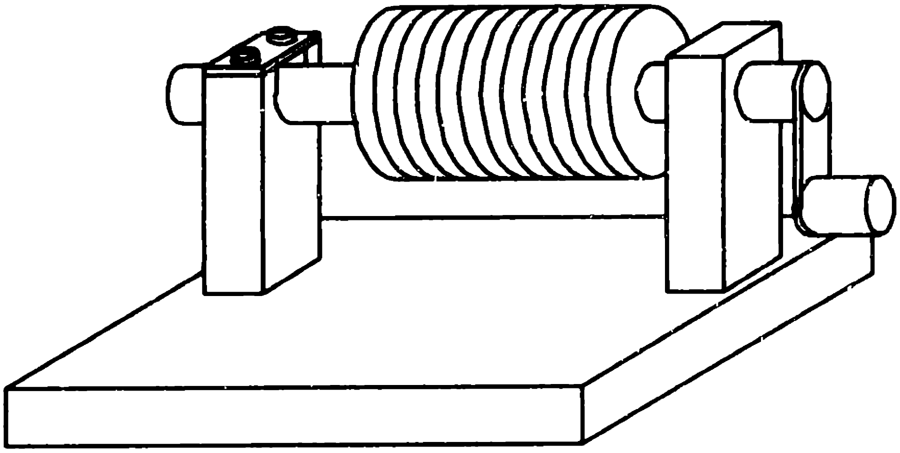

Figure 3-2: Experimental setup for the spring back and wrapping configurations.

3.1.1 Spool Holding

If long lead fibers were to be used in the FOG than it would be necessary to find a way to affix the long fibers in the machine. The majority of the spool winding concepts that we developed were based on the assumption that a spool winder under development elsewhere would be complete and available for use.

No space between spools

The wrapped spools would be taken with their center shaft from the spool wrapping machine and loaded into the pigtail preparation station. Once mounted, the fibers would have to be cut manually by the operator, using a cutting tool. An average of ten spools were wrapped on a hand operated spool winder (Figure 3-2) to test how the fiber would react to different spool winding techniques. When the fiber is wound continuously on the spools, it has to make a sharp turn in order to jump onto the next spool and this could potentially damage the fiber. Furthermore, the lack of space between spools dictates the use of an X-acto knife blade to cut the fibers, and the spools often get damaged in the cutting process. Finally, after cutting, the fiber ends often spring back into the spool, and a good deal of time is wasted fishing for these ends.

Small spaces between the spools

In this concept washers between each spool would open up the spacing between the spools, to ease the arduous task of cutting the continuous fiber. The spool winding machine would have to be modified slightly in order to take the spaces into account during winding. With this configuration, less spools would be wrapped in a batch. Therefore, more than two groups of wrapped spools would have to be loaded into the pigtail preparation machine. Again, the operator would have to manually cut the fiber at each spool.

When small spacers were placed between the carrier spools, it was found that it is actually more difficult to wrap the spools and cut the fibers. In order to jump from spool to spool, a complex motion of the fiber winder is necessary. Also, due to the tension in the fiber during winding, the fiber tends to pull the softer end of the spool over to the side, opening up the spool and causing the fiber to unwind.

Single wrap dummy spools between the spools

Dummy spools similar to the original spools would be positioned between each carrier spool. The spool wrapping machine would then be modified to wrap the fiber once on each dummy spool before proceeding to the next spool (Figure 3-3). With the dummy spools in place, even less spools can be wrapped at a time. Thus, there would be at least four shafts of spools mounted in the pigtail preparation machine. By cutting slots in both the carrier spools and the dummies, the fiber can be cut by a small saw running on a track along the edge of the spools. The wrapping process proceeds as usual, except that the fiber is only wrapped around the dummy spool once before starting to wrap the next carrier spool. After wrapping, the fibers are cut at the slots of the dummy spools, in order to obtain both ends of the fiber leads. By using the dummy spools to obtain the fiber lead ends, a great deal of time could be saved as fiber spring back would no longer be a problem.

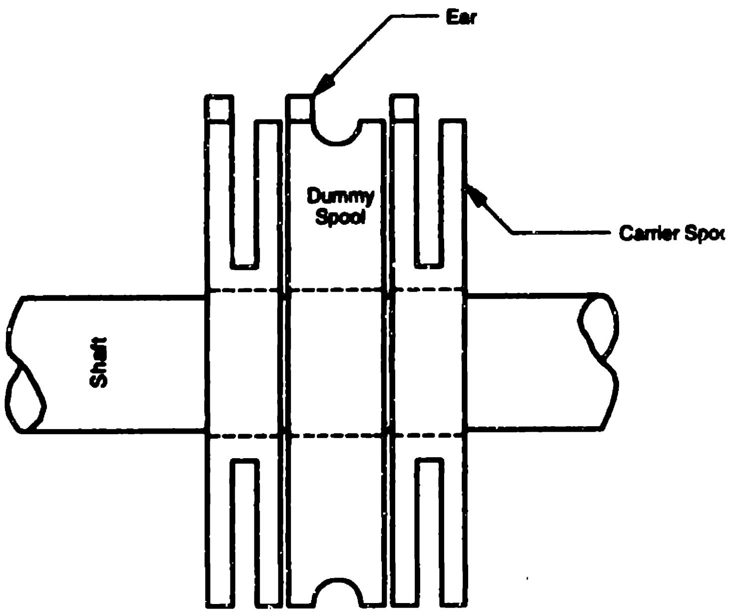

Figure 3-3: Configuration of dummy spools with the spools. The fiber is wrapped multiple times.

Wrapping spools one at a time

This concept was developed to overcome the potential difficulty of cutting the continuously wrapped fiber and manipulating the short fiber ends. Instead of using the spool winding machine, each spool would be wrapped one at a time by an operator at a semi-automatic wrapping station. The operator would take an empty spool, slide it on a short shaft, pull out the fiber end from the supply spool, affix the end on a notch in the spool, and wrap the fiber. The wrapping would be done by a small motor that automatically rotates the shaft a predetermined number of times. After the wrapping is completed, the operator would cut the fiber, take the carrier spool off the shaft and load it directly onto the spool holder shaft. Once the holder shaft is completely loaded, it can then be installed in the pigtail machine. Since the holder shaft is not constrained to fit within the winding machine, as many spools as desired could be loaded onto the shaft. Additionally, both ends of the leads would be available for use in the machine. The large amount of operator labor necessary to wrap the spools, and the cost of providing the additional

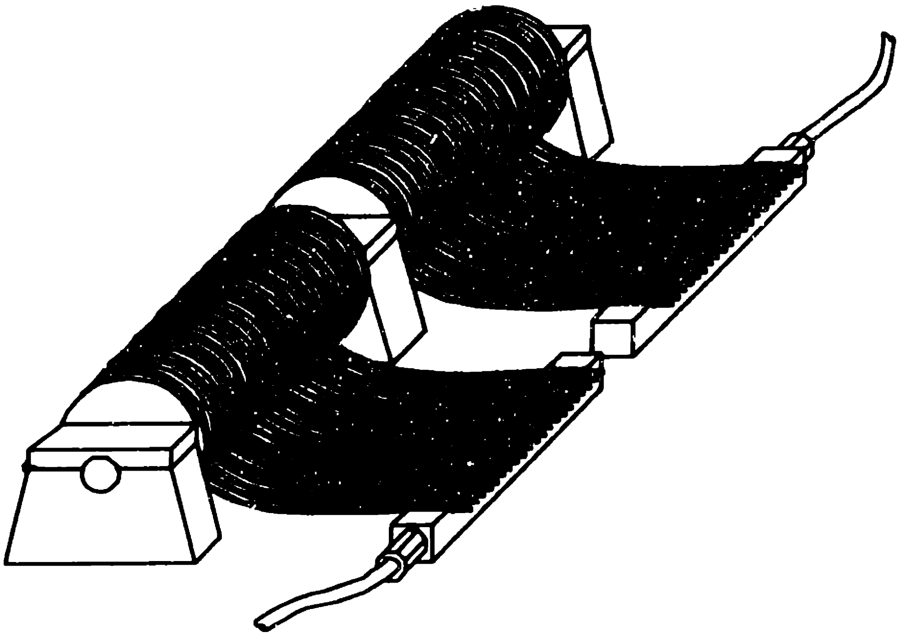

Figure 3-4: Side by side spool holder configuration shown with vacuum chuck fixture concept.

wrapping equipment were the main disadvantages of this method.

The spool winding configuration chosen would dictate the number of holder shafts that must be installed in the pigtail prep machine. The installation of these shafts into the machine will vary depending upon how many spools are on each shaft. In any case, the holders will most likely be placed end to end in the machine (Figure 3-4), or if necessary, in a two tiered system with one row of spools directly above the other (Figure 3-5).

Later in the program, the FOG designers decided that they would use short fiber leads. When using short fiber leads we do not have the need to wrap any long lengths of fiber on spools and then mount them on the machine. We could easily take a supply spool wrapped with hundreds of meters of fiber and pull out fiber in increments and produce fiber pigtails continuously.

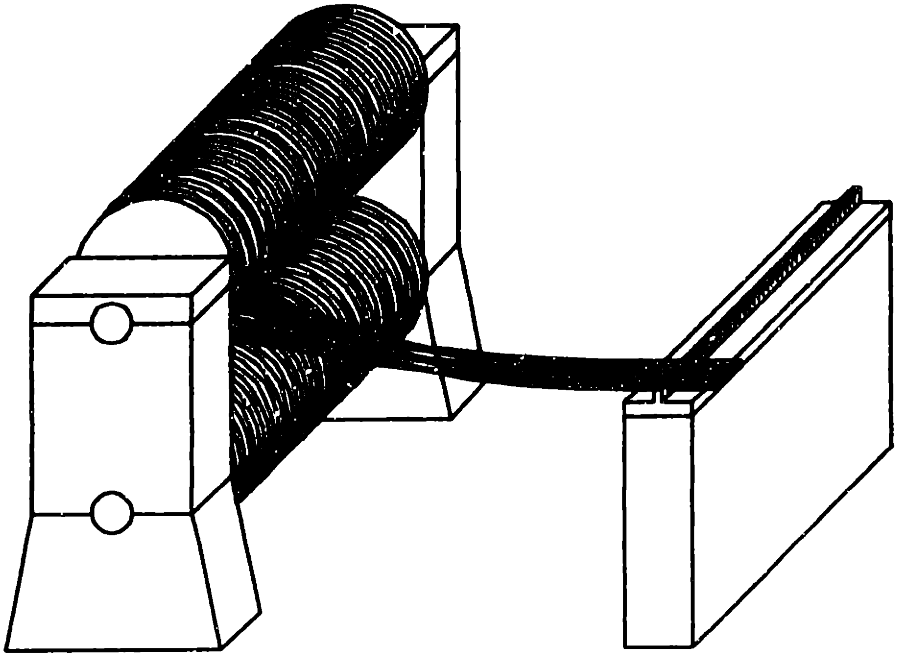

Figure 3-5: Vertically stacked spool holder configuration. Fibers are alternately loaded into the holding fixture from the top and the bottom spools.

3.1.2 Fiber Manipulator

The fiber manipulator would be used to pick up the fiber ends from the affixed locations and move the fiber to the various tooling locations in the machine. Depending upon the final design, the manipulator may also be used to insert the fibers into the carrier strip and perform the necessary rotational alignments. Three different ideas for the manipulator have been developed. Finger grippers, finger grippers with rotational alignment and the L-shaped gripper.

Finger grippers

The finger grippers would consist of one set of fingers that simply open and close in order to grasp the fiber. The fingers may be actuated using a solenoid or an air piston (Figure 3-6). They would then move the fiber to the various tools where other mechanisms would then grasp the fiber and work on it.

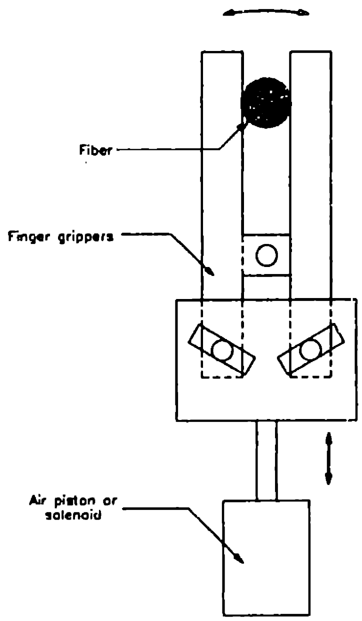

Figure 3-6: Finger gripper concept

Finger grippers with rotational alignment

The finger grippers with rotational alignment design would be essentially the same design as the previous one, except that this design would also have the ability to rotate the fiber during polarization alignment. This finger gripper concept will have the ability to rotate the fiber as well as move the fiber to the various tools where other mechanisms would then grasp the fiber and work on it. The finger gripping action would still be actuated using the air piston or solenoid and the finger rotation would be realized by using a rack and pinion where the pinion would rotate about the pivot point of the finger grippers (Figure 3-7).

An advantage to using the finger grippers with rotational alignment concept is that they have already been developed in another Manufacturing Institute Project [18].

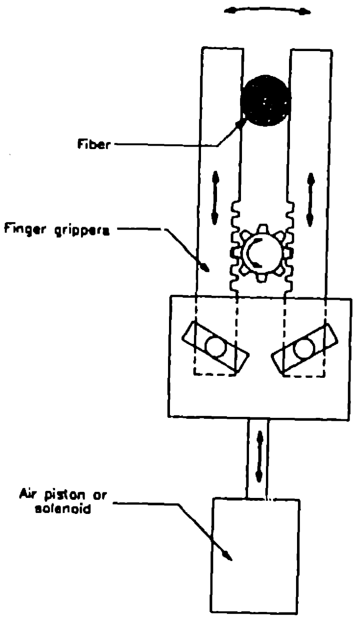

Figure 3-7: Finger grippers with rotational alignment

L-shaped gripper

The gripper in this case would be a holder with an L cross section. The fiber would sit in the corner of the L and then another plate, with an angled bottom made of some soft substance, would slide down along side the L and gently clamp the fiber in place. This mechanism would provide exact location information of the fiber during machine operations and would have rotational alignment capabilities (Figure 3-8).

3.1.3 Fiber Stripping

There are various stripping processes used in the fiber optic industry to date. The stripping concept that is under consideration is based on mechanical stripping techniques. This design was pursued in order to keep stripping time to a minimum, reduce machine complexity and keep the machine cost down.

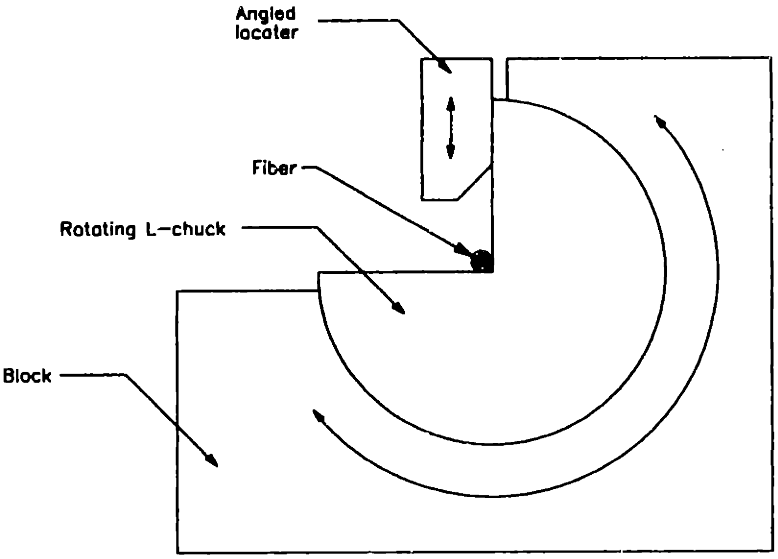

Figure 3-8: L–shaped gripper

Single fiber stripping

The single fiber stripping concept is very similar to most of the stripping operations that are currently in use. The fiber end would be moved to the stripping station and indexed into some type of holder chuck. Once there, two plates would slide together, closing in on the fiber and cutting into the buffer. There would be a small notch cut into each plate allowing the cladding to pass through unharmed. The fiber would be stripped by having the plates pull forward while the fiber is held stationary. Clamping the fibers would obviously be necessary during this process, and it is important that the clamping of the fiber would not damage the fiber.

The stripping tool can either be located under the station's working surface, or in an enclosed area above the machine. If the tool is under the fibers, it would move up when needed. Once used, the tool would move back down out of the way to prevent the fibers from getting tangled (Figure 3-9). The other option, with the tool above the main surface of the machine, involves constructing a fiber stripping box. The operator would simply insert the fiber in the opening of the mechanism where it would be grasped by

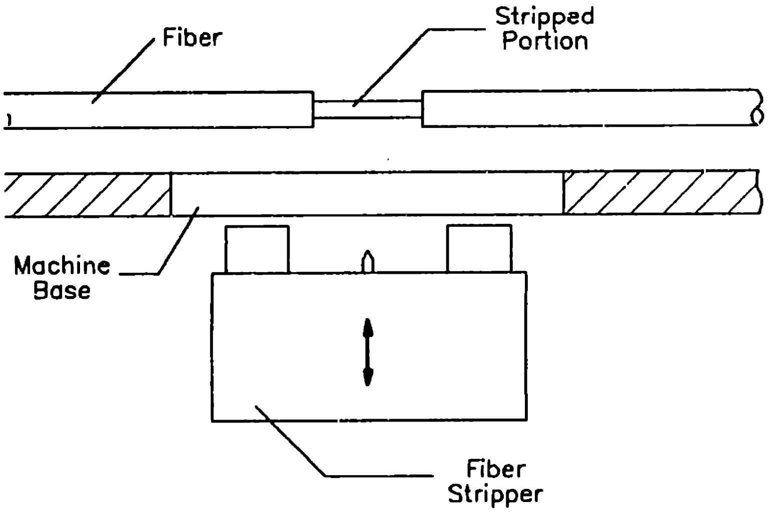

Figure 3-9: Fiber stripper tool moving under the base.

some type of grippers. The tools would then strip (and cleave) the fiber end, and alert the operator when it is done. Having the tools above the working surface would also help alleviate tangling of the fibers.

3.1.4 Cleaving

Two approaches for cleaving the fiber ends were under consideration. It is important to remember that an optical grade cleave is not necessary at this step. The quality of the cleave only needs to be good enough to clearly see the stress rods for polarization alignment.

After bringing the fibers to the cleaving station, the fiber manipulator would maintain its grip on the fiber. Another small gripper would then grab the very end of the fiber and pull gently, putting the fiber under tension. The pulling mechanism could be passive or active. Passive tensioning could be comprised of a spring, whereas active tensioning would be achieved with the main fiber grippers moving back a small amount. Another active tensioning device could be designed by using a mechanical frame that pushes laterally on the fiber being held between the two grippers. Once in tension, a small

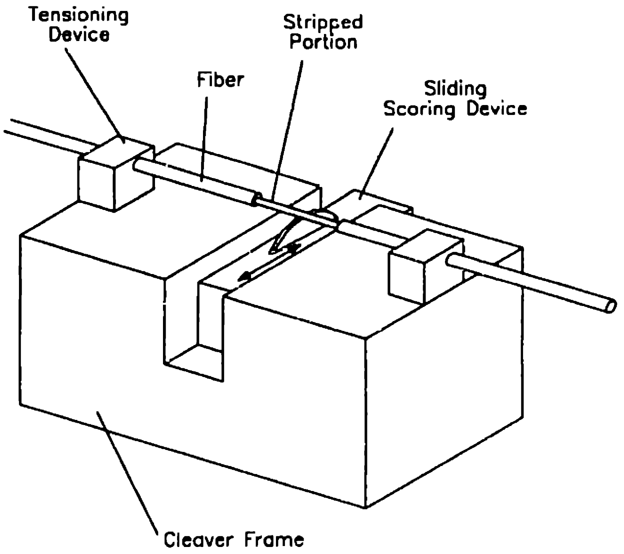

Figure 3-10: Cleaver with sliding scoring device.

diamond wheel or scoring device would score the fiber, causing it to snap. The scoring device could be mounted on a track and slide perpendicular to the fiber (Figure 3-10), or it could be mounted on the end of a shaft that rotates eccentrically (Figure 3-11). The cleaving apparatus would then drop down out of the way once cleaving is completed. This design's main strength stems from the fact that it is based on well known existing technology. Most manual cleavers on the market use this system to cleave stripped fiber ends. The waste from the cleaving would still have to be dealt with though, in order to prevent it from interfering with other workstation activities.

3.1.5 Stripper and Cleaver Clamp

In the stripping process the fiber must be clamped securely to ensure the fiber would not slip while stripping the fiber. The clamp must be able to close on the fiber slowly enough as not to damage it yet strongly enough to prevent it from slipping. In the cleaving process the fiber must be clamped tightly as in the stripper. Additionally the clamps must be able to apply tension to the fiber ends prior to cleaving. The cleave quality is

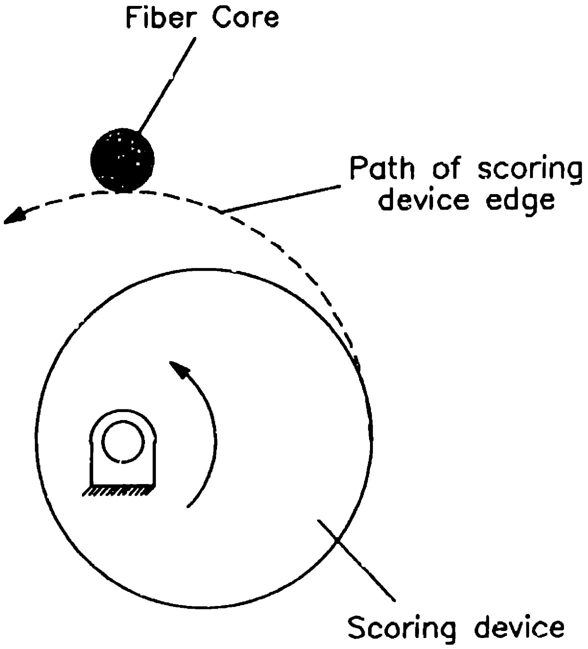

Figure 3-11: Scoring device mounted on an eccentric shaft.

highly dependant on the fiber tension.

Magnetic Clamp

In this concept design, we looked at a grooved block for the fiber to sit in, a cover plate pivoting about one side and a magnet on the other side to hold the plate down on the fiber securely (Figure 3-12). There would be a rod on the side of the magnet to push the plate up to free the fiber, and to simply let the plate down when clamping on the fiber. This concept was not pursued further due to the fact that there is no actual control of the clamping force on the fiber. The clamping force on the fiber can only be changed by changing the magnet which would be a tedious task if adjustment is required.

Clamping arms

In this concept, we tried to find a way to control the clamping force on the fiber. Figure 3-13 shows the schematic of the proposed design. The piston sitting on the bottom would

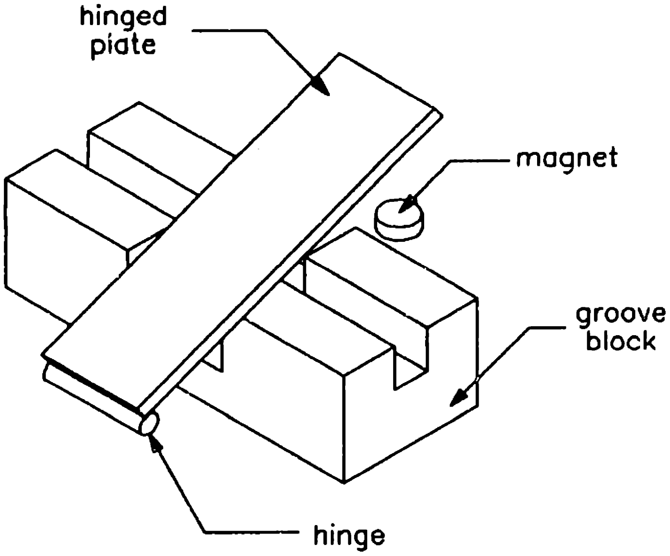

Figure 3-12: Sketch of the grooved magnet clamp.

extend thus compressing the spring. The compressed spring would start lifting the middle cam and thus force the clamps to close on the fiber. The piston would always extend the same amount and the middle cam would always go up a certain amount (until the clamping arms squeeze on the fiber). The spring which would be compressed between the piston and the middle cam would determine the clamping force exerted on the fiber.

Cleaver clamp

The cleaver clamp must be different from the stripping clamp in that the cleaving clamp would also precisely apply tension to the fiber during the cleaving process. One proposed design consisted of two magnet clamps (see Figure 3-12) actuated by piezoelectric actuators on each end. Figure 3-14 shows the sketch with the magnetic clamps on each end and the vibrating diamond wheel, which does the cleaving. The piezoelectric actuators are very precise and can exert high forces over moderately short distances.

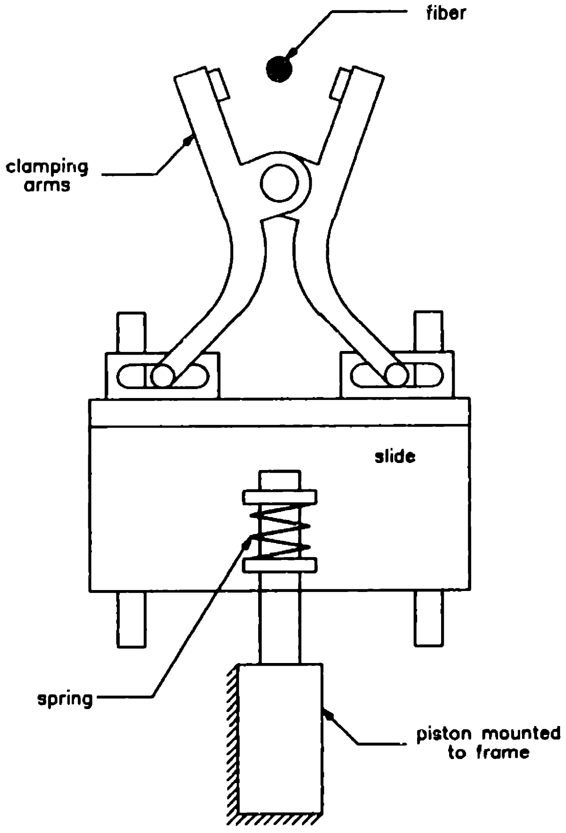

Figure 3-13: Piston actuated clamping arms conseptual sketch.

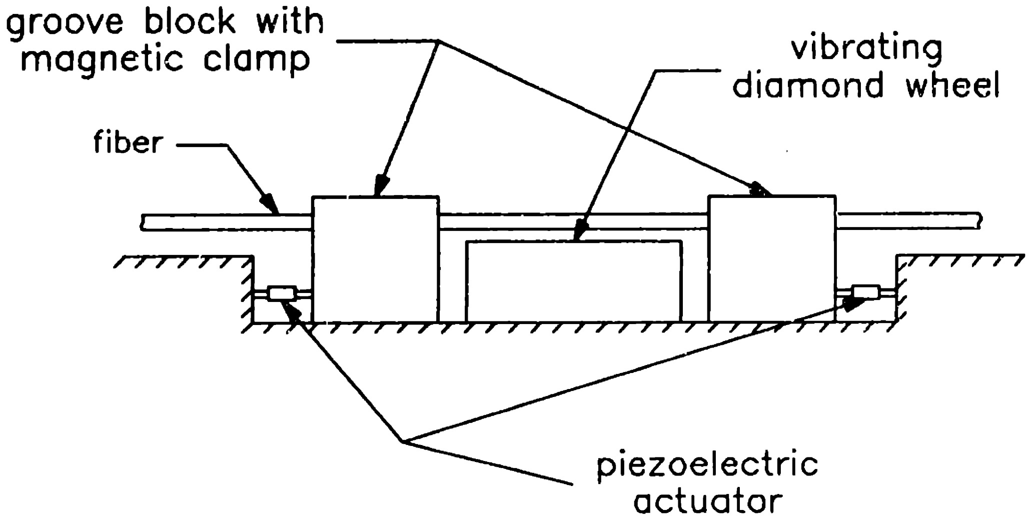

Figure 3-14: Piezoelectric actuated magnetic clamp.

Eccentric wheel concept

During the brainstorming process one idea that came up was using two eccentric wheels with rubber padding on their outer surfaces (Figure 3-15). When the wheel starts to turn, it would start closing on the fiber and eventually clamp it plus pull it towards itself a little (Figure 3-16). The double action of clamping and applying tension at the same time with one stroke was the advantage of this design. For definite clamping and precise location we decided to continue with the clamping arms concept.

3.1.6 Fiber Insertion

Inserting the fibers into the carrier strip requires a mechanism to align the fiber with the hole and insert the fiber end into the carrier strip hole. If the carrier strip hole location tolerances are tight enough to allow pre-programming of each carrier strip hole location then searching for the holes is unnecessary. Since the holes are in a predetermined place finding the exact hole location would be easy. These designs fall into two categories, passive mechanical aids for threading the fibers into the slots, and active placement of

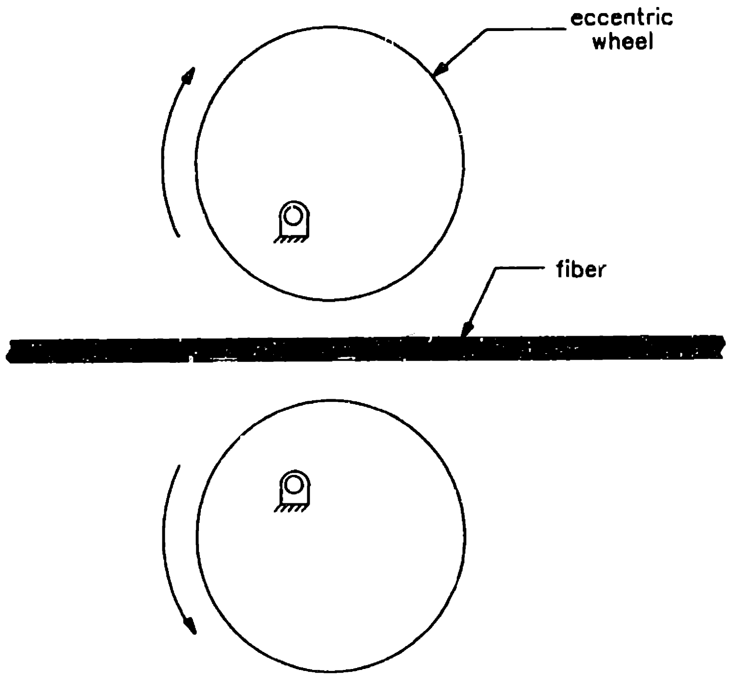

Figure 3-15: Eccentric clamping wheels rotating to clamp on the fiber.

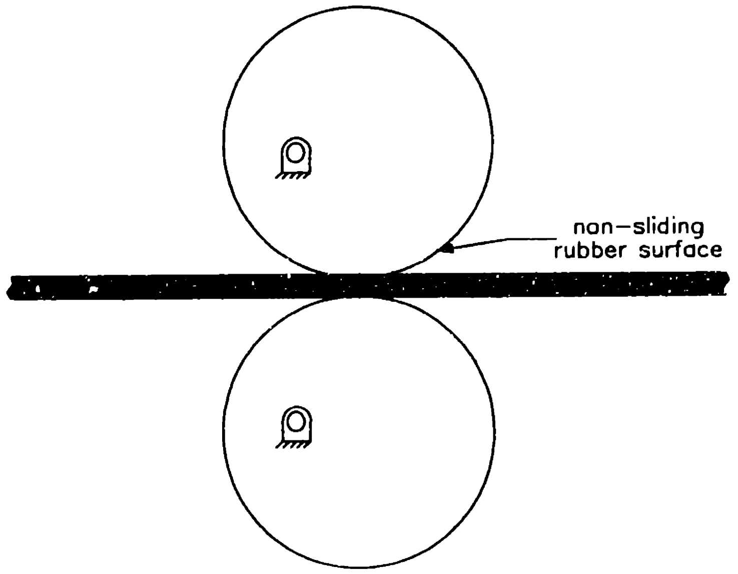

Figure 3-16: Eccentric wheels clamped on the fiber and pulling the fiber back a little to apply the necessary tension on the fiber.

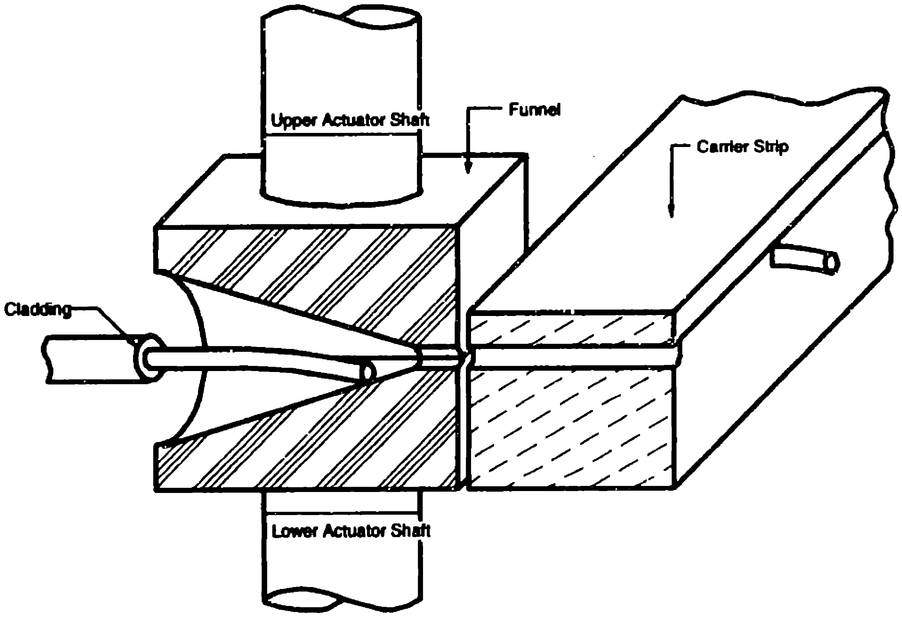

Figure 3-17: Funnel Concept

the fibers into their respective holes.

Passive alignment methods

In the passive placement design, the fiber would be moved to the insertion station by the manipulator after the cleaving is done. There, the manipulator would move forward, pushing the fiber into a funnel. The funnel would neck down to the same diameter as the slot for the fiber, and would guide the fiber into the slot (Figure 3-17). The funnel would have to be made in two pieces so that it can be removed from the fiber once the fiber is threaded into the carrier strip. Funnel disassembly and reassembly for the next insertion would be done automatically. While this method seems very quick and easy to use, it would be very difficult to manufacture such small funnels, and the funnels would not be able to compensate for the slots being misaligned due to variations in the slot's position that are within their tolerance limits.

Similarly, another proposed concept uses a fiber guide that would be very similar to one half of the funnel described above. The carrier strip would be at a different height than the fiber that is being moved into position by the manipulator. As the manipulator moves the fiber forward, the fiber would encounter a ramp and slide up (or down) to the slot in the carrier strip. The carrier strip in this case would have to be tilted so that the slot is tangent to the slope of the ramp. Again, the ramp would neck down to the width of the hole in the carrier strip and guide the fiber into the correct slot. This design faces the same blind alignment problems as the funnel, but is simpler in that only one piece is required instead of two. One flaw in this design is the fact that the fiber end may slide off the ramp in the wrong direction.

The final passive aid concept would use an indexing block mounted on a small track. This block would have a groove cut into it that is wider at the top and tapered down into a slot the same width as the carrier strip hole width. The manipulator would bring the fiber to the insertion station, where this block would raise up and the fiber would slide down into the slot. A small stop block would then be inserted into the groove on top of the fiber, clamping it in place, while the manipulator is releasing the fiber. Once the fiber is in place, the threader would move forward and slide the fiber into the carrier strip. This is possible since the block would be precisely indexed to the carrier strip hole locations. If the tolerances are such that preprogramming of the slot locations is not possible, then a vision system could be used for the final alignment of the block with the strip.

All of the above cases would also require a final insertion mechanism that would ensure that the fiber's buffer is pulled up tight to the carrier strip. Most likely this would just be a spring that pulls the threading mechanism and fiber up to the strip. For the funnel and ramp designs, a small secondary grip may also be required to hold the fiber while it is being moved into the final position.

Active alignment methods

In the active placement concept we assume that the fiber manipulator would have three degrees of freedom (up and down, side to side, and forward and backward). With this motion available, vision system cameras could be used to visually align the fiber end and carrier strip slot. The fiber manipulator would be used to move the fiber end, and once aligned, the manipulator would also insert the fiber into the carrier strip. By using a vision system to align the fiber end to the carrier slot holes, the repeatability of successful insertions would be much higher, since the machine would no longer be making blind insertions. This increased reliability comes with increased complexity and cost in the machine design.

The assumption is that the carrier strip itself would move a preassigned distance between insertions. All the other tooling (funnels, ramps, threaders, etc.) would remain fixed throughout the course of machine's operation. However, a method of registering the slots in the strip to the tooling would be needed. One concept is to shine a light source on one side of the carrier strip, and use a photo-detector on the other side of the strip to register where the holes are located (Figure 3-18). Pins in the tooling could also be used to either register each slot prior to insertion, or to register the strip itself to the particular tool. A third method would be to use the vision system cameras to not only locate the fiber ends, but to also determine the exact location of the carrier strip holes.

3.1.7 Polarization Alignment

The polarization maintaining fiber that would be attached to the carrier strip must be rotationally aligned before the epoxy can be applied. The alignment of the stress rods relative to the carrier strip is a very important process step in terms of the quality of the final pigtail. The better the alignment of the stress rods to the carrier strip the less additional alignment necessary at the pigtail–IOC assembly machine. Two different methods for aligning the stress rods have been developed, two of which would use an automated vision system to control the alignment and one using a polarizer.

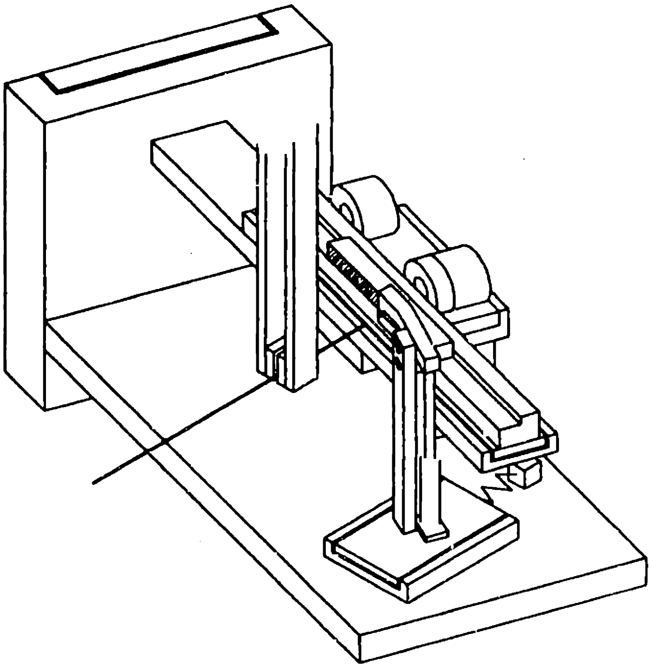

Figure 3-18: Insertion concept using a laser and photodetector

Finger gripper alignment using a vision system

If the finger gripper is used, it can also be equipped with the ability to rotate the fiber. After the fiber is inserted into the carrier strip the fingers would rotate the fiber to the correct alignment. The rotation would be done by having one finger of the gripper move up while the other moves down. The fiber, being captured in the carrier strip, cannot translate and would simply spin inside the strip. Again, the rotational motion would be controlled by a vision system looking at the stress rods on the end face of the fiber. By having a single tool that can do multiple tasks, machine complexity can be reduced.

Finger gripper alignment using a polarizer

This concept would use the finger gripper as described in 3.1.7. Instead of using a vision system, polarized light that shines through the fiber may be utilized. The preferred axis of the polarizer would be aligned with the geometry of the carrier strip. The fiber would

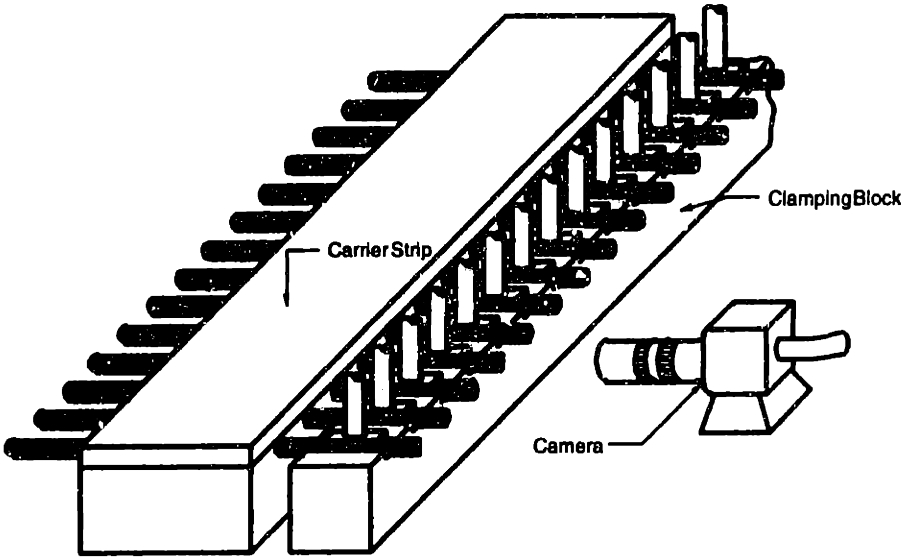

Figure 3-19: Loaded carrier strip with fibers clamped in place. Vision system camera also shown.

then be rotated until the light going through the polarizer is maximized. This would ensure that the polarization axes of the fibers are aligned to the strip.

3.1.8 Gluing and Clamping

Due to the time required for the glue to set, each fiber would be clamped after being glued, in order to minimize process time. Several clamping methods were developed to accomplish this task.

Gluing the fibers to the carrier strip can be done one of two different ways. One method is to glue each fiber as it is inserted and aligned in the carrier strip. A syringe type applicator would be used to automatically put a drop of glue on the fiber before it is pulled up tight to the carrier strip. The glue would be applied to the side of the strip that the fibers enter and the clamps would be on the backside of the strip (Figure 3-19).

The other method is to insert, align, and clamp all 80 fibers. Then the glue would be applied to all the fibers at once. Here, the applicator would most likely resemble some sort of brush. This brush would apply the glue to the backside of the strip, where the

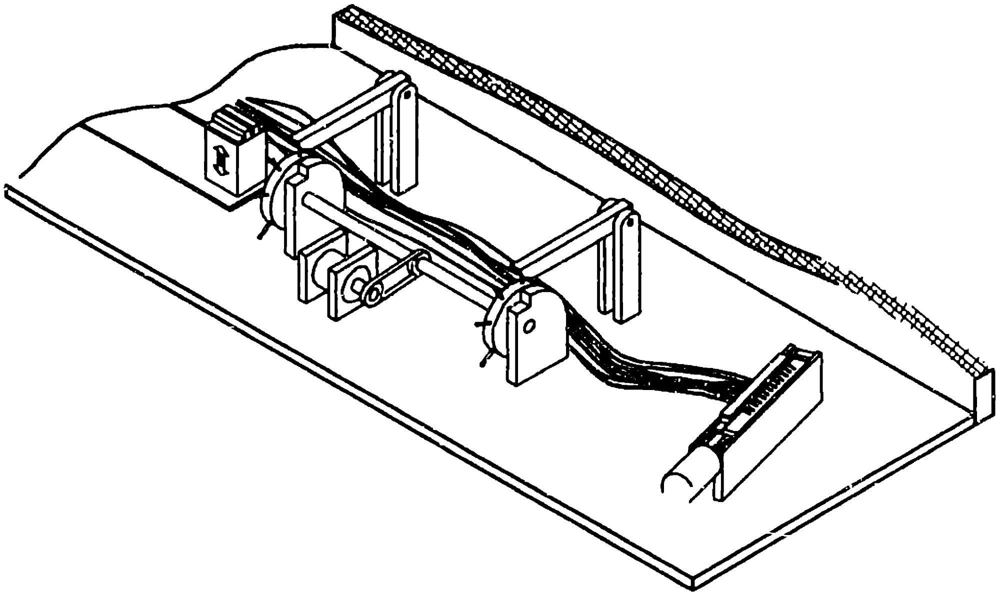

Figure 3-20: Fiber stowing using a spoked wheel

fibers exit the strip. In this case, the clamps would have to be located on the front side of the strip.

3.1.9 Fiber Tangling

If shorter fiber lead lengths are to be used, then a way to stow the inserted fibers must be found. One design is to use a spoke wheel to push the inserted fiber to the storage compartment (Figure 3-20). After the fiber is inserted into the carrier strip and the end is cleaved the fiber would fall between the spokes on the wheel. Then the wheel would rotate to push the fibers sideways into the storage area.

Another concept was to use pistons like fingers. After the fiber is ready to be stowed the pistons would extend from the side, grab the fiber and pull it back into the fiber storage area.

3.2 Critical Feasibility Experiments

A way to validate the concept designs and solidify them is to conduct feasibility experiments on some ideas that are not trivial. Feasibility experiments were conducted in order to resolve several design issues that arose during the conceptual design of the automated pigtail preparation workstation. In the following sections the description of the experiments that were carried out and the results obtained are described.

3.2.1 Buffer Stripping

The purpose of these experiments was first to decide on the dimensions of a straight fiber clamp that would be used to hold the fibers during stripping, and secondly to determine the best material to use on the gripping surfaces of these clamps. The fiber used in these experiments was the Fujikura 125 micron fiber.

The amount of fiber that would need to be stripped depends on the geometry of the carrier strip and the fiber cleaving mechanism. Taking these into account, the absolute minimum stripped length should be no less than 0.363 inches. Our conservative estimate for the amount of fiber to be stripped then, based on this information, is 0.5 inches.

For these experiments, the fiber was placed in between two plates that were used as a clamp and the following four parameters were varied: Stripped fiber length, S, length of clamping surface, L, clamping force, F, and clamping surface material. Figure 3-21 shows the experimental setup used. The speed of stripping was kept constant and does not affect the stripping process as long as the stripper is not jerked.

The minimum force required to hold the fiber, without any slipping, as a function of various clamping surface materials is shown in Table 3.1. Using ground steel as a clamping surface allowed the clamp to obtain a firm grip on the fiber, but this is due to the fact that steel is a much harder material than the buffer material and thus it digs into the buffer. It is this imbedding of the clamp into the buffer that provides the force to hold the fiber in place and not necessarily the friction force between the buffer and

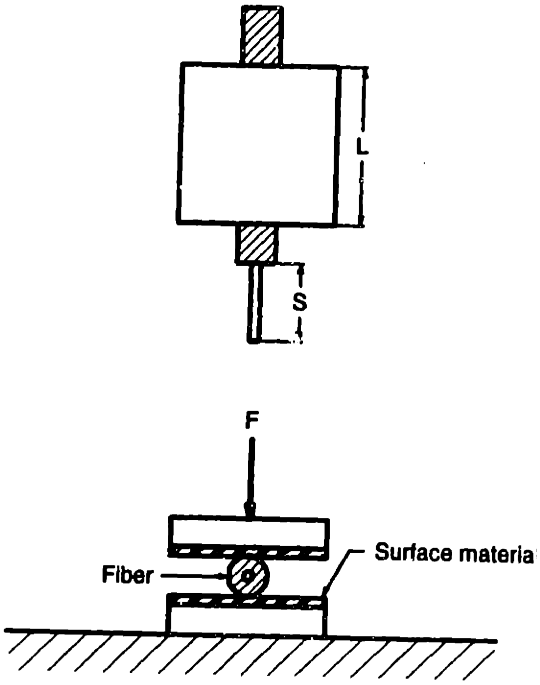

Figure 3-21: Experimental setup for buffer stripping experiments

steel. Because of this, we have decided that the steel is not a wise choice for a clamp surface, as there is a potential for irreversible damage to the buffer.

The foam clamp surface does not damage the buffer, but it has almost no ability to grip the fiber unless it is placed under a very large load. The silicon rubber surface gives the best results in terms of minimum clamping force necessary with no fiber slipping. The silicon rubber also has a sticky kind of surface that helps to hold the fiber in place, and we noted that the friction force is nonlinear relative to clamping force. The fiber is not damaged during the stripping process, and overall the silicon rubber proves to be a good material to use as a clamping surface.

3.2.2 Fiber Insertion

These experiments were divided into two categories: blind fiber insertion and active fiber insertion. Vertical alignment tests and testing of the mechanical aids for insertion were

Result of Fiber Stripping Experiment			
Surface Material	**L (in)**	**S (in)**	**F (oz.)**
Steel	1.0	0.5	12
Steel	1.0	1.0	17
Steel	2.0	0.5	9
Steel	2.0	1.0	14
Foam	1.0	0.5	165
Foam	2.0	0.5	78
Silicon Rubber	1.0	0.5	27
Silicon Rubber	1.0	1.0	36
Silicon Rubber	0.5	0.5	29

Table 3.1: Buffer stripping experiment results with a Fujikara 125 micron fiber

done during both types of tests.

Blind fiber insertion

A two inch long vacuum chuck for holding the fiber end was mounted on a precision xyz stage. This stage was placed in front of a computer controlled linear stage where the carrier strip was mounted. We then indexed the carrier strip an amount corresponding to the nominal distance between slots, and used the xyz stage to insert the fiber into the slots.

Despite the very close tolerances on the carrier slots' width and the slots' location, we found that it was possible to insert a fiber into all the slots of the carrier strip blindly, using only the given slot location dimensions as a guide, and keeping the same fiber on the chuck. However, variations between carrier strips and between fiber leads will cause problems. Alignment in the z direction should not be a problem, as we found that once the fiber and strip were lined up for the first slot, the remaining fibers no longer needed to be realigned for their insertion. Finally, one drawback to this method is that at this point there is no good method for determining whether or not the insertion was successful.

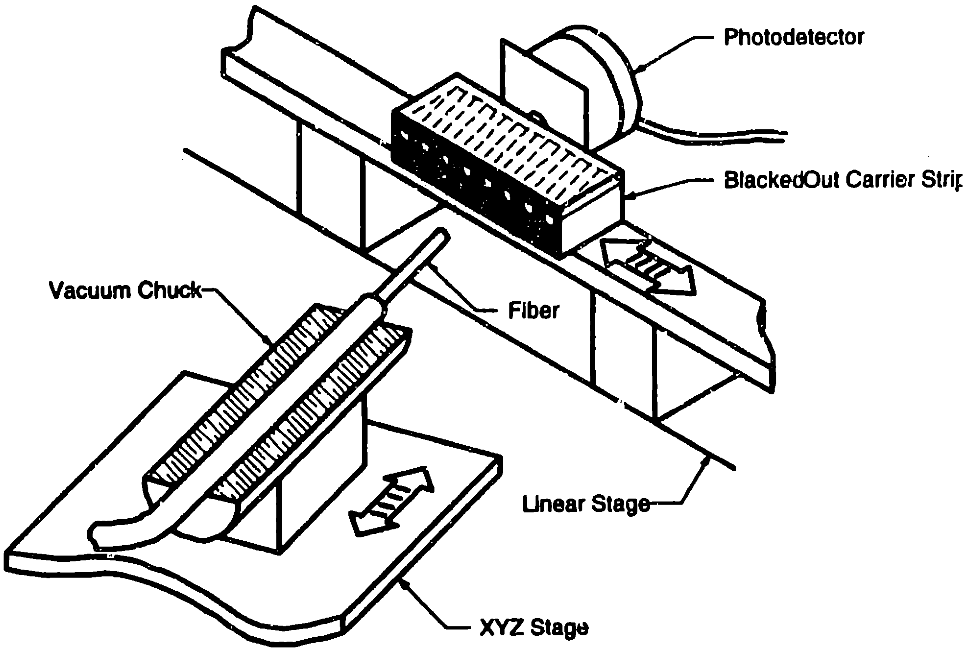

Figure 3-22: Experimental setup used in the fiber insertion experiments.

Active fiber insertion

In this experiment, a fiber pigtailed to a laser diode was placed in the vacuum chuck, and a photodetector was placed on the backside of the carrier strip. The photodetector had a cover placed over it, with just a small opening for the laser light to pass through. Again, the fiber was inserted using the xyz stage and the carrier strip was indexed using the computer controlled stage (Figure 3-22).

This configuration consisted of mounting an unmodified carrier strip in its holder and measuring the light intensity as the strip was moved relative to the laser and detector. While it was possible to detect the changes in light intensity as the slots were moved past the laser, the noise level (amount of intensity measured when the fiber was not at a slot) was very high, compared to the signal recorded when the laser was at a slot.

From this configuration, we also learned that the end face quality of the fiber being inserted plays a very large role in determining the relative light intensities received by the detector. Furthermore, when an insertion is successful, the light intensity increases as the fiber is being inserted and moved closer to the detector. This provides an excellent way of monitoring whether or not the insertion was actually successful, without the use of any additional equipment.

The side of the strip facing the fiber and laser was blacked out with a magic marker, in order to reduce the amount of light the detector received when the fiber was not lined up with a slot. The effect of the marker on the carrier strip was to reduce the noise somewhat, but when insertions based on this intensity data were attempted, they failed. Apparently, even though the light could only enter the strip at the slot positions, it could exit at any point, due to internal strip reflections, and hence the intensity readings did not necessarily correspond to the slot location.

This configuration also emphasized how important it was to have the fiber and laser oriented exactly parallel to the strip slot, in order to reduce internal strip reflections and to guarantee a good correlation between the measured intensity and strip position.

The final experiment we conducted involving active fiber insertion used a carrier strip with both sides of it blacked out with a marker. Here the amount of light that passed through the strip was at a minimum (i.e. there was minimal noise recorded) when the laser was not lined up with the carrier strip slots. With this configuration, a large jump in light intensity distinctly marked the start of the hole location, and all the attempted insertions based on this data were successful. Figure 3-23 shows a plot of laser intensity versus carrier strip position for this configuration.

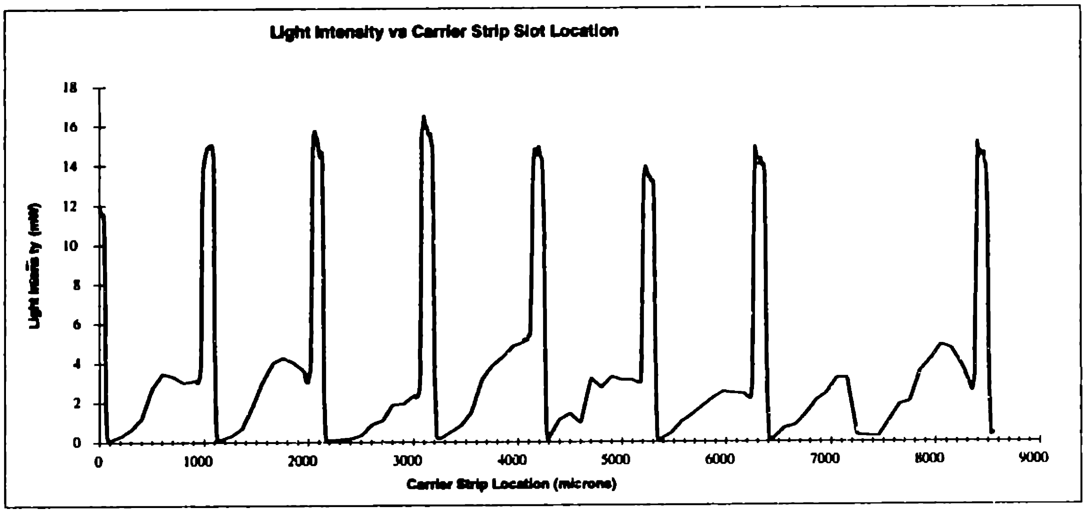

Figure 3-23: Light intensity vs carrier strip slot location

Chapter 4

Detail Design

The conceptual designs for the automated machine gave insight to how the final design would look like. Also the feasibility experiments show which points in the design process will define the overall performance and reliability of the designs. Another very important variable of the design is the requirements and specifications put on each process. During the conceptual design stage the requirements and specification of the machine were not outlined very precisely, but later were solidified.

The fiber lead for the FOG was decided to be a short lead of about 12 inches to 21 inches. To accommodate this design we decided to place each sub-module on a plate where we could later change the plate location on the main base to accommodate the required fiber lead lengths. The finger grippers were designed for another project and it was decided to incorporate the same design into the pigtail preparation machine.

4.1 Fiber Clamp

The functional requirements for the fiber clamp are as follows:

- Grip the fiber without damaging it.
- Provide a tension clamp for stripping (280 grams).

The buffer stripping experiments show that when using steel as the clamping surface, the force required to clamp the fiber while stripping are the lowest (Table 3.1 on page 58). The drawback of using steel as the clamping surface was that the steel had a tendency to "dig into" the buffer. The reason being that the clamping surface edges were sharp. It was decided that if the edges were rounded off, then the "digging into" the fiber buffer would not occur. Clamping will be done by two fingers that have a clamping surface width of 1 in. To reduce the complexity in the system, a pneumatic actuator coupled to a mechanism will be used to open and close the grippers on the fiber.

Initially the design was going to use a 6 link slider–crank mechanism (Figure 4-1). Link 2 is the piston rod which will extend and retract. As link 2 retracts links 3 and 4 will pivot about point O and close on the fiber and as link 2 extends links 3 and 4 will open letting the fiber free. The main disadvantage of this linkage system is that it will be very difficult to get the coupler links to the exact length. Additionally, the tolerances in the pin joints will introduce some asymmetry in the motion of the grippers. The fiber must be gripped exactly in the middle without moving it to the right or left. The asymmetrical motion in the grippers will shift it off center which will create problems in the stripping process where the blades must close precisely on the middle of the fiber for a clean strip.

To overcome the tolerances and for ease of manufacturability it was decided to use a cam to open and close the gripper pads (Figure 4-2). The cam will be directly coupled to the piston and as the piston retracts and extends, the gripper links will open and close on the fiber respectively.

4.1.1 Grippers

The grippers are the most important part of the system because they will define how well the clamp can hold the fiber without damaging it. As mentioned above it was decided to use a 1 in. clamping surface with the edge rounded to reduce the damage inflicted on the buffer. The gripper will be a two piece assembly consisting of the arm link and the clamping surface. The clamping surface needs a very fine finish to it so it can clamp the

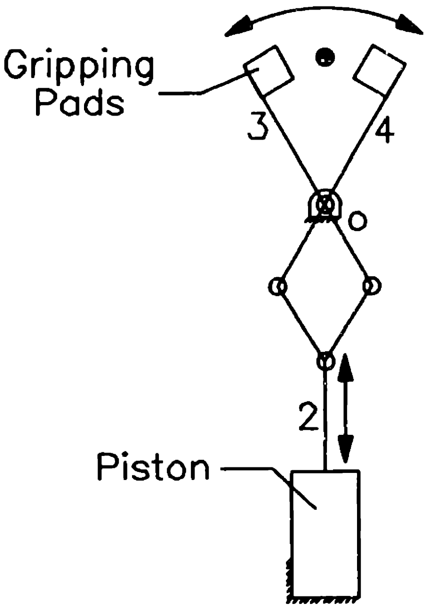

Figure 4-1: Six link slider–crank gripper design

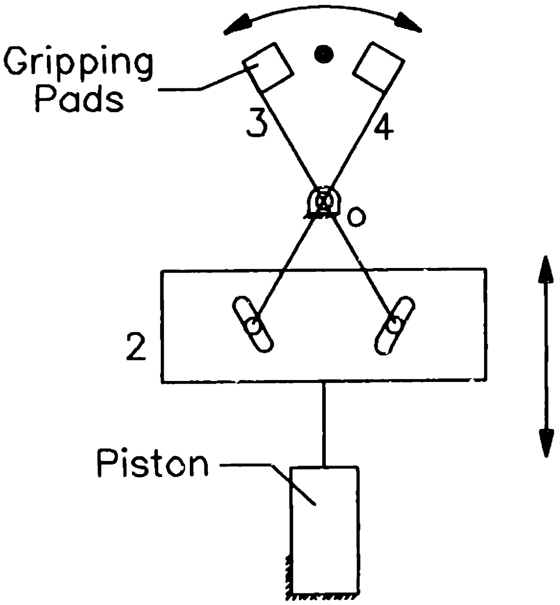

Figure 4-2: Cam link gripper design

fiber without damaging it.

4.1.2 Cam

The cam is the part that will define the kinematics of the gripper arms. The gripper arms will have dowel pins in them that will follow the slot in the cam link. The angle of the slot will define the force the piston must exert to attain the required clamping force on the fiber. Taking into account the fact that we want to also control the force and be able to change it, we decided to uncouple the cam and the piston rod. Instead, the piston rod will always extend to its fullest stroke but there will be a spring between a flanged surface on the piston rod and a flanged surface on the cam. At the full stroke of the piston rod the spring will push the cam up closing the gripper arms. When the grippers grip on the fiber, the arms will stop but the piston will still extend to its fullest stroke. At the end of the stroke the spring will be compressed to a predetermined amount by the assembly and will exert a force on through the cam to the grippers. If in the future it is necessary to increase or decrease the gripping force, a stiffer or softer spring may be used respectively. Adding the spring will also add some damping to the system. When pressurized air is applied to the piston it will extend and retract rapidly. The spring will slow down the gripping on the fiber thus reducing the impact force on the fiber.

The finalized design of the fiber clamping sub–module is shown in Figure 4-3 and the actual system is shown in Figure 4-4.

4.2 Spool Holder

The short lead requirement made it possible to use the fiber directly from the supply spool it comes on when purchased. The supply spool would be attached directly on a shaft and secured. Then, the operator would pull out the fiber and thread it to the stripper where the pigtail preparation process will start. Since there is a need to have a light beam travelling in the fiber for insertion purposes, a light source must be pigtailed

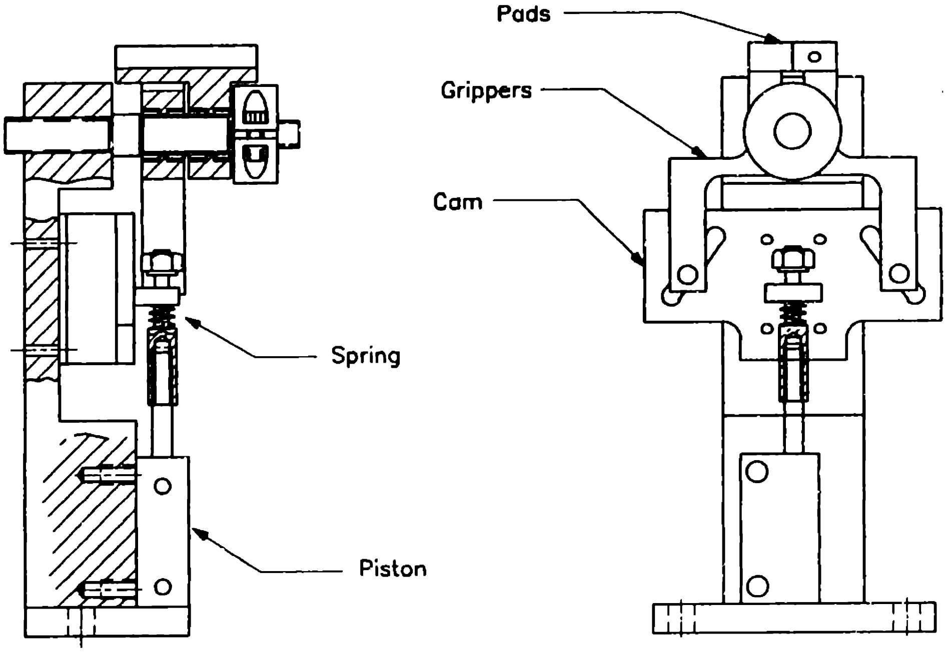

Figure 4-3: Fiber clamp deign.

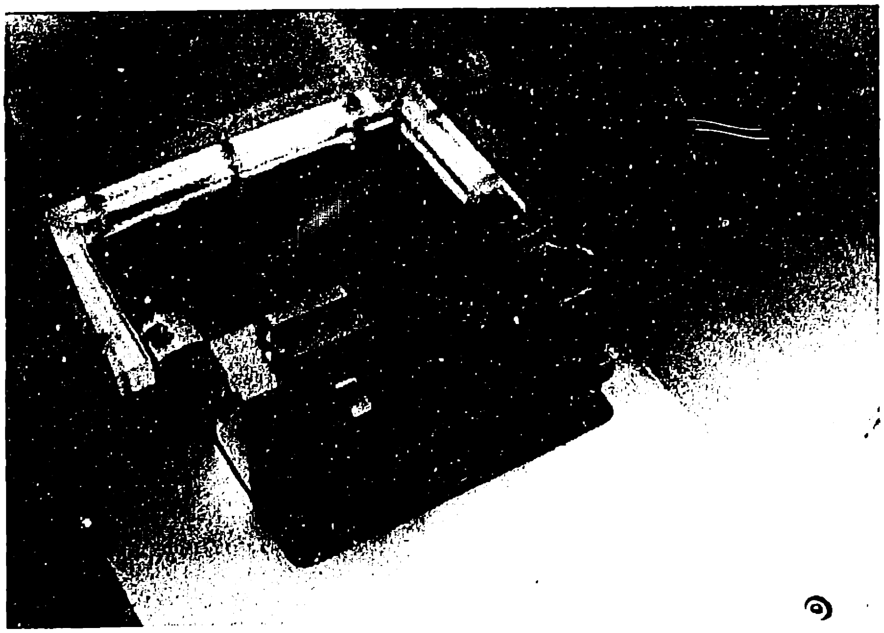

Figure 4-4: Picture of the clamp in the stripping sub–module.

to the one end of the fiber. The light source must be able to rotate with the supply spool as the fiber is being pulled out. Also, there are three different fiber types, thus three different supply spools with varying dimensions that must all be accommodated in the same spool holder. As the fiber is pulled out for processing at each station, it is necessary to put some tension on the fiber so there will be no slack in the fiber. The supply spool will only have as much fiber on it as it can take without attenuating the light travelling in the fiber to the extent that we can not get any measurements at the insertion station. The general functional requirements of the spool holder is as follows:

- Maintain low tension on the fiber as it is being pulled out (100 grams).
- Align the fiber both horizontally and vertically for proper feed into the workstation.
- Provide power and a mounting location for the optical unit.
- Measure angular rotation of supply spool.

4.2.1 Spool Clamp

As mentioned above there are three types of supply spools. These supply spools are reels with different bore diameters and outer rim diameters. The spool clamp should be able to lock down these different supply spools fairly concentrically with the shaft it will ride on. It was decided to use two cone–shaped lock nuts on both ends of a cantilevered shaft. The cone shaped lock nuts could then locate the supply spool concentrically to the shaft.

4.2.2 Light Source

The light source must rotate with the supply spool as it will send light through the fiber when necessary. The light source consists of the electronic drivers, the laser pump, and some fiber lead from the laser pump end to splice to the fiber end of the supply spool. Electrical power will be supplied to the laser via a pancake slip ring.

4.2.3 Tensioning System

There are two ways tension may be applied to the fiber. The first would be to use a simple motor coupled to the rotating supply spool shaft or a more sophisticated controller where the tension would be measured as fed back. We are applying tension to the fiber so the slack can be eliminated and as long as the fiber does not get damaged and the fiber pulling mechanism can pull the fiber without any slippage, then the applied tension may be arbitrary, i.e., we do not need any sophisticated feedback tension control. It was decided to use a motor directly coupled to the shaft end and to apply a predetermined torque to the shaft.

4.2.4 Aligning Pulley

When the fiber is pulled out from the supply spool the fiber will unwind from different directions. The fiber must be routed to a specified path for the other sub-modules to interface with the fiber. A pulley that has a V-shape will be mounted in front of the supply spool. The fiber will be threaded through the aligning pulley by the operator for the first run. Then, as the fiber is pulled out, it will follow the aligning pulley and be aligned for the next processes. The assembly of the spool holder sub-module design can be seen in Figure 4-5 and the picture of the spool holder can be seen in Figure 4-6.

4.3 Fiber Stripper

Initially it was decided to design a stripper with custom-made blades. After some research, it was determined that designing and manufacturing our own blades would be too risky. Instead, we decided to incorporate commercially available hand-held stripper blades into our automated module.

The fiber would be threaded through the fiber clamp and then through the stripping blades by the operator. From there on the fiber will continuously be pulled through the stripper. At certain points in the pigtail preparation process the fiber would be

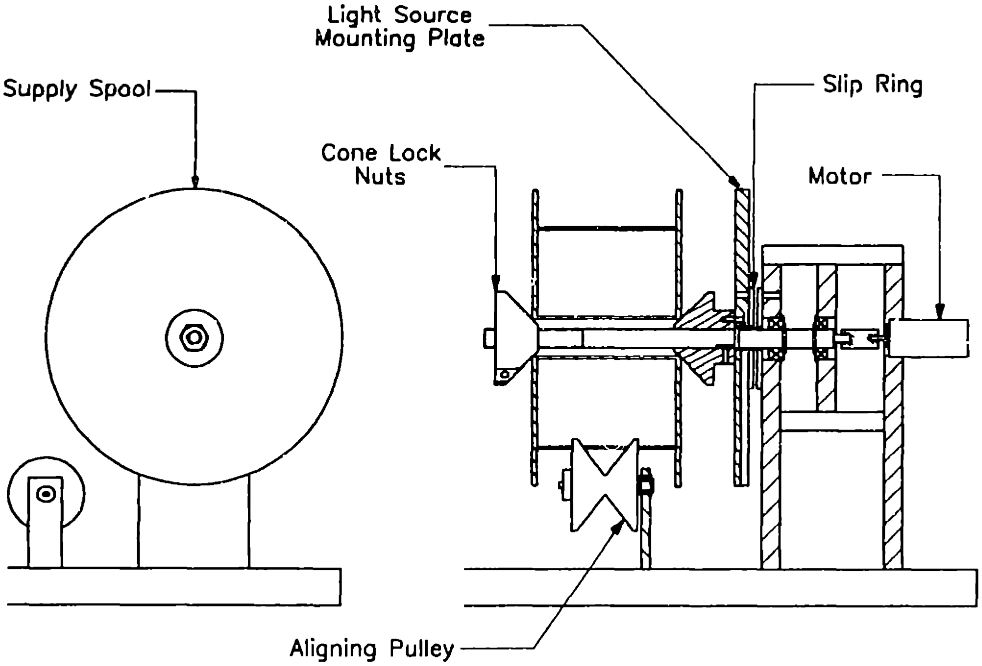

Figure 4-5: Spool holder design.

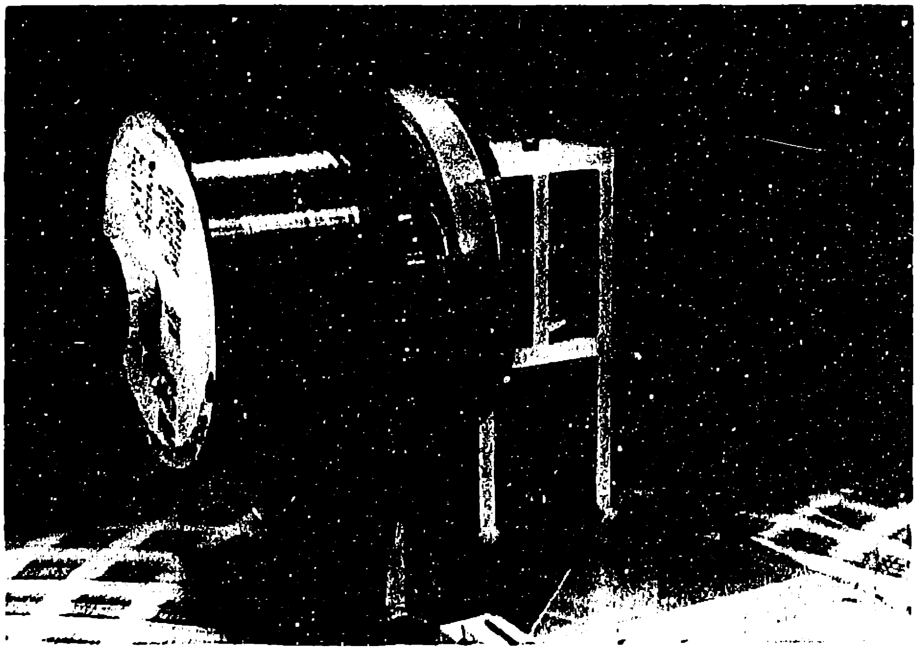

Figure 4-6: Picture of the spool holder.

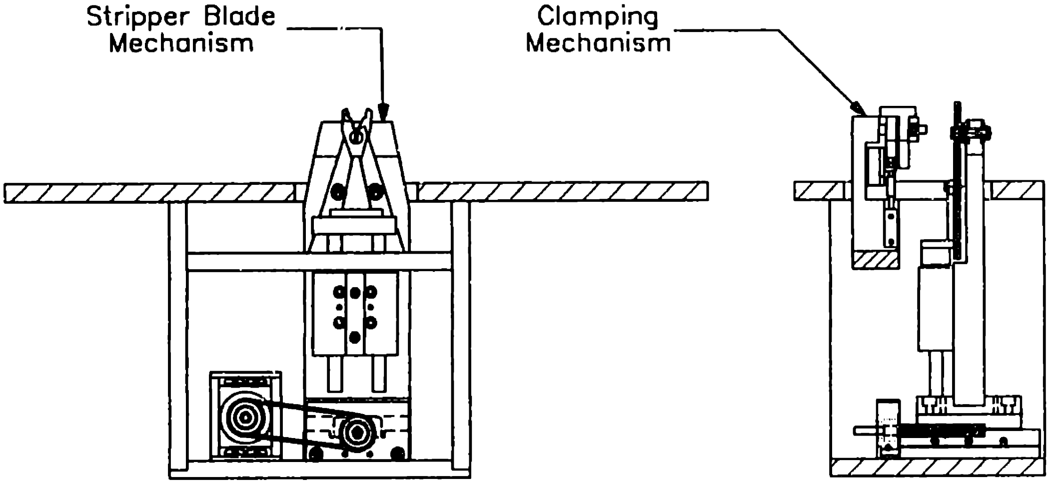

Figure 4-7: Fiber stripping submodule.

held stationary and clamped by the fiber clamps. Then, the stripper blades which are mounted on a motorized stage would close on the fiber and strip the necessary length of buffer off the fiber, leaving the cladding bare.

The assembly of the stripping sub–module is shown in Figure . For more detailed information on the design and operation of the stripping sub–module please refer to [22].

4.4 Fiber Cleaver

The functional requirements are as follows:

- Cleave fiber in the middle of the stripped portion.
- Cleaver must be lowered after cleaving so that the fingers can have an unobstructed path to pull the fiber.

The fiber cleaver uses the current technology used in industry. A diamond wheel scores the glass cladding which is under tension, cleaving the fiber. The tension applied to the fiber and the diamond wheel speed are the two variables that affect the cleave quality the most. In the fiber insertion sub–module, the holes are scanned with the light

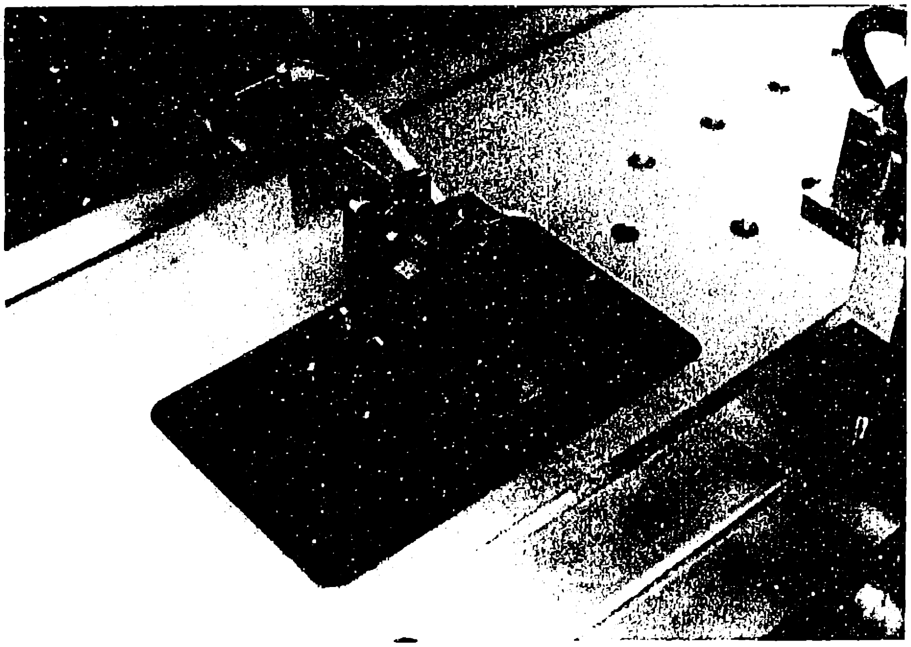

Figure 4-8: Picture of the cleaver sub–module.

beam coming out of the fiber end. For better accuracy in locating the carrier strip hole, it is essential that the light exiting from the fiber end does not scatter. The cleave angle and cleave end surface quality will affect the light scattering thus affecting the insertion process.

The cleaver consists of a diamond wheel mounted on an eccentric shaft. When the shaft rotates, the wheel slowly rises and scores the cladding. The tension to the fiber will be applied with a clamp very, similar to the one used in the stripper sub–module, on one side of the fiber, and the finger manipulator on the other side of the fiber. When the tension is reached, the wheel will be rotated using a stepper motor. As the wheel rotates the diamond edge will eventually score the cladding causing the fiber to snap. At this point the tension would suddenly drop indicating the cleaving process is completed. For more details see reference [23]. The picture of the cleaving sub–module is shown in Figure 4-8.

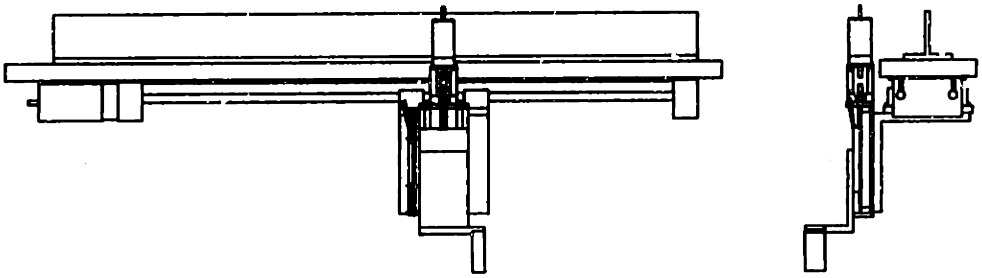

Figure 4-9: Fiber transport sub–module.

4.5 Fiber Transport Mechanism

The fiber transport is the system that pulls out fiber and takes the fiber to the necessary sub–modules for processing. The finger manipulators are a part of the fiber transport mechanism. They will grasp the fiber while pulling it out and angularly align the fiber after insertion. The functional requirements are:

- The fiber transport system should be able to handle fiber lead lengths of 12 in, 15 in, 18 in and 21 in.
- Maximum cleaving tension would be 200 gr.
- Cleaving tension accuracy should be 10 gr.
- Resolution of y-axis alignment: 0.5 micron
- Resolution of z-axis: 50 micron
- Resolution of angular alignment: 0.5 Deg.

Figure 4-9 shows the fiber transport design and Figure 4-10 shows the picture of the actual sub–module. Figure shows the fiber grippers mounted on the fiber transport slide.

Figure 4-10: Picture of the fiber transport sub-module.

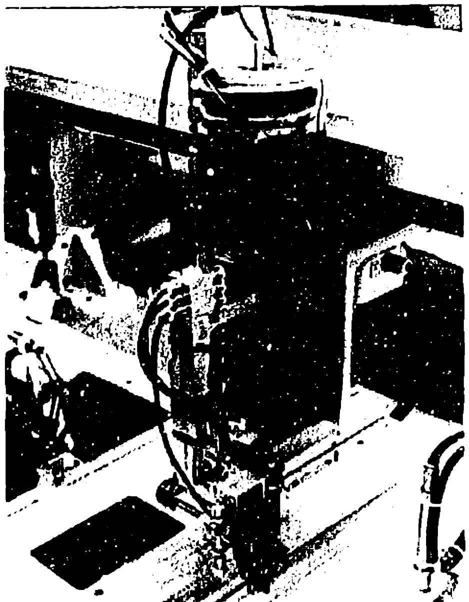

Figure 4-11: Picture of the fiber grippers mounted on the fiber transport slide.

4.6 Epoxy Dispenser

The epoxy would be applied using an extended arm with a syringe on the tip. The arm would be attached to a stepper motor which would rotate one full cycle to lower and raise the arm. When the arm is lowered the epoxy droplet on the needle end would wick into the carrier strip hole with the fiber in it.

4.7 Machine Base

The machine base serves as a platform on which all the sub–modules are mounted on. The sub–modules are first mounted on independent plates so they can be moved to accommodate for various lead lengths. The complete automated fiber optic pigtail preparation machine is shown in Figures 4-12 and 4-13.

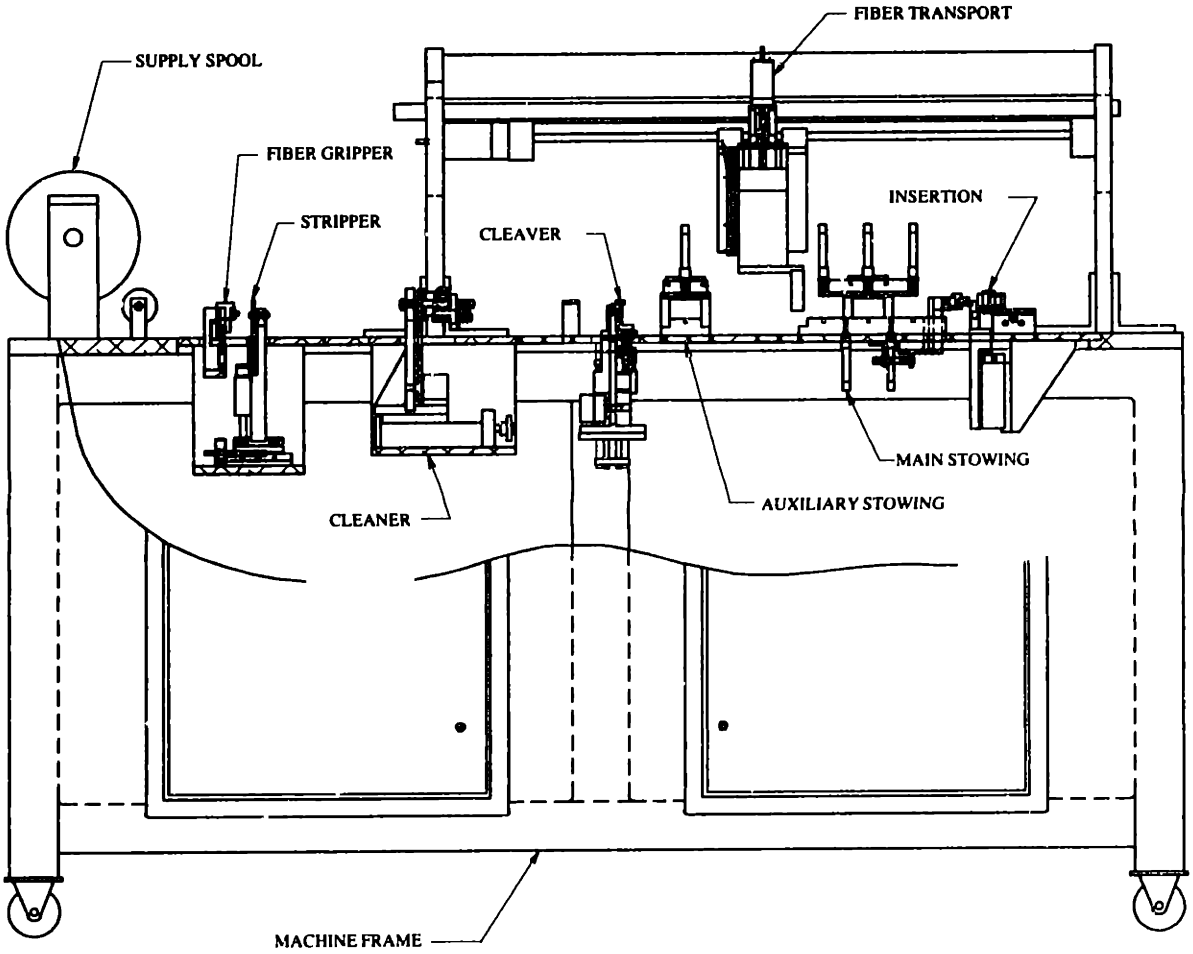

Figure 4-12: Automated fiber optic pigtail preparation machine

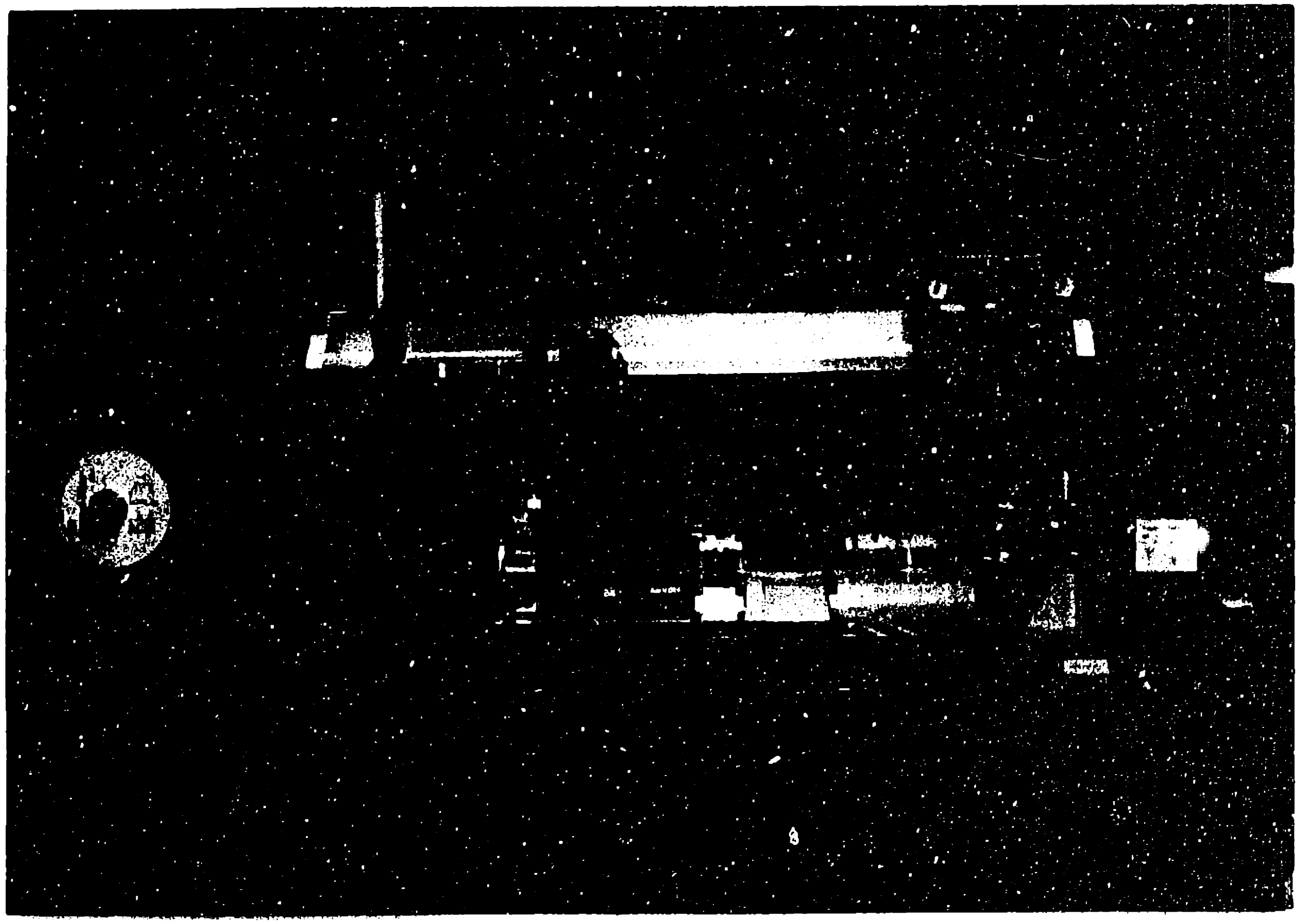

Figure 4-13: Picture of the automated fiber pigtail preparation machine.

Chapter 5

Special Issues Related To Automated Fiber Pigtail Preparation

During the design process of the fiber pigtail preparation machine several issues surfaced. These issues were not predicted in the beginning of the design but rather came about as the design was progressing. In this chapter we will try to explain the issues encountered, how they were dealt with, and what their impact was on the sub–module level design as well as overall machine.

5.1 Failure Conditions

Every machine will have certain failure conditions inherent in the design. Pinpointing the areas of probable failure and finding solutions to eliminate them is vital to the machine's overall performance. The following are the failure conditions most probable to occur in the automated fiber pigtail preparation machine.

5.1.1 Fiber Breakage

The fiber supply is wound on a supply spool and then mounted on the machine. During production the fiber is pulled out of the supply spool by the finger manipulators. The fiber stops at each station for stripping, cleaning and cleaving. The fingers release the fiber and then grab it again during the production process. With this much fiber handling there is a probability of the fiber breaking at the stripper station or the cleaning station as well as for the fiber to slip out of the finger grippers. Thus, the supply spool sub–module needed some kind of monitoring system to detect any fiber breakage.

The supply spool sub–module was designed with a motor on the supply spool shaft to apply tension continuously while the fiber was pulled out of the reel. The motor also has an encoder mounted on it. When the fiber breaks or the clamps or finger grippers do not hold the fiber adequately the fiber will start winding back on the supply spool due to the torque exerted on it by the motor. By monitoring the encoder on the spool motor, the fiber back winding may be detected instantly.

5.1.2 Failure of Finding The Hole On The Carrier Strip

The fiber end will be inserted into the carrier strip holes after stripping, cleaning and cleaving. The hole on the carrier strip will be located using light shining through the end of the fiber. On the other side of the carrier strip there is a photodetector that will detect any light going through the hole.

Possible reasons for failure in finding the hole are the burning out of the laser, the carrier strip hole being clogged, or the photodetector not working. The laser burnout can be monitored using an electronics check. The photodetector can be monitored from its output. The photodetector will always send a voltage output due to noise. If it is not working than there would be no output, thus indicating a problem. Upon these two failures the process will stop and the operator will be alerted. If the hole is clogged then the machine will attempt to search for the next hole.

5.1.3 Failure To Insert Fiber Into Carrier Strip Holes

After the hole is assumed to be found, the fiber end is inserted into the carrier strip hole. The insertion of the fiber end can be monitored using the photodetector. As the fiber goes in and gets closer to the photodetector the output from the photodetector will increase. If the photodetector reading does not increase or it suddenly decreases, then that indicates that the insertion failed.

5.1.4 Clamp Failure at Stripping

The fiber will be clamped at the stripping station. If the clamps used during the stripping process can not hold the fiber and the fiber starts to slip in the clamps, the fiber will start winding back on the supply spool due to the tension applied from the motor. By monitoring the encoder on the spool during the stripping process, slippage can be detected.

5.1.5 Failure To Cleave

The fiber will be inserted into the carrier strip hole before cleaving the upstream end. While cleaving is in progress, the photodetector output may be monitored. When the fiber end is cleaved, there will no longer be any light detected by the photodetector. Thus we can monitor the success of the cleave.

During the cleaving process, the fiber is also tensioned using the finger grippers. The force is measured using strain gages mounted on the finger gripper bracket. For the cleave process to be successful, the tension in the fiber must be controlled. If the fiber breaks or slips in the finger grippers before the tension rises to the predetermined level then the force feedback will drop thus indicating that the cleaving process has failed.

5.2 Fiber Cleaning Effects

During the design process several concerns were raised over the effectiveness of mechanically cleaning the silicon residue off of the fiber after stripping. Therefore, in an effort to quantitatively define fiber cleanliness, its effect on pigtail quality, and our cleaner concept, we decided to conduct several experiments in order to resolve these issues.

The best way to determine the effect of fiber cleanliness on the pigtail is to determine the force necessary to pull the fiber out of the carrier block. Once a nominal value has been determined, based on the current manual cleaning process, various cleanliness levels and cleaning methods can then be tested and compared to this value in order to determine if they are acceptable.

The configuration for the pull tests consisted of inserting and epoxying various types of fiber into carrier strips. These fibers were cleaned to different degrees. After the epoxy fully cures, half of the carrier strips were diced while the other half remained undiced. Then, the carrier strip/blocks were secured and incremental weights were hung on the fiber until the bond between the strip/block and fiber failed. Two different tests were performed using this setup. The first test used fiber that was cleaned using the current manual method. The second test consisted of fibers that are cleaned by MIT. The results of these tests provided us the data necessary to validate the current cleaner design.

The cleanliness levels used by MIT were as follows:

1. Very clean: These fibers were cleaned and then inspected under a microscope. This process was repeated until no gobs of silicon were visible on the stripped portion of the fiber.

2. Slightly dirty: For the Fujikura and 3–M fibers, three wipes were used, with the fiber being rotated 90° between wipes. The Spectran fiber was only wiped twice, again with a 90° rotation between wipes. In this configuration, two stripping actions were necessary in order to ensure that all the buffer was stripped away.

3. Very dirty: Due to the fact that the Spectran fiber buffer was quite brittle, it had

less debris to remove than the other fiber types, therefore no wipes were used after stripping. Both the 3-M and Fuji fiber received one wipe after stripping. Again, two stripping actions were required for this configuration, and both of the dirty levels (slightly and very) were cleaned using cotton dental rolls.

All the fibers prepared were visually inspected under a microscope in order to maintain consistency among the various levels and fiber types used. In addition, photographs of all the fibers in their varying cleanliness states were taken.

Most of the fibers broke off at the root of the fiber/carrier strip interface. There were only a few that pulled out of the carrier strip during the test and they were not related to the cleanliness of the fiber. The test results concluded that the fiber cleanliness had no big impact on the overall strength of the fiber pigtails.

5.3 Tooling Contamination

During the course of fiber pigtail production, debris from the stripped fiber buffer will accumulate on the station. This debris could come in contact with several of the workstations tools, and may cause a degradation in their performance. Therefore, we have identified the areas where we believe contamination may be an issue and have developed precautions to guard against any performance loss. The tooling areas, where contamination may be a problem, are the stripping, cleaning and cleaving areas. Other workstation tools are too far removed from the debris source to be contaminated.

The majority of the debris will be generated at the stripping station, with most of it remaining on the stripper blades. Some preliminary testing has shown that blowing the debris off the blades with an air jet is the easiest method with which to clean the blades. In order to protect the linear slide and other mechanisms under the machine work surface, a flexible skirt was fitted over the opening through which the tool protrudes, preventing the debris from getting to these mechanisms.

The cleaning station was designed such that fresh cotton or other wiping material will be used to clean each fiber as it passes through the station [22]. At the end of each machine run, the operator will remove these wipes, dispose of them, and install fresh ones for the next run. In the event that any debris should fall from the wipes onto the work surface, another flexible skirt was used to again protect the slides and other mechanisms that are under the work surface.

Since the fibers will be clean when they enter the cleaving station, contamination should not be an issue. But, if any debris does accumulate on the cleave wheel, the quality of the cleave may be jeopardized. Therefore, we have decided that the operator must clean the cleave wheel prior to each run.

Chapter 6

Discussion

The automated fiber optic pigtailing preparation machine was successful in proving that the current process may be automated. In the following sections every sub-module as well as the whole machine will be analyzed and the current problems and potential improvements will be examined.

6.1 Supply Spool

Mounting the electronics for the laser source on the rotating supply spool proved well as it reduced the noise that would have otherwise been generated by sending the signals through the slip ring. The mounting shaft which was suitable for various size supply spools, worked well. The tensioning system was successful in detecting any fiber breakage but the tensioning system was crude.

Currently, when tension is applied to the fiber, a constant current is sent to the motor thus applying a constant torque on the supply spool. As the fiber is pulled to the required stations, it must be accelerated and decelerated to various speeds. During acceleration and deceleration the supply spool would sometimes over turn due to the inertia, thus creating some slack in the fiber. Then, when the motor pulls back on the fiber, the spool would gain some speed due to the extra slack, thus applying a sudden jerk to the fiber.

The fiber would then slip slightly in the finger grippers thus losing registration. This problem was overcome by reducing the acceleration and deceleration as well as varying with the motor torque exerted on the supply spool.

A redesign of the supply spool would include an active tension control system. The active tension control system may consist of a rocker arm connected to a motor and a force measuring device to measure the tension in the fiber. Implementing this redesign would give better control over the tension applied on the fiber.

6.2 Epoxy Application

The epoxy is currently applied using a extended arm with a syringe on the tip. The problem with this design is the registration between the needle and the hole. When we scan the holes in order to locate it, the determined hole position will vary, each time, relative to the frame. Since the epoxy applicator is mounted on the frame, it is possible to miss the fiber with the needle. One idea is to have the epoxy applicator sit on the finger gripper slide so that it would always be registered to the inserted hole.

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