MATERIAL TESTING OF SHAPE MEMORY POLYMERS FOR MODULAR ROBOTICS APPLICATIONS AND DEVELOPMENT OF A PROTOTYPE SMP GRIPPER FOR mini-PR2 ROBOT.

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ABSTRACT

Goals that have yet to have been realized in the field of modular robotics include low cost mass production, and scalability. Shape memory polymers are light weight, low-cost, and have a large degree of flexibility in material design. For these reasons these polymers have the potential to help reach current goals of modular robotics. The percent recovery and force of these materials for use in actuation was tested in this research. A prototype SMP gripper consisting of two reconfigurable one way SMP actuators was developed that successfully picked up an object weighing one gram in 90% of trials. This SMP gripper is compatible with the CKbot modules from Dr. Mark Yim's laboratory at the University of Pennsylvania and it was installed on an existing modular robot, the mini-PR2, and the robot was programmed to use the gripper successfully. While there remain other obstacles in scaling and mass production problems, the shape memory component of this gripper could be produced on a wide range of scales, and with the proper equipment, made in large quantities for mass production. Future work to improve the SMP gripper will need to involve developing a method of making the gripper reversible.

1. INTRODUCTION

Self reconfigurable robots are built from modules, each of which has all the components required for a functioning robot, such as actuators, sensors, batteries and processing power. A module must be able to communicate with other modules, move with respect to other modules, and allow for connection to and disconnection from other modules. It is widely agreed that robots of this type potentially have three main advantages: their versatility, their robustness, and their low cost [1, 2]. The ability of modular self reconfigurable robots to adapt and change shape allows them to be versatile robots that can accomplish a wide variety of tasks. The robots are robust in two aspects: first, a damaged or nonfunctional module can be compensated for by others [1]. In addition, since modules are all equivalent, there is the possibility of robots replacing broken parts autonomously, allowing for self repair [2]. The final advantage of self reconfigurable robots is their potential for lowering production cost. Since these robots consist of many copies of one or a few types of modules, mass production could potentially lower the overall cost of the robot. In addition, since one modular self reconfigurable robot can achieve many tasks, it could be reused in many situations, saving costs.

These advantages however have not yet been fully realized. The advantage of versatility is only applicable in some situations. A modular robot will probably perform inferiorly to a robot custom designed for a specific task [2] However in a situation in which one robot must complete multiple different tasks, or the nature of tasks is unknown before a robot is deployed, the versatility of modular robots is extremely desirable. A proposed example of such a situation is space exploration missions [2]. There is also potential for success with these types of robots in other unpredictable situations such as search and rescue missions.

Low cost modular robots have also yet to have been realized. While in theory mass production of many identical modules would reduce cost, current robot designs have not yet made mass production feasible. Although control algorithms have been developed to handle millions of units, currently the modular robot with the largest number of active modules is Polybot with 56 modules, developed by Yim et al.[2]. Without hardware design improvements, the mass production of thousands or millions of modules is not possible.

Another challenge faced by modular robots is scalability. The precision with which a modular robot can approximate a complex shape is a function of the module size. The smaller each module is, the more accurately a modular robot can take on a complex form. Smaller robots can also accomplish tasks that would be unfeasible for larger robots [3]. Examples include squeezing through very small spaces, such as under a door or through a human artery. The smallest module created to date is Miniature, developed by Yoshida et al, with a module dimension of 40 x 40 x 50 mm [2].

2. BACKGROUND

2.1 Actuators

Actuators can allow individual modules to move within the environment and allow modules to move with respect to one another in order to achieve locomotion and self reconfiguration [1]. Increased numbers of actuators improve module autonomy, degrees of freedom of the modular robot, and the ease of motion and self reconfiguration for the robot [1]. However, these improvements come at the cost of simplicity, as well as size and weight of the modules. One of the major obstacles to overcome in the effort to scale down the size of modules is the space taken up by actuators [3]. Typically, actuators contribute more than 50% of the volume and weight of the whole module [3]

2.2 Current Actuator Types

Stoy et al. [1] provide an overview of current actuator types used in modular robotics. To date, most modular robotic systems utilize brushless motors as their actuators due to these motors' medium size and high efficiency. However brushless direct current (DC) motors are highly complex and relatively expensive. Another option for actuation are brushed DC motors. These motors are less efficient and larger than brushless DC motors but are easier to control. Stepper DC motors are another alternative – while being slightly more complex than brushed DC motors they are useful if high precision is necessary. However, DC motors become impractical as module size decreases. More recently, shape memory alloys have been used in self reconfigurable robots as a smaller scale actuator.

Shape memory alloys have the property of returning to a memorized shape with a change in temperature. They exhibit high force and are extremely small. This property has been utilized to make several micro scale shape memory alloy actuators [4, 5] One design that showed particular promise for self reconfiguration applications was Yoshida et al's [6] shape memory alloy actuator, which could be utilized in micro scale modular robotics. The actuator consists of two counter torsion shape memory alloy springs. The springs memorize the 0 degree rotation shape and are preloaded by twisting 180 degrees in the reverse direction. The springs remain in the original zero degree position until heat is applied. When one of the coils is heated by an electric current, its Young's modulus increases resulting in a large torque in the direction to restore the zero degree rotation state. This causes the assembly to bend, allowing for actuation. Despite these accomplishments, shape memory alloys do not solve all scaling problems in modular robots since they are difficult to control and react fairly slowly - the alloys need time to cool down and expand before each contraction [1].

2.3 Shape Memory Polymers

Shape memory polymers (SMP) are another smart material with potential usefulness for modular robotics applications. Shape memory polymers are polymers that are able to memorize temporary shapes and then recover their permanent shape with some external stimulus – usually a thermal change [6]. The permanent shape memorization is achieved through chemical or physical crosslinking, and temporary shapes can be fixed in the glass transition or melting transition phase [6]. Xie and Rousseau [7] conducted material testing on these polymers. The samples were immersed in a 70°C water bath for 6 seconds, and then deformed manually into a temporary shape. The temporary shape was set by dipping the sample into a cold water bath at 20°C, while maintaining the deformation load. Shape recovery was achieved by again immersing the sample in the 70°C water bath. Figure 1 depicts the shape memory capabilities of these types of polymers.

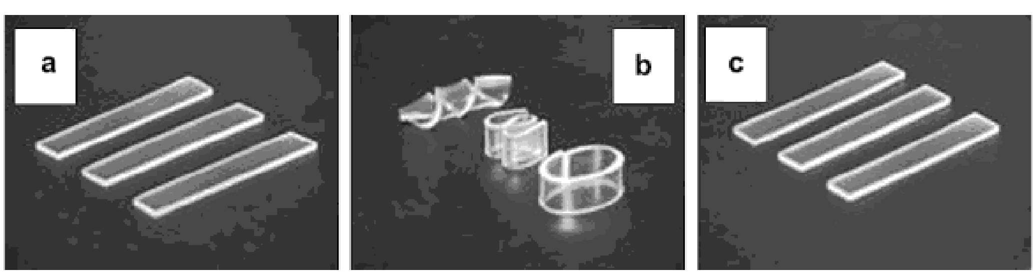

Figure 1a) original/permanent SMP shape b) fixed temporary states c) recovered shapes [7]

In comparison to shape memory alloys, SMPs have some unique advantages. They are light weight, and have great flexibility in terms of material design [6]. They also exhibit high recovery strain and are low cost [7]. Shape memory polymers are also advantageous since it is possible to tailor their material properties. In work reported in 2009, Xie and Rousseau [6] showed that it is possible to precisely tune the glass transition temperature of epoxy shape memory polymers, so they can meet specific application needs. They accomplished this by reducing the polymer's crosslink density or introducing chain flexibility. SMP's with distinctive glass transition temps ranging from 30 to 89°C were achieved. All of the polymers achieved fairly stable moduli in their glassy and rubbery regions and the difference between glass modulus and rubber modulus ranged from two to three orders of magnitude. Xie and Rousseau saw experimental evidence to suggest that a larger difference in glass and rubber moduli indicated greater shape fixity. Despite these advantages, the use of these polymers as functional materials remains rare, and they have yet to have been utilized in the field of modular robotics.

Shape memory polymers do have some disadvantages however. The recovery stress and fatigue strength of SMPs is less than that of shape memory alloys [8]. In addition they lack some particular functions that would be useful for practical applications such as good electric conductivity and high recovery force [7]. For this reason efforts have been made to develop shape memory composites.

2.4 Shape Memory Composites

Shape memory composites (SMC) consist of shape memory polymers reinforced by various other materials. Tobushi et al [8]developed a shape memory composite that consisted of two kinds of shape memory alloy tapes, one showing shape memory effect and the other showing superelasticity, that were heat-treated to memorize the round shape. These shape memory alloy tapes were arranged facing in opposite directions and sandwiched between two shape memory polymer sheets. The resulting SMC belt combined positive characteristics of both the SMA and SMP. A large recovery force was observed at high temperature, a deformed shape could be held at low temperature and then be recovered, and a large load could be carried. The SMC bends in the direction of the shape-memorized round shape of the shape memory effect SMA when heated and bends in the opposite direction toward the memorized round shape of the superelastic SMA during cooling.

Shape memory composites filled with particles such as carbon black, Ni, carbon nanotubules or short fibers have also been developed [7]. These types of SMC have demonstrated new functions such as electrical conductivity and magnetic-responsive performance. Added functions such as electrical conductivity could be utilized in heating the SMPs. If an SMP was conductive, current could be run through the polymer to heat it up rather than using an outside heating source. However there was little improvement in the mechanical properties of these types of composites. Lan et al [7] developed a continuous fiber reinforced SMC that has excellent mechanical properties, namely a large strain in bending. They also created a hinge actuator using the fiber reinforced SMC, and demonstrated it moving a prototype solar panel.

3. APPLICATION OF SMP'S FOR MODULAR ROBOTICS

The advantages of shape memory polymers make them a good candidate for exploration into new forms of actuation in modular robots. If the recovery force of two SMPS could be used in an antagonistic fashion, a shape memory polymer actuator could be created. Such an actuator could be used with current modular robots and have potential to help in the design process of developing small scale, mass-producible robots. The purpose of this research was to manufacture and characterize the material properties of a shape memory polymer to determine the material's feasibility to be used in its pure form as an actuator for use in modular robotics. A shape memory polymer actuated gripper prototype was developed, tested, and installed on an existing robot. This gripper uses two one way actuator SMPs as a reconfigurable gripper. The gripper can be opened into one of a variety of different shapes each time it is used. This provides versatility in picking up objects of differing sizes and shapes. Since the SMPs used on this initial prototype are one way actuators, they must be retrained after each pick up cycle. A method of antagonistic actuation is needed to allow the SMP actuators to operate autonomously for more than one cycle.

4. METHODS

4.1 Fabrication

The method developed by Xie and Rousseau [6]was used to fabricate the shape memory polymer samples for this research. The diglycidyl ether of bisophenol A epoxy monomer (EPON 825) and the curing agents poly(propylene glycol)bis(2-aminopropyl)ether (Jeffamine D230) and decylamine (DA) were used. The samples' composition was as follows: 0.02 mol of EPON 826, 0.005mol D230 and 0.01mol DA. The EPON 826 was weighed into a glass bottle and then placed in an oven preset at 70°C to melt for thirty minutes. After melting, the appropriate volume of Jeffamine D230 and decylamine were inserted into the glass bottle. The glass bottle was shaken vigorously by hand to mix all the components. The mixture was then poured into a mold. For the purposes of this research, rectangular molds were chosen. The mold was then placed in a 100°C oven for 1.5 hours to cure the samples, which were then postcured on a hotplate at a temperature of 130°C for one hour. The time for curing was kept precise, as this is the factor that determines the glass transition temperature of the polymers. In this case, the fabricated polymers had a glass °transition temperature of about 80°C.

4.2 Steady State Temperature Testing

A Steinel 34100 Ultra Heat Dual Temperature Heat Gun was utilized throughout this research as the method of heating the shape memory polymers. This heat gun had two settings, a low temperature setting of 600°F or 316°C and a high temperature setting of 950°F or 510°C. A consistent method of heating the shape memory polymer to temperatures at and around its glass transition temperature using a heat gun needed to be determined. For this reason steady state temperature testing was conducted using the heat gun and an LM35 Precision Centigrade Temperature Sensor. The LM35 Temperature sensor is calibrated to measure temperature in degrees Celcius, and was connected in the circuit shown in Figure 2. An input voltage of 5 volts and a 1K resistor were used. The output voltage from the temperature sensor circuit was directed through Measurement Computing's USB-1208FS device which, along with its accompanying software, converted the output voltage to an array of temperature readings in MATLAB.

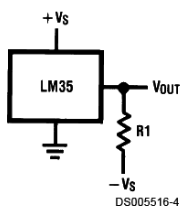

Figure 2. Circuitry for LM35 Temperature Sensor. Vs=5V, R1=1000Ω. [9]

The heat gun and temperature sensor were arranged level with each other at varied distances apart, and two minute long sample periods were taken with the heat gun on, to determine the ambient temperature reached at the temperature sensor. Temperature sensor data was verified for accuracy with a thermometer placed next to the temperature sensor to verify that sensor output was reasonable. The experimental setup for steady-state temperature testing is shown in Figure 3.

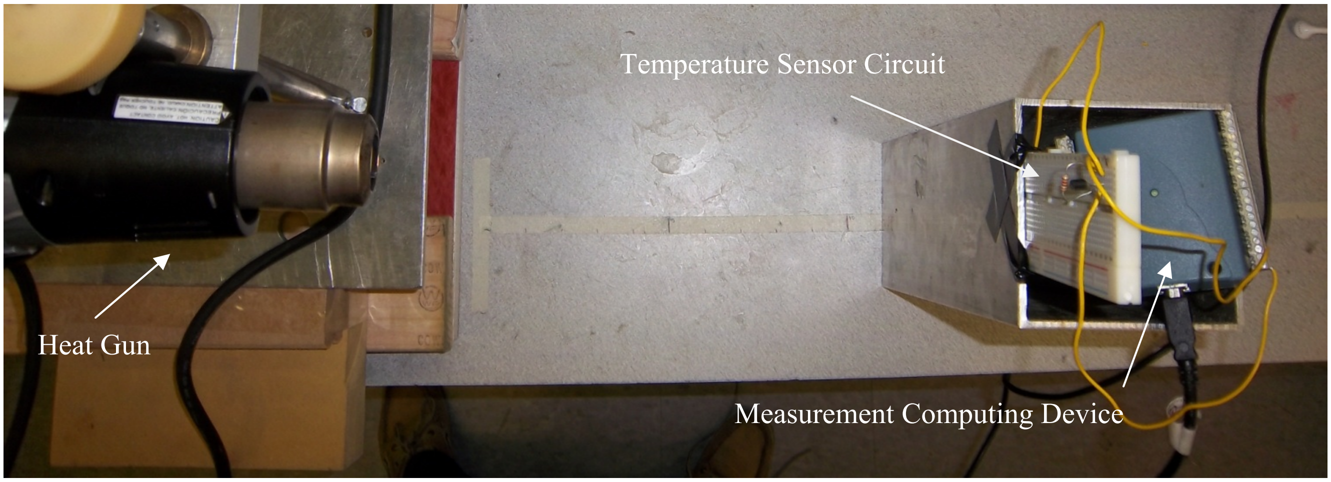

Figure 3. Set up for Steady State Temperature Testing

4.3 Tensile Testing

Tensile testing using an Instron Model 5544 Electromechanical Test System was conducted on the shape memory polymers, both at room temperature and above glass transition temperature. Before beginning tensile testing, the original dimensions of the samples were recorded. In order to accomplish material testing without damaging the shape memory polymer samples a pair of aluminum clamps was manufactured. The SMP samples were clamped into these aluminum clamps, which were in turn clamped into the Instron 5544 for testing. Figure 4 illustrates the experimental setup.

Figure 4. SMP sample mounted to aluminum clamps in Instron machine for tensile testing

Before each tensile test the sample was aligned vertically with Instron's grips. At room temperature ten tensile tests were conducted consecutively on the same sample. The Instron was set to move at a rate of 1mm/minute, and the room temperature samples were allowed to deform up to 2% strain. A tensile test was also conducted above glass transition temperature of the polymer, with the Instron set to move at a rate of 1mm/min, and the sample allowed to deform up to 15% strain. This test was destructive to the sample, so only one trial was conducted.

4.4 Percent Recovery Testing

In order to conduct percent recovery testing the apparatus shown in Figures 5 and 6 was constructed. The apparatus includes a platform the shape memory polymer was clamped to, a platform to which the heat gun was mounted, and an adjustable platform. The distance away from the SMP that the heat gun platform was located could be adjusted. The adjustable platform had a force sensor with a probe clamped to it. When this platform was moved up and down, the force sensor's probe could deform the SMP.

For the percent recovery testing, the original shape of the SMP was a flat bar with dimensions 30mm x 10mm x 1mm. The SMP was mounted onto the apparatus, and the thermometer was placed as close to the SMP as possible without touching it. The heat gun was turned on medium and the SMP was allowed to heat up for one minute. The ambient temperature reported by the thermometer at the end of one minute was recorded. The adjustable platform was then raised, allowing the force sensor probe to make contact with the SMP, and deform it to a new stored angle. The ambient temperature at the end of deformation was recorded and then the heat gun was turned off. The SMPs were heated for one minute before deforming because steady state temperature tests indicated that it took one minute for a constant temperature to be reached using the heat gun as the source of heat. The SMP was allowed to cool for five minutes, to ensure that the SMP cooled down to room temperature, allowing the temporary bent shape to be stored. After five minutes of cooling, the force sensor was moved down and the SMP was removed from the apparatus. Its stored angle was measured and recorded. The SMP was then placed back in the apparatus, and it was ensured that nothing was in the way of the SMP freely deforming back to its original shape. The heat gun was then again turned on for one minute, heating the SMP, allowing it to recover. The ambient temp at the end of one minute was recorded and then the heat gun was turned off. The SMP was again allowed five minutes to cool, and then was removed from the apparatus and the recovered angle was measured.

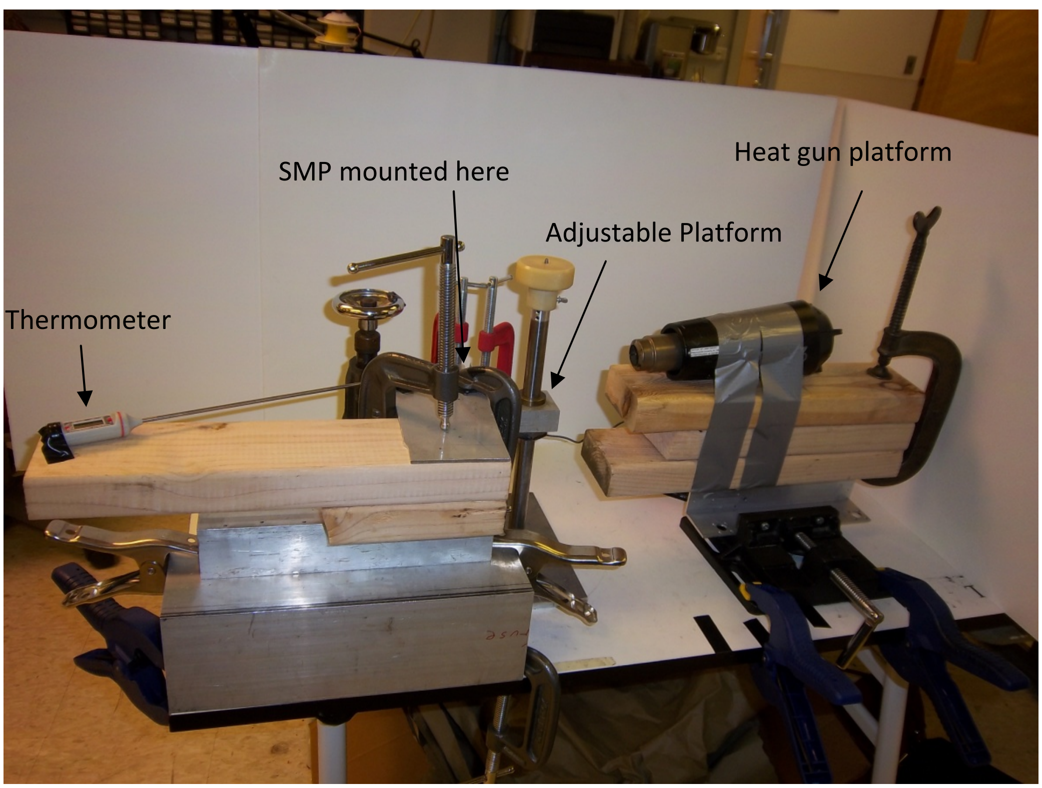

Figure 5. Apparatus used for SMP percent recovery testing.

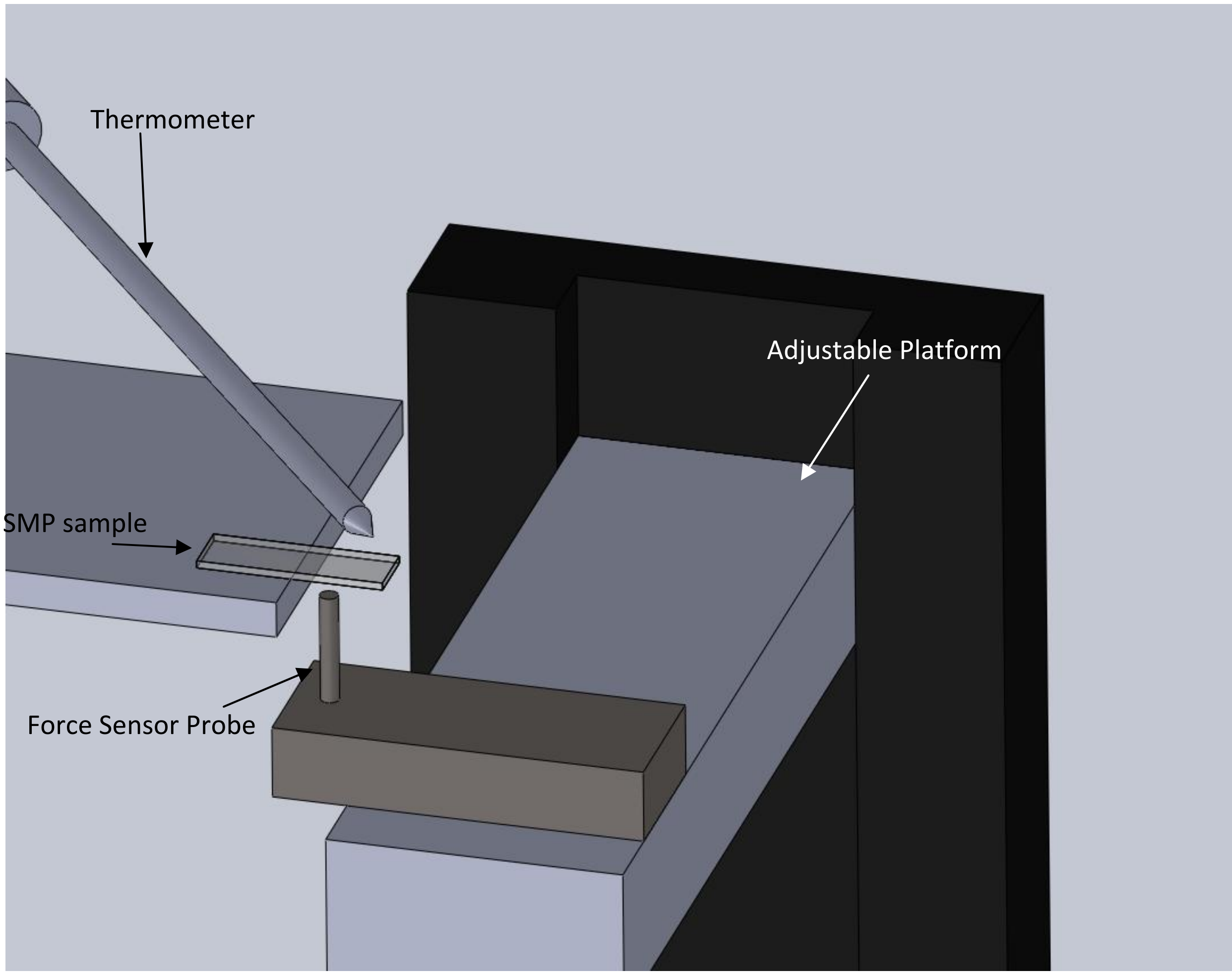

Figure 6. Close up of schematic of an SMP sample ready for percent recovery testing.

The percent recovery was calculated as the ((stored angle) – (recovered angle))/(stored angle). Throughout the trials, the smp was always heated up before deforming with the heat gun at a distance of seven inches away. During recovery, the heat gun was placed at varied distances away to obtain different recovery temperatures. A range of angles from small to large were deformed and recovered at each heat gun distance.

4.5 Force Testing

The same apparatus as was used in percent recovery testing was also used to conduct force testing. A longer probe was used on the force sensor however, to minimize drift of the force sensor's results due to change in temperature. The force sensor only compensates for temperature change up to 71.1°C, and much of the testing needed to be above this temperature since the SMP's glass transition temp is 80°C. Using a longer probe distanced the force sensor device from the heat enough to eliminate drift effect due to heat.

Before each force test the force sensor was zeroed, and then the heat gun was turned on for one minute, allowing SMP to heat up. Ambient temperature was recorded at the end of one minute. The force sensor was then moved upward, deforming the SMP to a new stored angle. The maximum reading on the force sensor during this process was recorded as the force to engage. The heat gun was then turned off and the SMP was allowed to cool for five minutes. The force sensor's position was not moved. Once the sample had cooled, it was removed from the apparatus and the stored angle was measured. The SMP was then clamped back on the apparatus, and the heat gun was turned back on for one minute. The maximum reading on the force sensor was recorded as recovery force. The force sensor was moved down to allow the SMP to freely recover, and then the heat gun was turned off and the SMP was allowed to cool for five minutes before beginning the next trial. Throughout the force testing trials, the SMP was always heated up before deforming with the heat gun at a distance of seven inches away. During recovery, the heat gun was placed at varied distances away to obtain different recovery temperatures. A range of angles from small to large were deformed and their recovery force was measured at each heat gun distance.

4.6 Static Friction Testing

Static Friction Tests were conducted to determine the static coefficient of friction μ between the SMP samples and aluminum, ABS plastic's rough side, and ABS plastic's smooth side. Five SMP samples were used for this testing and each sample was placed on the surface being tested (aluminum, ABS rough or ABS smooth). The surface was tilted until the SMP slipped down the surface. The angle at which slip occurred was recorded and the coefficient of friction μ was calculated as the tangent of this angle. Each of the five samples was tested four times on each surface, for a total of 20 recorded angles for each surface.

4.7 Design of a Shape Memory Polymer Gripper for mini-PR2 Modular Robot

Once all material testing was complete, a SMP gripper was designed. The gripper was designed to be compatible for fitting with existing CKbot modules in Dr. Mark Yim's lab. The mini-PR2 robot uses these modules and the SMP gripper was installed on and used by this robot. The gripper consists of a clamping device that holds two SMP samples parallel to one another at a variable distance apart. The distance between the SMP samples can be varied by changing the width of the middle component of the gripper. Middle components of width 8mm, 12mm, 16mm, 20mm, and 24mm were manufactured. The device components were cut from ¼ inch thick ABS plastic on a laser cutter machine. The finished device, holding two smp samples, is pictured in Figure 8.

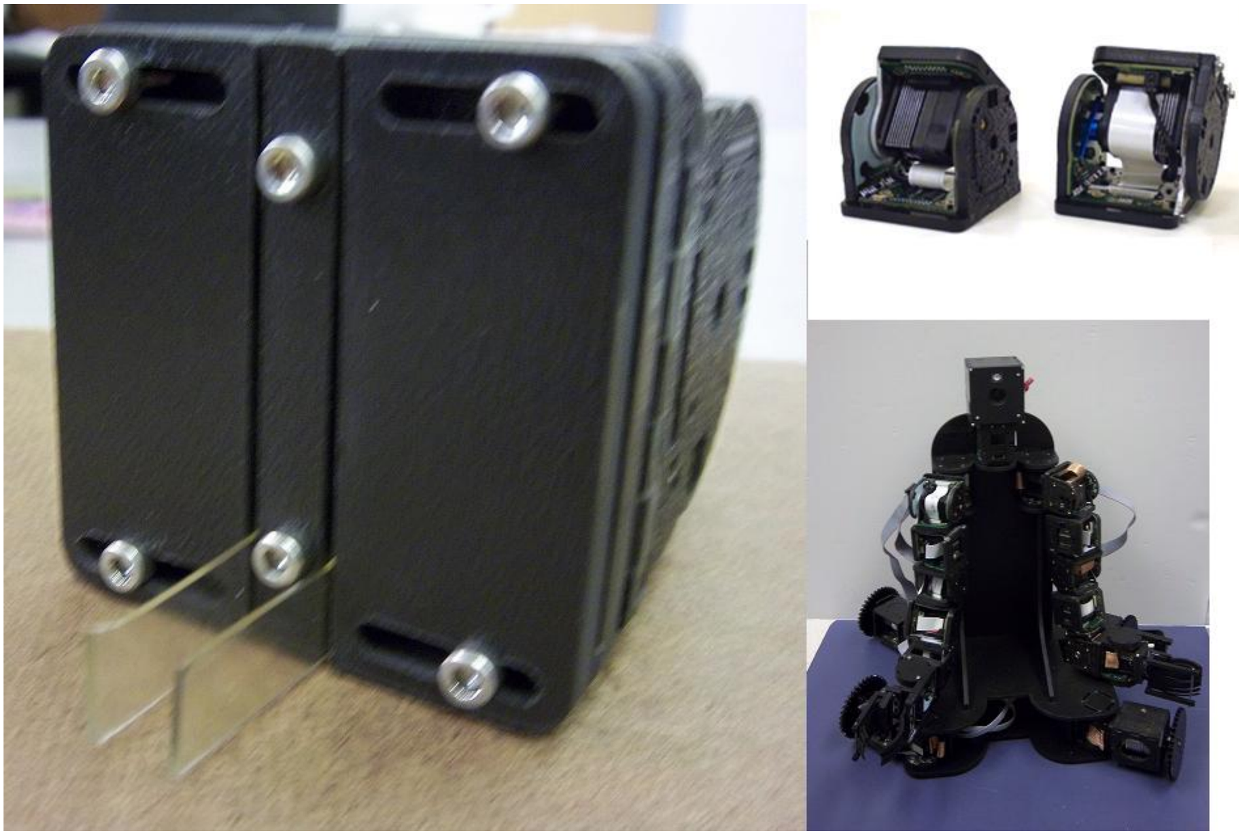

Figure 8. Left: SMP Gripper, attached to the face of a CKbot module. Top Right: CKbot Modules. Bottom Right: Mini-PR2 robot that was programmed to use the SMP gripper.

The gripper is designed to be deformed by heating up the SMPs in the clamps, and then pressing them against a specially designed structure, to deform them to an open gripper shape. Different templates can be used in deforming the gripper to attain different open gripper shapes. I hypothesize that different open shapes will be work more efficiently with differing object sizes and shapes. After being deformed to the open shape of choice, the gripper is then allowed to cool, and can be positioned around an object that needs to be picked up. Then SMP is then heated up again, and the SMPs deform back to their original shape, closing around the object in question.

5. RESULTS

5.1 Steady State Temperature Results

Through the steady state temperature testing, it was determined that a distance of seven inches was optimal placement for the heat gun for ensuring that SMP samples be heated to above their glass transition temperature. At a distance of five inches, the ambient temperature leveled off at a temperature of 130°C, too hot. At a distance of ten inches, the ambient temperature leveled off at a temperature of around 90°C, just slightly above the glass transition temperature. For this reason a distance of 7 inches with the heat gun on medium heat setting was chosen. This ensured that even if there were some alignment errors with the flow of air from the heat gun that we could be confident that the shape memory polymer had reached a temperature above its glass transition temperature. It was also determined that heating for one minute would be sufficient to reach a stable temperature. The graphs of the recorded temperature data at five and ten inches can be seen in figures 9 and 10 respectively.

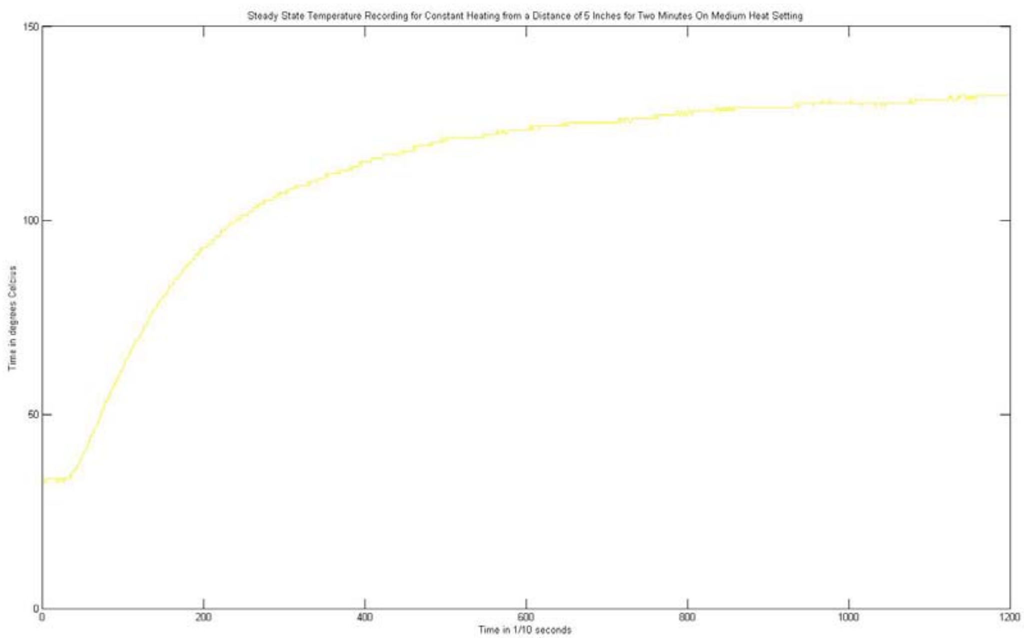

Figure 9. Temperature Recording for Medium Heat from a Distance of Five Inches

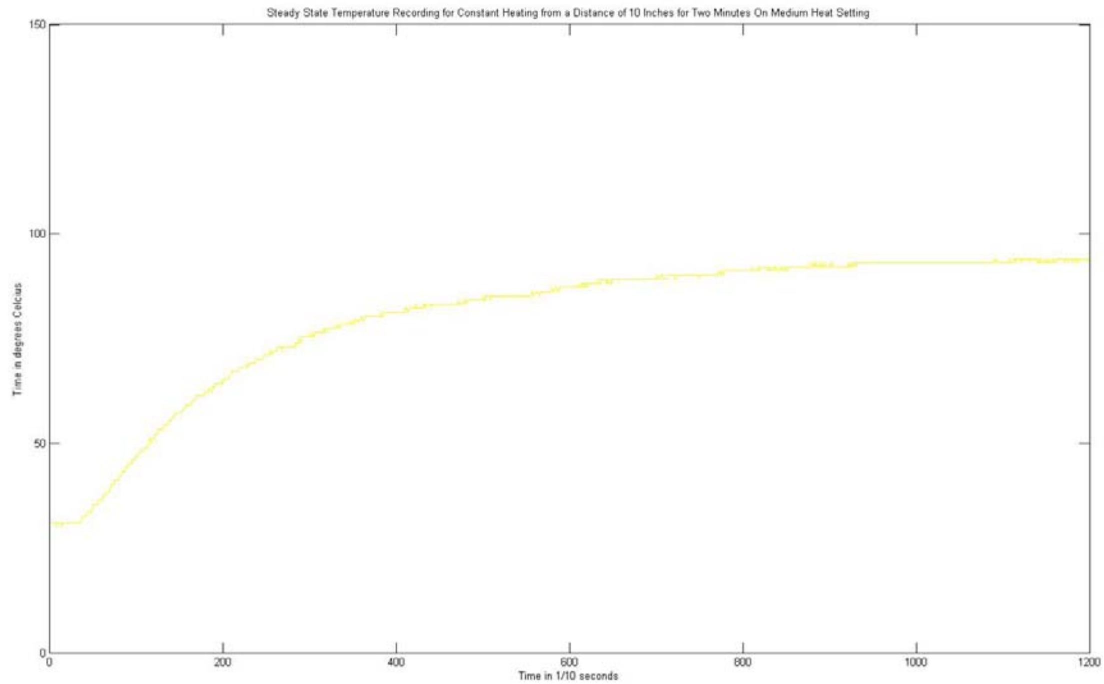

Figure 10. Temperature Recording for Medium Heat from Distance of 10 Inches

5.2 Tensile Testing Results

Before tensile test results on the SMP sample were analyzed, an identical test was ran using ABS plastic, with a known Young's Modulus, to check for accuracy of the results. A linear regression was calculated in the approximately linear region of strain less than 0.5% for each trial, to obtain a value of Young's Modulus. The Young's Modulus values obtained ranged from 35.394 MPa to 54.772 MPa, with an average modulus value of 49.594MPa. These values differ drastically from the expected known modulus of ABS plastic of 2 GPa.

For this reason, it is clear that data obtained from the Instron machine was skewed and inaccurate. For this reason, the stress-strain values obtained during testing of the shape memory polymer are not considered to be accurate. However the stress strain curves for the SMP at room temperature are plotted next to the stress strain curve of the SMP at glass transition temperature for comparison in Figure 11. The data obtained from an SMP at room temperature are plotted in black, and the data for an SMP heated above glass transition temperature is plotted in red.

As can be seen in Figure 11, when the SMP was heated about its glass transition temperature it was able to deform to strains much larger than that of the SMP at room temperature. The average modulus value obtained for the room temperature SMPs at strain greater than 1.75% was 58.716MPa. The Young's modulus obtained for the heated SMP for strain between 9% and 13% was 4.2896 MPa. These strain ranges were chosen because they were the regions in which the stress strain curves for the room temperature and heated SMP were linear. A modulus value was not calculated for the heated SMP at lower strain, even though this section of the graph is also linear, because the polymer experienced some drooping upon heating, and was not truly in tension until strains of around 9%. While none of the these modulus numerical values are considered to be accurate, we can still conclude that the modulus of SMPs at room temperature is more than 13 times larger than the modulus of the SMP heated above glass transition temperature. This indicates that SMPs at room temperature are more than 13 times stiffer than the same SMP when it is heated above its glass transition temperature.

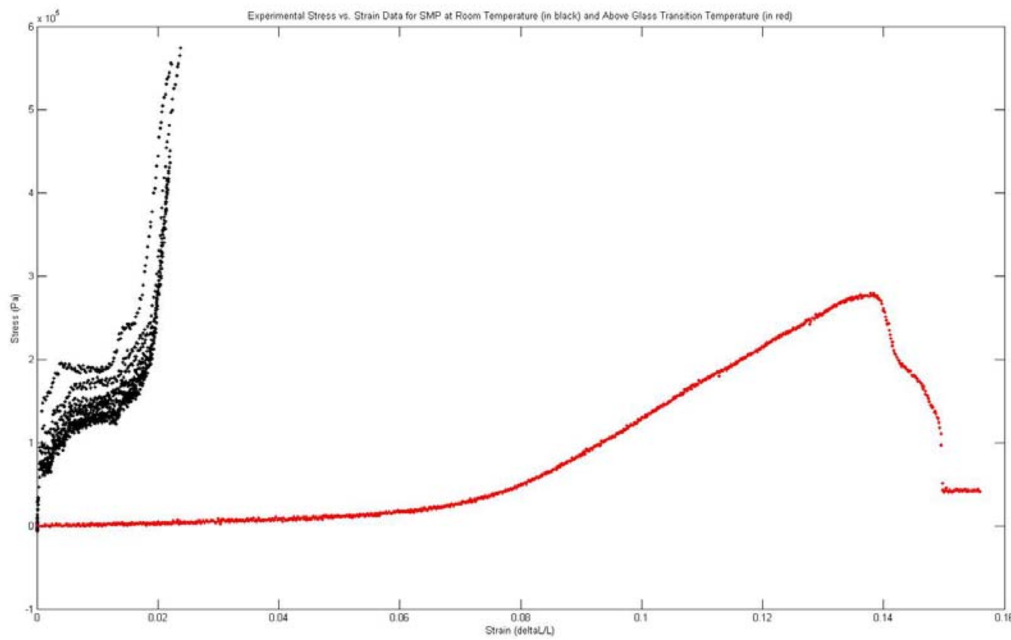

Figure 15. Stress Strain Curves for Room Temperature and Heated SMP.

5.3 Percent Recovery Testing Results

Percent recovery is plotted versus ambient recovery temperature in Figure 16. The green dashed line indicates the shape memory polymer's glass transition temperature. As can be seen from the figure, above the polymer's glass transition temperature, 100% recovery was seen for all trials. In fact, 100% recovery was observed at all temperatures above 70.5°C, 9.5° below glass transition temperature. 100% recovery was even seen at temperatures as low as 63.8°C, although not in all trials. At temperatures lower than this, the percent recovery observed dropped quickly, with recoveries less than 15% below 50°C.

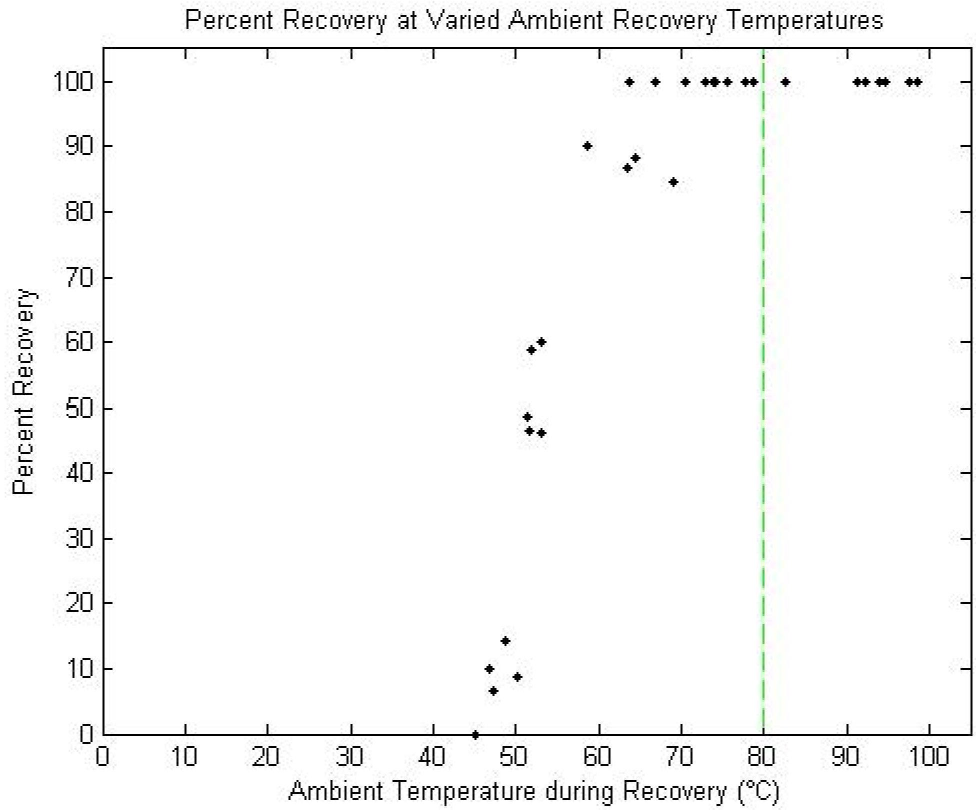

Figure 16. Percent Recovery vs. Ambient Recovery Temperature from SMP bending Test.

Figure 17 plots percent recovery vs. varied stored angles. Stored angles from small to large were all tested at a variety of temperatures ranging from about 30° below glass transition temperature and about 20° above glass transition temperature. As can be seen from the graph, there is no correlation between the value of the stored angle and the percent recovery observed. This indicates that the SMPs on the SMP gripper could be deformed to any shape or angle without affecting the percent recovery, as long as a recovery temperature of close to the glass transition temperature were reached.

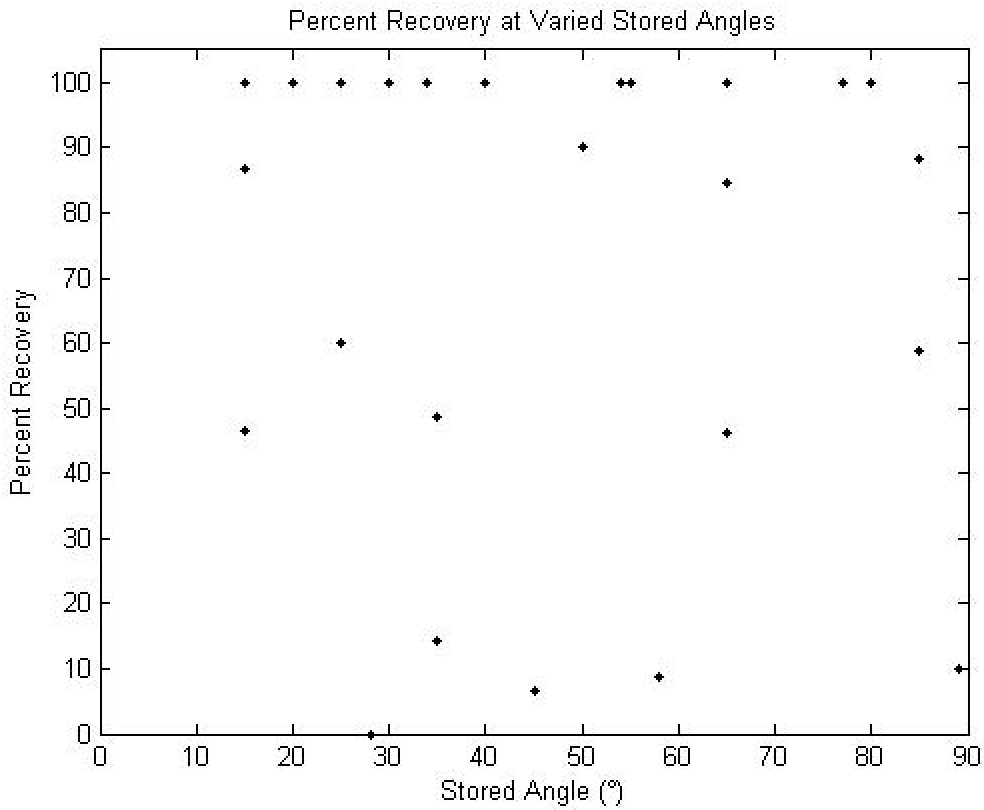

Figure 17. Percent Recovery vs. Stored Angle Value for SMP Bending Test.

5.4 Force Ratio Testing Results

The recovery force of the SMP in grams is plotted against a range of stored angles in Figure 18. As can be seen from this figure, the recovery force is positively correlated to stored angle value. The data follows a trend of increased recovery force for increased stored angle values. The R^2 value for the linear regression of this data is 0.825, indicating a fairly strong correlation. The recovery force ranges from 0.56 grams to 3.11grams.

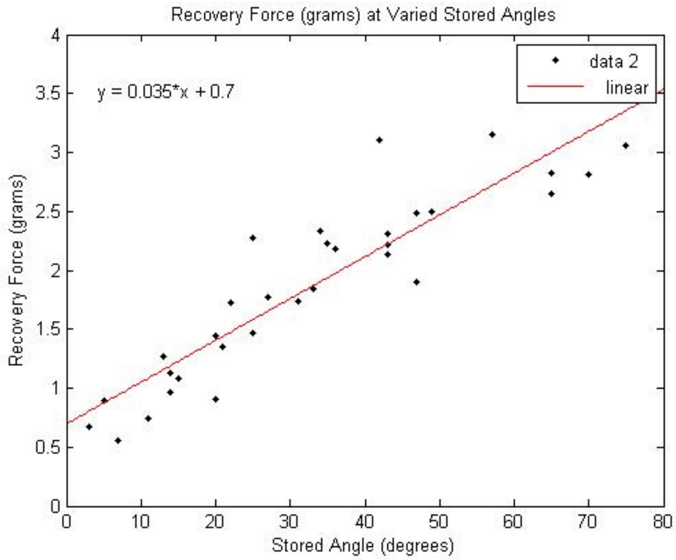

Figure 18: Recovery Force (grams) at Various Stored Angle Values

However, while recovery force increases with greater stored angle values, so does the force to engage the SMP. This can be seen by plotting force ratio against various stored angle values. The force ratio was calculated as the (recovery force)/ (force to engage). Force ratio's greater than one are considered desired results, as this indicates that less energy need be used to engage the SMPs, than for them to recover. As can be seen in Figure 19, the force ratio is close to one across all stored angle values. The R^2 value for the linear regression of this data is 0.05, suggesting that the value of stored angle will not influence the efficiency of the gripper. Larger stored angle values recovery with greater force, but also required greater force to engage.

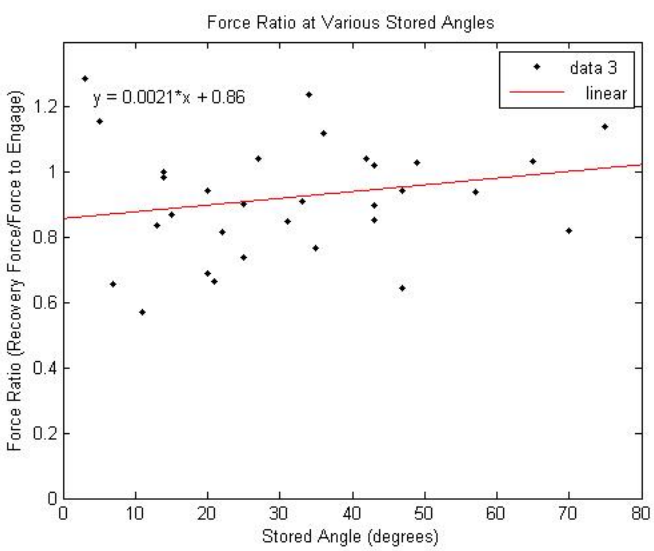

Figure 19: Force Ratio at Various Stored Angles

Figure 20 plots the calculated force ratio's vs. varied recovery temperatures. As can be seen from this figure, the force ratio appears to have no correlation with temperature. A linear regression of the data has a slope of -0.004, near zero, with an R^2 value of .09, indicating that the force ratio does not depend on temperature. In other words, the efficiency of the SMP gripper cannot be improved by manipulating the temperature at which the SMPs recover.

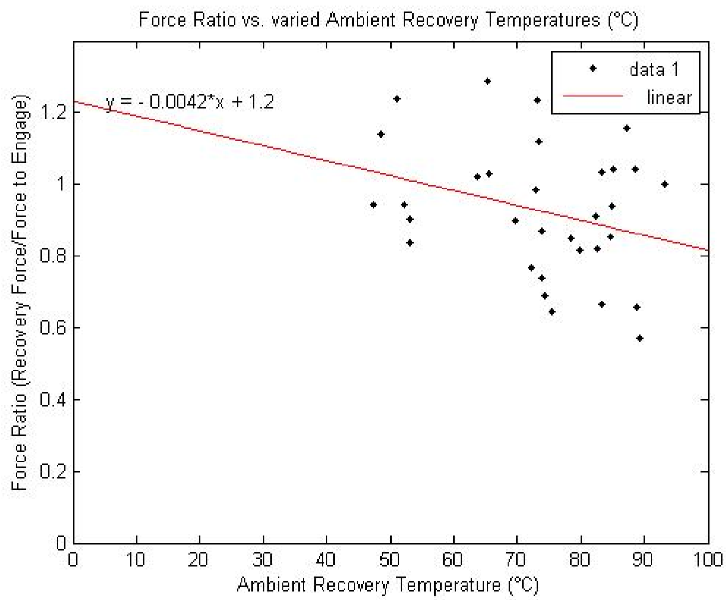

Figure 20. Force Ratio (Recovery Force/Force to Engage) vs. Varied Ambient Recovery Temperatures (°C)

Since the force ratio was not found to be correlated to stored angle or ambient recovery temp, an average force ratio can be taken across all trials. The average force ratio across all of the trials was 0.9265. This indicates that on average, 92.65% of the energy used to engage the SMP to a new stored angle will be exerted back during recovery. While ideally the force ratio should be greater than 1, 0.9265 is still fairly efficient.

Recovery Force increased with larger stored angle values. For this reason, recovery force data was normalized with respect to stored angle value before plotting recovery force vs. ambient recovery temperature. The data was normalized using the following equation: (trial recovery force)*(Maximum Stored Angle/trial Stored Angle). The Maximum stored angle was 75, the largest angle for which force data was collected. This scaled the recovery force data, by increasing the recovery force for angles smaller than 75. This scaled data is plotted in figure 21 vs. ambient recovery temperature. The R^2 value for the linear regression is .0004, indicating that the ambient recovery temperature has no correlation with the recovery force.

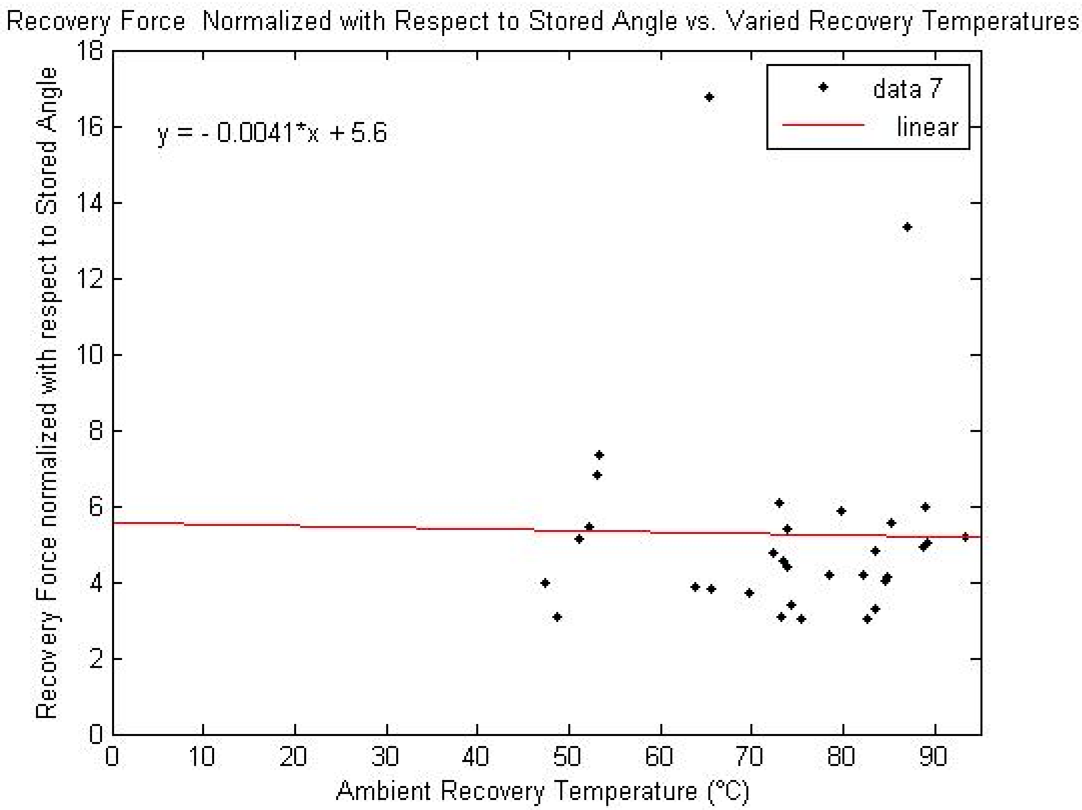

Figure 21: Recovery Force Multiplied by a factor of Max Angle/Trial Angle vs Various Ambient Recover Temperatures.

In order to obtain an estimate of the maximum weight the SMP gripper could pick up, recovery force data was averaged across all trials. The average force recovery was found to be 1.86 grams. This can be considered a conservative estimate for average force recovery since trials in which small stored angles were used are included in this average. Since force recovery increased with greater stored angle, an average was also calculated for those trials in which the stored angle was greater than 40°. 12 trials out of 32 were conducted with stored angles greater than 40°. The average force recovery for this data set was 2.60grams. This is probably a more realistic force recovery estimate for application with the SMP gripper, as it is unlikely the SMPs mounted on the gripper will be deformed for practical use to angles less than 40°. The maximum recorded recovery force across all trials was 3.15grams.

5.5 Static Friction Testing Results

The average value for μ, the coefficient of friction, between aluminum and the SMP samples was found to be 0.61. The average value for μ between the rough side of ABS plastic and the SMP samples was found to be 0.62. The average value for μ between the smooth side of ABS plastic and the SMP samples was found to be 0.64. While it seems unusual that a higher value for the coefficient of friction was found for the smooth side of ABS than the rough side of

ABS, this is likely because the dimpled nature of the rough side of ABS plastic allowed for less contact between its surface and that of the SMP.

5.6 SMP Gripper Testing Results

Based on the force ratio testing, the maximum weight of an object that could be picked up with the SMP Grippers was determined. This weight was calculated by multiplying the maximum recorded recovery force, 3.15grams, by the highest of the three recorded coefficients of friction, 0.64. This predicted that the maximum weight object that the SMP grippers would successfully pick up would be 2.02grams. However a more conservative estimate of recovery force obtained by averaging across all trials was 1.86 grams. Multiplied by 0.64, this estimates that the gripper should be able to pick up objects of at least 1.19grams. For this reason, objects weighing 1 gram were used in initial testing of the SMP gripper. This limited the likelihood that a failed lift attempt could be attributed to the force of the SMPs. Since it was observed that recovery force increased with greater stored angles, we beleive that if the SMP gripper were deformed to larger angles then it would be able to pick up heavier objects. Two of the designed structures to be used in deforming the smp gripper's to an "open" position provided successful lifts of an object. These two configurations are shown in Figure 22. Configuration A allows the SMP's to be deformed into a circular shape. Configuration B allows the SMP's to be deformed into an open V shape

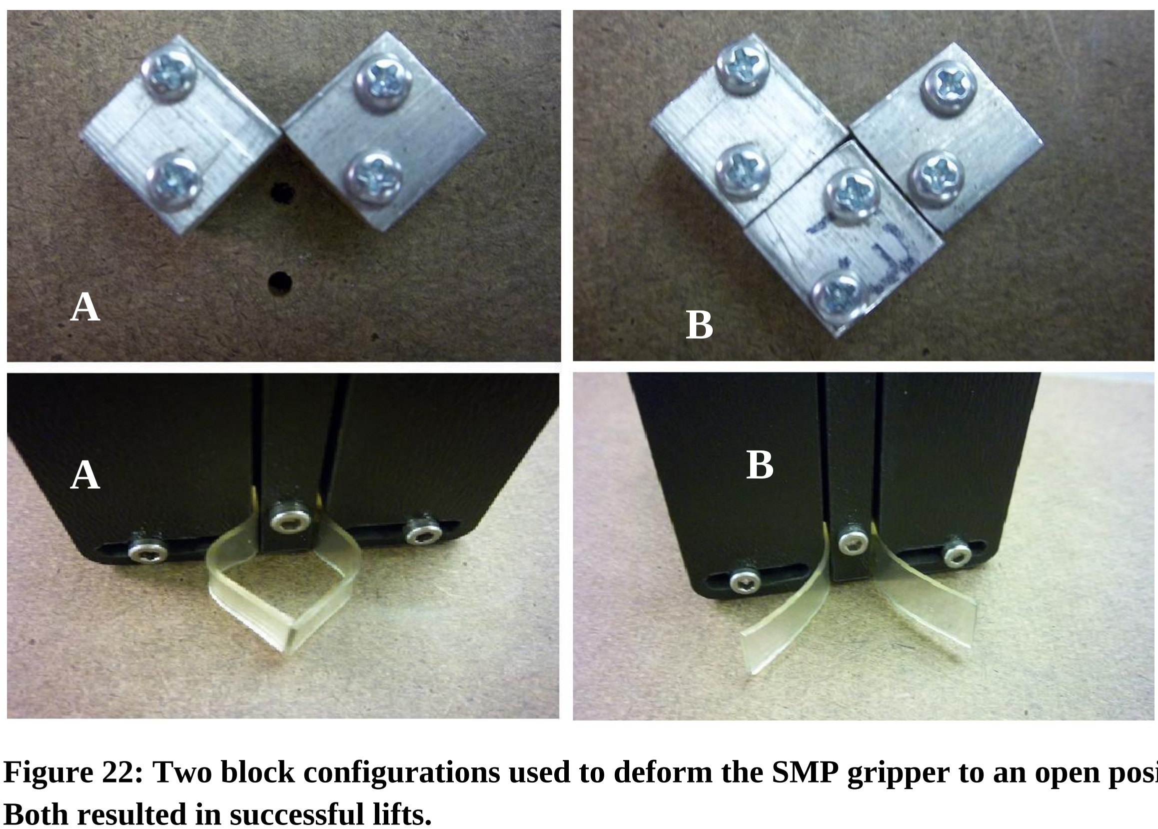

Figure 22: Two block configurations used to deform the SMP gripper to an open position. Both resulted in successful lifts.

For both of these configurations, ten attempts at picking up the same object were conducted, keeping conditions consistent. The SMPs on the gripper were heated for 45 seconds from 7 inches away with medium heat from the heat gun. Then the gripper was pressed into the configuration deforming the SMPs, and was allowed to cool for three minutes maintaining force against the configuration. Three minutes to cool was chosen because this was the minimum time that allowed the polymers to cool to a temperature that would guarantee they would maintain their current shape. The gripper was then positioned in place for picking up a small plastic tube connector, weighing one gram, and then the SMP's were heated again for 45 seconds from seven inches away. The SMP gripper's were allowed to cool for another three minutes before the gripper was picked up to test for successful lift of an object. A successful lift was considered lifting the blue plastic piece off the table top and maintaining grip on the object as the gripper's orientation was inverted. For both of the configurations used, nine out of ten lift attempts were successful. For this reason they are considered equally valuable methods of deforming the SMP, and each one could prove advantageous in picking up objects of varied shape. Also, since the configurations are the inverse of one another, it was decided that a platform be created that could mount either of these configurations

Once the platform was created, the SMP gripper was installed on the mini-PR2 robot, and the robots graphical user interface (GUI) was used to program the robot to use the smp gripper. The GUI allows the robot to memorize a sequence of positions to move between. The motion necessary to deform open the smp gripper, place the open gripper around an object and then lift and move the object were programmed. The mini-PR2 was then able to successfully use the SMP gripper to pick up the tube connector weighing one gram. Configuration B was used during the mini-PR2 demonstration because the open V shape gripper was more forgiving on alignment errors when approaching an object.

6. DISCUSSION AND CONCLUSIONS

Tensile testing conducted on the Instron Model 5544 Electromechanical Test System did not yield reliable results. It is possible that the clamps used to protect the shape memory polymer samples allowed for some slipping of the samples, giving inaccurate stress-strain results. However even when testing a tensile sample of ABS plastic without the metal clamps, data did not yield a modulus close to the known value of 2GPa. For this reason I suspect that there was some malfunction with the Instron's calibration or grip function. For meaningful stress-strain curves, tensile tests need to be repeated using another mechanical testing system.

It was found that 100% recovery could be observed for stored angles less than 90° at ambient recovery temperatures greater than 70.5°C. This indicates that for repeatable use of SMPs, an ambient temperature of at least 70.5°C must be reached during recovery.

Force testing and static friction tests predicted that the SMP samples used in this research could lift a maximum weight of 1.5 grams. A SMP gripper prototype and corresponding apparatus for deforming the gripper to an open position were manufactured, and successful lifts of an object weighing one gram were demonstrated. This prototype compatible with the existing modular robot PR2 in Dr. Mark Yim's laboratory at University of Pennsylvania, and the robot was programmed to successfully use the gripper. However more work must be conducted to make this gripper stronger, more autonomous and reversible.

The SMP components of this device are low cost and well suited for mass production. With the proper equipment, the components of the polymer could be melted and combined in large batches and then poured into large molds that could be cut into thousands of SMP pieces for the gripper. As opposed to traditional gripper material, this would be a much easier, lower cost, production method. In addition, since all plastic components of the device were cut from a laser cutter, this process could also be done on large scale fairly quickly and efficiently. Despite these possibilities there are still many hardware design improvements necessary before an entire module could feasibly be mass produced at low cost.

7. RECOMMENDATIONS

While the SMP gripper developed in this research was successful in picking up an object weighing one gram, there are several recommendations for future improvements on this device.

Additional effort must be taken in developing a method to heat up the SMPs autonomously. A proposed solution to this problem is circuitry with resistive wires that would heat up when current was applied across them. These wires could be formed around or even placed within the SMP. The effect of such additional wires on the SMP's percent recovery and force would need to be tested also. Another possible solution would be to mount a heat gun or similar heating element on the base of the PR2 robot that could be autonomously turned on and used to heat SMPs. It may be helpful in these efforts to manufacture a SMP with a lower glass transition temperature, as it would make reaching glass transition temperature easier.

Incorporation of any of the composite materials discussed in section 2.4 of this paper, including carbon black, Nickel, or short fibers, into the SMP samples used with this gripper could aid in autonomous heating of the SMPs. Addition of these types of materials can improve the polymer's conductivity. If the polymer was more conductive, it may be possible to apply a current directly across the polymer to heat it up, or speed up the heating process if a resistive wire still needed to be used.

In order for the SMP gripper to able to pick up a wider range of objects, the force and strength of the SMP samples used must be improved. The continuous fiber reinforced SMP composite developed by Lan et al [7] looks particularly promising in improving mechanical properties of SMPs and may work well with the SMP Gripper.

Finally, the current SMP gripper prototype is not reversible. In other words, there is no method of reopening the gripper once it has picked up an object besides deforming it again against the apparatus used to open it initially. However this means that an object could not be released and placed in a desired position. Future work will need to develop a method of making the SMP gripper reversible. This could be done by having an antagonistic actuator placed in opposition to the SMP grippers. A shape memory alloy could potentially be used as this antagonistic actuator.

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