On the Design and Practical Application of a Spatial Neutron Modulator for Neutron Compressive Sensing

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I am submitting herewith a thesis written by Patrick Ellis entitled "On the Design and Practical Application of a Spatial Neutron Modulator for Neutron Compressive Sensing." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

William R. Hamel, Major Professor

We have read this thesis and recommend its acceptance:

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
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ABSTRACT

The need for higher resolution in materials characterization is increasing faster than current technologies. When characterizing materials, the molecular interactions within a sample are of critical importance such as when studying polymer degradation in nuclear plants or molecular bonding in batteries. Currently, the most used technique is vibrational or IR spectroscopy. The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) uses a neutron vibrational spectrometer, VISION. Using neutrons for this type of spectrometry is advantageous because of increased penetration depth into a sample without degrading its structure. However, currently it is only possible to take bulk measurements. The SNS seeks to use a technique called compressive sensing (CS) to increase the resolution of vibrational spectra and allow prediction of material properties throughout a sample instead of a generalized prediction of the entire sample.

This thesis approaches the challenge of designing and fabricating a mechanical system, the Spatial Neutron Modulator (SNM), to apply compressive sensing techniques for neutron spectroscopy. This mechanism must operate reliably in a high vacuum, extreme low temperature neutron beam environment. The design considers the size constraint of the beam chamber, neutron transparency of chosen materials, thermal expansion and shrinkage throughout thermal cycles, as well as off-gassing effects of materials under high vacuum.

Ultimately, the system underwent proof-of-concept testing in its final form in an optical experiment before being tested in the harsh environment of the neutron beam.
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CHAPTER ONE
INTRODUCTION AND GENERAL INFORMATION

1.1 Background

In many cases, it is important to identify a material or ensure a sample is free of voids and/or defects that may affect its characteristic properties. This is possible using a number of techniques which usually destroy the sample which means, after identifying the material, no further testing can be performed on it. Vibrational spectroscopy, however, is a non-destructive identification technique that measures the vibrational energy of the sample when it is subjected to electromagnetic radiation. There are two major types of vibrational spectroscopy: Infrared (IR) and Raman [1].

IR spectroscopy uses a light beam in the infrared spectrum (700nm – 1mm or 4.3 x 10^{17} – 300 x 10^{9} Hz) passed through a collimator to excite the chemical bonds within the sample; the sample is subjected to a spectrum of frequencies. The design of an IR spectrometer is shown in Figure 1.1. [1].

The mirrors in this design isolate a specific wavelength from the beam so the sample is only exposed to a desired radiation wavelength.

When a chemical bond is exposed to a specific frequency, the bonded atoms will vibrate at that frequency; this is analogous to resonance in a mechanical mass-spring system.
Figure 1.1. Design of an IR Spectrometer [1]
When this “spring” is stretched or compressed (shown in Figure 1.2), spring forces are induced in following with Hooke’s law:

\[ F = kx \]  \hspace{1cm} (1)

Where F is the spring force, k is the spring constant, and x is the change in distance between atomic nuclei [1]. The energy in a spring can be similarly defined as:

\[ PE = \frac{1}{2} kx^2 \]  \hspace{1cm} (2)

A detector will measure the reduction in frequency caused by the absorption of electromagnetic radiation energy by the molecule (the spring system) which results in a peak in the frequency plot.
Raman spectroscopy is *similar to* IR spectroscopy in that they both induce chemical bond vibration frequencies. Both techniques can be used for most samples in any state (gas, liquid, or solid) [1].

Raman spectroscopy *differs from* IR spectroscopy because it measures the scattering of light by the vibration of molecules in the sample. The difference between the scattered intensity and the source intensity is attributed to the vibrational absorption of the sample. The source in a Raman spectrometer is usually a fixed wavelength in the near IR whereas an IR spectrometer uses spectral interference to isolate a specific wavelength to send to the sample. The design of a Raman spectrometer is shown in Figure 1.3 [1].

The Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL) houses a vibrational spectrometer, named VISION, used for experiments in chemistry and materials science. This spectrometer uses a neutron source instead of a light beam allowing deeper surface penetration and sensitivity without damaging or destroying samples using a technique called inelastic neutron scattering (INS). A small summary of the advantages and disadvantages of INS are shown in Figure 1.4 [2].
Figure 1.3. Design of a Raman Spectrometer. [1]

Figure 1.4. Advantages and Disadvantages of Inelastic Neutron Scattering [2]
It is currently impossible to use this technique to map a spectral response across an entire sample. Current techniques take a bulk measurement across the entire sample. This means the collected data represents the vibrational response integrated over the entire samples. To increase the resolution of these techniques would require running the test for a number of small subsets across the sample equal to the desired resolution, this is called raster scanning, as shown in Figure 1.5. In Figure 1.5, each box is a sample to be characterized by 1000 data points. Each red dot indicates a subset. The left sample is a bulk measurement whereas the right sample has a resolution of 24 (4:6) pixels. Each red dot, however, still requires 1000 data points. This shows the increase in computation for nominal increases in resolution. While this is possible, the time and computational cost is prohibitive. Compressive sensing (CS) offers a potential solution to the time expense of other methods.

Compressive sensing typically requires fewer samples than raster scanning. Normally, the Nyquist sampling theorem dictates that the sampling frequency is roughly double the highest signal frequency. In neutron testing, beam time is at a premium, so minimizing time requirements is a priority. Using CS, which exploits the sparsity of most signals, we can sample signals more efficiently than the established Nyquist technique [3]. CS works based on imposing a sampling matrix on a signal. This matrix is a binary representation of an image and must have no relationship with the signal, this is called incoherence of basis. The design of the sampling matrix will be discussed further in Chapter 2.
Figure 1.5. Example of higher resolution raster scanning.
The simplest way to form an incoherent sampling matrix, however, is to randomly generate it. A random matrix has a high probability of incoherence with a sample signal [4].

For this thesis, we will use a single detector for proof-of-concept testing. In single detector applications, the sampling matrix is superimposed on the signal before it reaches the detector. In optical testing, a light beam is used with a spatial light modulator (SLM) to imprint the matrix on the signal. A common SLM is a digital micromirror device (DMD) as shown in figure 1.6. The mirrors in the system redirect portions of the light beam to the sample.

The resulting imprinted signal can then be used with a compressive sensing algorithm, like TVAL3 in this case, to reconstruct the original signal [5].

Figure 1.6. Digital Micromirror Device [4]
In this application, our reconstructed signal will be an image of the sample’s vibrational spectrum. In a neutron application, we need a spatial neutron modulator (SNM) to imprint our sampling matrix on our source signal, the neutron beam.

1.2 Motivation and Scope of Thesis

Motivated by a need for more efficient methods of using neutrons to perform spectral imaging of samples, the scope of this thesis is to build a mechanism capable of applying vibrational spectroscopy methods to a neutron source. Starting with an additively manufactured polymer prototype of the SNM developed by Daniel Garza [3], the design will be revised for application in the harsh environments of the VISION chamber. This design must be built from suitable components capable of operating at approximately five kelvin and 10 millibar vacuum conditions while also meeting the imposed size requirements.

While using vibrational spectroscopy for material characterization is currently possible by performing spectral imaging on small sections of a sample and combining the results post-test, this is extremely time intensive. Using the principle of compressive sensing, we can expect to reduce the time cost for this process by approximately two-thirds. Proof-of-concept testing is necessary to confirm the feasibility of the compressive sensing technique.

Previously, software has been developed during the prototyping phase of this project which will be used for testing and data analysis.
CHAPTER TWO

COMPRESSIVE SENSING

2.1 Proposed Concepts

Beginning knowing only that we wanted to apply a CS technique to neutron imaging, a few potential concepts were considered. Our major requirement was using a concept that would result a randomly generated sampling matrix for each iteration. If we were to repeat matrix configurations, our repeated measurements would cost us time and computational expense, but fail to increase resolution or reconstruction data.

ORNL has done previous research on compressive sensing using a “box of rocks” method of creating random mask configurations [6]. This system used free moving beads in a transparent container. This experimental setup is shown in Figure 2.1 below. Between each sample measurement, a compressed air jet rearranged the beads in the container resulting in a new mask configuration. This design was an improvement on a similar design that used a smaller particulate like salt or sugar rearranged by an electric motor shaking the container. Using a small particulate led to clumping between configurations and, ultimately, reduced resolution of the reconstructed images because the configurations were not “random” enough. To apply this design to neutron imaging, it was suggested that the particulate be made up of two materials as shown in Figure 2.2: one that is neutron transparent like aluminum and one that is neutron opaque, normally a boron compound. The red outline in the figure is a projection of the aperture.
Figure 2.1. "Box of Rocks" Mask as Potentially Applied to Neutron Imaging [6]

Figure 2.2. ORNL Experimental Setup [6]
While these are viable options for optical imaging with a light beam, the neutron beam cannot be oriented vertically like in [6]. These potential concepts would also require more space than is available in the VISION experimental chamber. The size constraint will be covered in Chapter 3.

2.2 Chosen Concept

Another option, and the one ultimately pursued, is to have an overlapping, offset grid made of a neutron stopping material, Boron Carbide (B\textsubscript{4}C). Each mask can be rotated at a slightly different rate which creates a “random” overlap of the two. This design can be applied to a small space and only requires one degree of freedom to operate. The simplicity of this design secured it as the best option available.

Boron Carbide was chosen for the mask material due to its neutron opacity and it can be additively manufactured. The mask design was created by Dr. Stephen Jesse from ORNL. Ultimately, several grid sizes were 3D printed in Boron Carbide. The grid mask used for testing in this thesis is 64.5 millimeters in diameter. The grid is made up of one millimeter spars and two-by-two millimeter open boxes. Finally, the grid boxes were randomly filled in to result in the mask shown in Figure 2.3 below.

The masks were overlapped and offset to generate unsynchronized motion throughout testing. Each mask rotates at a slightly different rate as exemplified in Figure 2.4 below. Finally, the image is cropped to the size of the aperture, as shown in Figure 2.5, to be used with the reconstruction algorithm.
Figure 2.3. Mask Matrix for Compressive Imaging

Figure 2.4. Rotated Masks in Configuration 100. The red outline in the image is the size of the aperture.

Figure 2.5. Cropped Image of Aperture at Configuration 100
With the concept generated, we simply needed a machine to execute the mask positions. These images were created by a Matlab™ algorithm that simulates the mask position for each test configuration. The algorithm, in its entirety, is shown in the Appendix. Its function is to create simulated images of each mask configuration in each test. These images are then converted to binary representations that form the sampling matrix.
CHAPTER THREE
DESIGN OF SPATIAL NEUTRON MODULATOR

3.1 Design Constraints

The design of the SNM must not only be able to repeatably and reliably position the masks in each configuration, but also fit into and survive the harsh environment in the VISION chamber. The VISION chamber has a diameter of 82 mm and reaches a temperature of five Kelvin, a pressure of ~10 mbar. A diagram of the sample stick and the VISION chamber are shown in Figures 3.1 and 3.2 below. We must also consider the material choices for reasons of neutron transparency and nuclear excitation.

The development of a reliable and repeatable SNM has been completed in a predecessor to this thesis [3]. The goal of Garza’s thesis was to develop and build a proof-of-concept, 3D printed polymer prototype of the SNM. His design used a single motor to drive a gear train which rotated the offset masks at different rates as shown in Figure 3.1 below. The scope of this thesis is to adapt the features of Garza’s SNM to survive the neutron beam environment previously described.

Garza’s design used 70 and 72 pitch diameters spur gears which were bored to accept the 64.5 mm outer diameter of the mask disks. Each mask-gear assembly was enveloped by appropriate support gears at four points. Both mask gears were connected to a drive gear attached to the motor that rotated both with a single power input as shown in Figure 3.4. The complete gear design is shown in Figure 3.3 below.
Figure 3.1. Sample Stick Diagram
Figure 3.2. Diagram of VISION Chamber
Figure 3.3. Prototype Single Power Input for Driving Two Mask Gears

Figure 3.4. Support gear and mask gear design.
Using this design, the motor would complete 168 revolutions before mask configurations would begin to repeat. In 168 motor revolutions, the 72 pitch mask gear would completely rotate 35 times while the 70 pitch gear would rotate 36 times. With this known relationship, we can calculate the step size based on the desired number of samples. For example, if we wanted 1000 samples in a test:

\[
\frac{(360^\circ/\text{rev}) \times (35 \text{ rev})}{1000} = 12.6^\circ/\text{step}
\]

for the 72 pitch gear and

\[
\frac{(360^\circ/\text{rev}) \times (36 \text{ rev})}{1000} = 12.96^\circ/\text{step}
\]

for the 70 pitch gear.

These values are important in our sampling matrix control software. More importantly, however, we need to know the target angle for each configuration to plan our motor control.

\[
(168 \text{ rev}) \times \left(\frac{360^\circ}{\text{rev}}\right) \times \frac{1}{1000} = 60.48^\circ/\text{step}
\]

These same gears and control relationships were used in the final design for the SNM as well.

Garza’s design also included a feature to avoid problems due to thermal shrinkage of the gear train by allowing adjustment of the top supporting gears and the drive gear for each mask as shown in Figure 3.5. This design feature is streamlined to save space in the final design as shown in Figure 3.6, but is functionally identical.
Figure 3.5. Adjustable Bearing Plates to Overcome Thermal Shrinkage

Figure 3.6. Bearing Plates Designed for Flush Mount Screw Heads
Since the SNM is made up of rotating gears, it was important to consider potential options for bearings or bushings. The bearings for each gear’s shaft were pressed into plates that screwed into slots in the main structure allowing for enough adjustability to account for the predicted shrinkage in the testing environment. These slots also allow alignment of the support gears.

Typical ball bearings are made of stainless steel and use oil or grease as lubrication. Stainless steel is an acceptable material, but oils or grease will evaporate at extremely low pressure and contaminate the work cell. Therefore, we require the use of solid lubricant capable of -450°F. After searching for commercial bearings and bushings, we concluded that Graphalloy bushings (link) offer the best lubrication and performance at extremely low temperature and pressure. These bushings are made of a proprietary graphite lubricant in a solid matrix which is rated down to -450 °F/ 5 K.

Potentially the most important constraint to meet, however, is the overall size of the VISION chamber. The entire structure, as well as the gears and electrical hardware, must fit within an 82 mm round footprint. There is little concern for the overall height constraint.

To remain under the size limit, it was necessary to save as much space as possible as exemplified by the bearing plates previously discussed. Motor hardware could be mounted ~5 mm closer because of the inset bearing plates and flush screw heads. In addition, the sample holding was integrated into the structure to save another 6 mm as shown in Figure 3.7.
Figure 3.7. Integral Sample Holder Highlighted in Blue
The most significant space-saving design feature is the mounting of the motor. The AttoCube ANR101 Piezo Stepper is the smallest available motor built for the temperature and pressure conditions in the neutron beam with an overall length of 15.2 mm and a 24 by 24 mm footprint. Its 15.2 mm length, while small, would account for 18.5 percent of the diameter limit. To save more space, the motor is set back into its mounting plate by 10.5 mm, reducing its added length to 4.7 mm. The motor mounting is shown in Figure 3.8 highlighted in blue.

Even with the other space-saving design features, the assembly would not fit the size limit with a rectangular footprint. The outer edges of the assembly were rounded to follow the chamber wall with at least one millimeter clearance. Combining the space-saving design features described here, the assembly meets the size constraint as shown in Figure 3.9 where the orange circle is the size constraint; the dashed line and top plate (highlighted in blue) represent the footprint of the SNM.

After confirming the SNM met its size constraint and had design features to account for the temperature and pressure conditions in the beamline, it was important to consider material choices.
Figure 3.8. Motor Attached to Motor Mounting Plate.

Figure 3.9. Footprint of the SNM Compared to Size Constraint.
Each material has a neutron transmittance percentage based on its elemental composition and dimensions. Heavier atoms and/or thicker walls typically have a lower transmission than lighter materials and/or thinner walls [7]. Table 3.1 shows the neutron transmission probability for various materials and thicknesses. Based on Table 3.1, the SNM is mostly made of aluminum alloy and stainless steel to minimize unintentional scattering of the neutron beam. Though the table does not define neutron transmission for the thickness of parts in the SNM, we can extrapolate the table’s data to conservatively predict a transmission probability greater than 75 percent.

With the design meeting all of its constraints, it was then necessary to reconfirm the functionality of the design from a number of perspectives: movement, accuracy, and usefulness.

Table 3.1. Neutron Transmission for Various Materials and Thickness [7].

<table>
<thead>
<tr>
<th>Thickness(mm)</th>
<th>Aluminum pure</th>
<th>Aluminum 1050</th>
<th>Steel</th>
<th>Carbon Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.9934(1)</td>
<td>0.9934(1)</td>
<td>0.9880(1)</td>
<td>0.9921(1)</td>
</tr>
<tr>
<td>1</td>
<td>0.9869(1)</td>
<td>0.9869(1)</td>
<td>0.9861(1)</td>
<td>0.9843(1)</td>
</tr>
<tr>
<td>2</td>
<td>0.9739(1)</td>
<td>0.9739(1)</td>
<td>0.9823(1)</td>
<td>0.9689(1)</td>
</tr>
<tr>
<td>3</td>
<td>0.9611(1)</td>
<td>0.9612(1)</td>
<td>0.9301(1)</td>
<td>0.954(1)</td>
</tr>
</tbody>
</table>
3.2 Testing Procedure

The most basic test of the SNM was to confirm the AttoCube motor had the power to drive the gear train. This was a simple test by running the motor continuously with its built-in GUI, called Daisy. Daisy’s interface is shown in Figure 3.10 below. The test ran for 30 minutes continuously, proving the SNM could run under motor power.

Next, the accuracy of the system was tested and this relies mostly on the encoder output from the motor. It was found during testing that the built-in encoder had undefined regions where its absolute position was unknown. These regions occurred at approximately 60º, 89º, and 337º to 360º. This could be overcome by planning tests to avoid mask configurations at or near these values. These are most likely due to hardware or electrical integration issues. Excluding these values, the encoder readout proved to be accurate when compared to simulated configurations from the Matlab™ sample matrix algorithm. It is important to note that, because of these “dead zones,” it is impossible to confirm the accuracy and/or repeatability of mask configurations between tests.

Most importantly, the SNM completed a proof-of-concept test in an optical setup using a Helium Neon (HeNe) laser in place of the neutron beam. The optical test setup is shown in Figure 3.11.
Figure 3.10. Daisy GUI Interface

Figure 3.11. Optical Test Setup.
Most importantly, the SNM completed a proof-of-concept test in an optical setup using a Helium Neon (HeNe) laser in place of the neutron beam. The optical test setup is shown in Figure 3.11. This small scale test confirmed the feasibility of the project goal and reinforced the results seen with the prototype in [3]. Garza successfully reconstructed a Gaussian distribution using a 780 nanometer laser during proof-of-concept tests. His results are shown in Figure 3.12 below.

A second, functionally identical SNM was designed to be used exclusively for optical testing of alternative mask designs. This allows for optimization and experiments to continue after the primary SNM was put into service in the neutron beam. Since the bombardment of neutrons excites the atomic structure of the entire assembly, the SNM is slightly radioactive after each test. This means that the SNM would be considered contaminated equipment and deemed unusable in the clean optical laboratory. The optical SNM is shown in Figure 3.13 and 3.14.

To facilitate continued optical testing, the second polymer SNM was designed to be 3D printed and work with a much cheaper Pololu/Sanyo Denki stepper motor with a built-in optical encoder. This encoded stepper was controlled with Pololu's Tic T825 stepper motor controller and their own software. The interface for the Pololu GUI is shown in Figure 3.15 below.
Figure 3.12. Reconstructed Image of Gaussian Beam using 780nm Laser [3].

Figure 3.13. Optical SNM Side View.
Figure 3.14. Optical SNM Iso View

Figure 3.15. Pololu Tic Stepper Motor Controller GUI.
CHAPTER FOUR
RESULTS AND CONCLUSIONS

4.1 Results

The focus of this work was to continue developing spatial neutron modulator from a prototype designed by Daniel Garza. The major constraints were size, operable temperature range, vacuum operation, and neutron transparency.

Ultimately, the SNM met all size and operating requirements while maintaining the design vision of previous work. The prototype is shown in Figure 4.1 and the final assembly in Figure 4.2 through 4.4.

Using the optical setup shown below, experimental proof-of-concept testing was performed. The goal of the preliminary test was to image a black “0” sticker on a glass slide using the HeNe laser and the polymer, optical SNM. The beam was expanded using a lens and attenuated so not to oversaturate the detector. The beam was passed through the sample and the SNM’s masks before finally being refocused into the detector. Data collection was facilitated by Labview™.

The first test used 100 data point and successfully reconstructed an image, but did not clearly resolve the “0.” This, however, is to be expected of short data sets using compressive sensing algorithms. The result of this test is shown in Figure 4.5 below. Note the rounded shadow at approximately [200,275]. This could potentially be the early formation of the “0” which would resolve more fully with larger data sets.
Figure 4.1. Final Assembly of SNM, Side View
Figure 4.2. Final Assembly of SNM, Iso View
Figure 4.3. Final Assembly of SNM, Rear View
Figure 4.4. Final Assembly of Prototype by Garza [3].
Figure 4.5. Reconstructed Image from 100 Data Point Test.
The overall shape of the reconstructed image is correct. Note the corners are blank; this is similar to the sample matrix shown in Figure 2.5.

The second test was performed identically, but using 500 data points to further resolve the reconstructed images. The goal of the second test was to reconstruct the same black “0” sticker on the glass slide. This test was predictably more distinct due to the larger sample size. The test, however, did not resolve the sticker. This is most likely due to the large coverage area of the mask throughout its range. Ideally, the mask maintains approximately 50% coverage throughout the test configurations. The result of this test is shown in Figure 4.6 below.

Garza was able to reconstruct the beam profile of a 780 nanometer laser using a 400 data point test as shown previously. This thesis has confirmed and expanded on Garza findings by imaging a small “0” sticker.

Another 500 data point test attempted to replicate Garza’s results by reconstructing the beam profile as shown in Figure 3.12. This test was performed identically to the previous tests and had similar results as shown in Figure 4.7.

Note the “swirl” shape in the middle of the image. This could possibly be the start to resolving the beam profile, but it is still highly probable that the mask has too much coverage and distorts the reconstruction. In other words, not enough information is being gathered to resolve a clear image due to constant coverage at each test configuration.
Figure 4.6. Reconstructed Image from 500 Data Point Test

Figure 4.7. Reconstructed Image from 500 Data Point Beam Profile
These results, however, are encouraging for future research to apply these techniques to the beamline because the neutron beam is approximately collimated like the laser used in these tests. If the characteristics of the neutron beam mimic the laser previously used, the same results can be expected when applied to neutron imaging. More testing and optimization of mask design will take place to achieve more resolved images.

4.2 Issues Encountered

A few issues were encountered both in design and testing. The encoder allowed us to rebuild images using a predicted image of the mask configuration. We used an algorithm that input the motor angle and output an overlaid image which we used for reconstruction. Using the AttoCube built-in encoder, we found it had uncertainties at 60°, 89°, and 337°-360° where its absolute position was undefined. This made it difficult or impossible to reconstruct images using configurations near these undefined regions. To resolve this problem, we chose our step size to avoid these configurations during testing.

Another issue in the design and assembly portion was setting the masks in their ring gears. If the spars of the masks were not aligned similarly with respect to the gear teeth, their “zero” position would result in skewed alignment. If the masks were misaligned, we could account for it in the algorithm by adding an initial angular offset. Determining the value of the offset, was difficult to estimate. Any error in the initial offset potentially adds error to the reconstructed image. A
procedure for aligning the masks in their ring gears that focuses on minimizing error due to misalignment would eliminate this issue.

Due to a miscommunication during the design process, the SNM featured a 5/16"-18 threaded hole at its absolute center for attachment to the sample stick in the VISION chamber. The diagram of the sample stick shows a 1/4"-20 threaded sample attachment. Obviously, these are not compatible, but the issue is resolved with a five-dollar female to male, 1/4-20 to 5/16-18 thread adapter. This solution offsets the SNM down by about an inch but, since there was little concern about the overall height of the SNM, the beam could be redirected to the new sample position.

4.3 Conclusions and Recommendations

In conclusion, the design and implementation of the spatial neutron modulator was successful. The SNM contains design features that predict operation at extremely low temperature and high vacuum while remaining within the space available in the VISION chamber. It was shown that the final assembly could run under its own power and accurately position the masks consistent with the predictive Matlab™ algorithm. It has been previously shown that the idea of using two overlapped masks to perform compressive sensing is feasible and this thesis has attempted to reconfirm these results [3].

This thesis addressed problems from the prototype by integrating a motor encoder to avoid taking pictures of each mask configuration as well as providing comparative results using a different mask. More masks could be easily tested
using the 3D printed optical SNM by simply replacing the current masks with another design and running identical tests until optimal results are obtained.

Overall, this thesis further developed an SNM from an existing prototype to a final assembly with potential to apply more efficient compressive sensing techniques to a neutron beam for the first time.
LIST OF REFERENCES


APPENDIX
Daniel Garza

%sampling matrix file
file_name = 'Hypercool_Mask_25_bw-ConvertImage';

%name for output file
resultname = 'Hypercool_Sample_Matrix_2';

%creates directory for output if one does not exist
if ~exist('sample_matrices', 'dir')
    mkdir('sample_matrices');
end

plot_mask_configs_cond = 0; % plot mask configurations? 0 = no, 1 = yes,

%Reads in matrix file and creates logical
diskl = imread([ file_name '.jpg'], 'jpg');
diskl = im2binary(diskl);

%Rotates given file since starting position in experiment is 90 degrees
different than file. Sets second disk to be the same as first disk
disk1 = imrotate(diskl, 90, 'crop');
disk2 = disk1;

%Individual mask rotations per step
dm1 = 12.5625;
dm2 = 12.9214;

count=0;
for cycle = 0:1:499
    %Rotates the disks at each iteration
disk1rot = imrotate(diskl, cycle.*dm1, 'crop');
disk2rot = imrotate(disk2, cycle.*dm2, 'crop');

    %Offsets the disks
    disk1pos = imtranslate(disk1rot, [0, -28]);
disk2pos = imtranslate(disk2rot, [0, 28]);

    %Puts the disks into the same matrix (image)
double_disk = disk1pos.*disk2pos; %AP: elementwise (*) matrix multiplication
[y, x] = size(double_disk); %AP: number of rows and columns

    %Sets the aperture limits and crops away the matrix not within aperture
    %Aperture limits were found via the relationship:
    %aperture length:mask diameter::aperture length(pixels):mask diameter(pixels)
y_ap_max = round(y/2)+353;
y_ap_min = round(y/2)-353;
x_ap_max = round(x/2)+212;
x_ap_min = round(x/2)-212;

    %For displaying aperture over disks
figure(1)
imshow(double_disk)
hold on
rectangle('Position', [x_ap_min y_ap_min (x_ap_max-x_ap_min) (y_ap_max-y_ap_min)], 'EdgeColor', 'r', 'LineWidth', 3)

% The matrix visible in the aperture
samp_mat = double_disk(y_ap_min y_ap_max, x_ap_min x_ap_max);

% Displays and saves result
if plot_mask_configs_cond
    sample = count+1;
    imwrite(samp_mat, [resultname '_' num2str(sample) '.jpg ']);
end

end

count = count+1;
## Technical Specifications

### Size and Dimensions
- **footprint; height**: 24 mm x 24 mm; 15.2 mm
- **weight**: 36 g

### Materials
- **positioner body**: titanium
- **actuator**: PZT ceramics
- **connecting wires**: insulated twisted pair, copper

### Coarse Positioning Mode
- **travel range (step mode)**: 360° endless
- **maximum drive velocity @ 300 K**: ~ 30 °/s

### Fine Positioning Mode
- **fine angular positioning range @ 300 K**: 70 m°
- **fine angular positioning range @ 4 K**: 14 m°
- **fine positioning resolution**: µ°

### Accuracy of Movement
- **repeatability of step sizes**: typically 5 % over full range
- **typ. forward / backward step asymmetry**: typically 5 %
- **wobble**: ± 1 mrad

### Position Encoder
- **readout mechanism**: resistive sensor
- **encoded travel range**: 315°
- **sensor resolution**: ~ 6 m°
- **repeatability**: 50 m° (unidirectional)

### Load (@ ambient conditions)
- **maximum load**: 1 m°
- **maximum dynamic torque around axis**: 0.8 Ncm
VITA

Patrick Ellis was born and raised in Knoxville, Tennessee where he attended the Webb School of Knoxville. After graduating from Webb in May 2015, he attended the University of Tennessee at Knoxville to study mechanical engineering. Patrick conducted undergraduate research with Dr. Chad Duty studying thermal expansion of 3D printed materials for Boeing. He received his Bachelor's degree in Mechanical Engineering in May 2018. Following his Bachelor's degree, he began his Master's Degree in August 2018 with Dr. Bill Hamel. Throughout graduate school, Patrick worked on the current project with the Oak Ridge National Laboratory at the Spallation Neutron Source.