

## **DESIGN OF A VARIABLE STIFFNESS LEG USING SHAPE MEMORY POLYMER COMPOSITES**

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### **1. Introduction**

Biomechanical studies have shown that animals modify their leg stiffness to adapt to changes in their running environment<sup>1</sup>. A recent empirical study investigating the performance of mechanically variable stiffness legs on a dynamic hexapedal robotic platform, Edubot, has shown that optimal performance was measurably increased by adaptively modulating the leg stiffness<sup>2</sup>. While effective, the resulting mechanism was too heavy, complex, and fragile for extended field operation.

The aim of this study is to develop an electrically activated variable stiffness leg for Edubot using a class of polymeric smart materials called shape memory polymers. Shape Memory Polymers (SMPs) experience a several order of magnitude drop in modulus as they approach their glass transition temperature. By fabricating a composite using a SMP as the resin matrix, a shape memory polymer composite is formed. A shape memory polymer composite (SMPC) developed in this manner should be capable of sustaining the high bending loads required of a locomotion appendage. By modulating the leg stiffness, the robot will then be capable of adaptation to variations in terrain and payload.

We present a design for a variable stiffness leg that utilizes a polymeric smart material to modify the leg compliance without any external mechanism. In section 2 the styrene-based shape memory polymer material used in the legs design is described and characterized. The design of and fabrication of the robot legs using this material are detailed in section 3, and the experimental testing of the legs is reported in section 4. Section 5 describes the results and directions for future work.

### **2. SMPC Material and Characterization**

In order to develop a leg with smart material based stiffness modulation, a source of shape memory polymer resin had to be secured and a shape memory polymer composite material had to be developed. In the absence of an available

commercial shape memory polymer resin, we synthesized a styrene-based chemically crosslinked co-polymer resin with shape memory properties. We designed the polymer to have a glass transition temperature of 75°C as well as a large glass transition zone to give a wide range of temperatures suitable for the control of leg stiffness. Unreinforced shape memory polymer, however, lacks the requisite mechanical properties (high strength, fracture toughness and recovery force) passively compliant robotic legs require. Recent research<sup>3-5</sup> aimed at incorporating continuous fiber reinforcement in an effort to create a shape memory polymer composite has shown that using continuous fiber reinforcement can significantly increase critical mechanical properties. The unanimous selection for the reinforcing fiber in these studies was carbon fiber.

To characterize the effect of replacing the current epoxy-based composite legs used in Edubot, three different composites using 3k T-300 carbon fiber were fabricated. The mechanical properties of the SMPC developed in this study were evaluated in comparison to composites made with two commercial resins. The styrene-based shape memory polymer resin was tested alongside a commercial epoxy resin (US Composites 635), as well as a commercial vinyl ester resin (IVEX 400).

These composites were evaluated at room temperature (the nominal case for a zero power hold SMPC mechanism), in accordance with ASTM standards. The SMPC had comparable properties to the epoxy composite and exceeded the composite made with IVEX-400 (another polymer resin) in every tested category. Material properties for composites all three resins are given in Table 1.

Table 1: Mechanical properties of tested composites

		SMP Resin	USC 635 Epoxy	IVEX-400	
Ultimate Tensile Strength	UTS ( $\sigma_{UTS}$ )	335.0 (24.5)	350.0 (20.8)	202.7 (29.7)	MPa
Elastic Modulus	E ( $\sigma_E$ )	31.75 (1.53)	31.83 (0.91)	29.86 (2.29)	GPa
Strain at Failure	$\epsilon_f$ ( $\sigma_{\epsilon_f}$ )	11.4 (1.46)	11.2 (0.78)	6.1 (0.19)	$\epsilon \times 10^{-3}$
Short Beam Shear Strength	$\tau_{SBS}$ ( $\sigma_{\tau_{SBS}}$ )	28.05 (1.77)	24.06 (0.81)	23.27 (2.16)	MPa

Although SMP appears to be an adequate substitute for epoxy in these legs, in order to achieve variable stiffness behavior, it was not required to fabricate the leg entirely from SMPC. We found that more reliable mechanical properties could be attained in the SMPC by fabricating it in smaller geometries. Therefore, a segment of SMPC was included in the leg at the effective center of deflection, 15% of the leg length away from the fixed attachment point. To increase the strength of the bond between the SMPC section and the epoxy leg, we used a methacrylate adhesive to bond the two composites at the fiber level. The completed leg, shown in Fig. 1, has the same nominal properties of the original leg with a diameter of 11.4 cm and a nominal stiffness of 1,100 N/m measured at 10% deflection of the leg.

### 3. Design

We considered several methods of activation for the composite leg for electronic control of the leg such as fabricating the composite using an electroactive polymer, or heating through the fiber matrix of the composite itself.

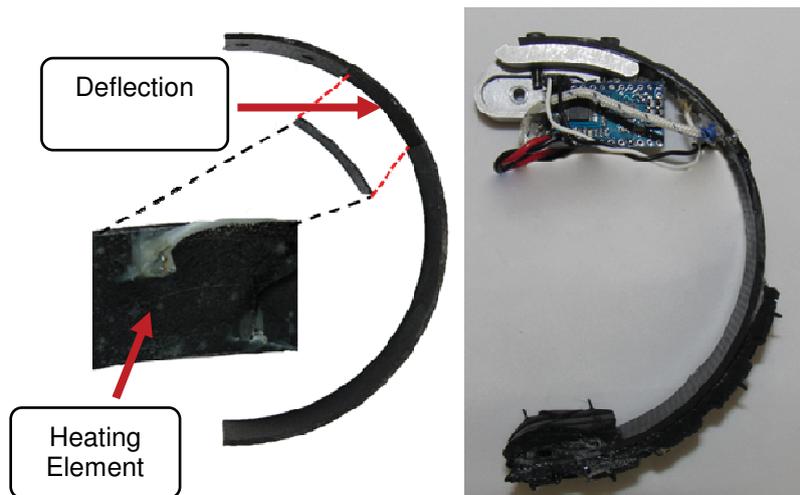


Figure 1: Variable stiffness leg, showing SMPC section (left), and complete assembly (right)

We elected to use Joule heating as our actuation method, wherein thermal power is dissipated into the leg from a resistive heating element. A Nichrome wire heating element and thermocouple were embedded in a thin fiberglass scrim and applied to the SMPC section of the leg. A miniature microcontroller, complete with an ATmega328P processor, MAX6674 cold junction compensated thermocouple ADC and motor driver was attached to the leg itself. This controller is designed as an independent unit with its own power source to eliminate the need for a rotor and stator as used in the alternative design<sup>2</sup>. The resulting leg weighs 25 grams and is 70% lighter than the previous, mechanical variable stiffness design. The most suitable heating element for this geometry was found to be an ‘S’ shaped curve.

### 4. Results

We first evaluated the performance of the electro-activation hardware. Figure 2 is an infrared photograph, showing that the ‘S’ shape heating coil configuration

chosen results in an even heat distribution across the shape memory composite specimen.

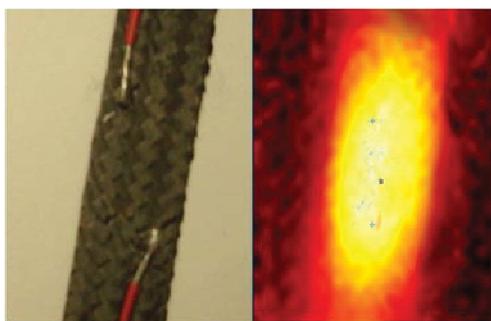


Figure 2: Heat distribution across the SMPC specimen

The heat activation system was designed to draw less than 2.5W when operating at its maximum temperature (85°C) to allow for comparable battery life between the temperature control circuits and Edubot. Steady state power consumption was measured for the temperature control unit and the peak power consumption falls within our design parameters, as shown in Figure 3. The time constant for heating actuation was found to be fairly low, on the order of 8s, with the selected heating element design. However, the cooling and stiffening of the leg requires heat transfer based on ambient conditions, and is much slower. Therefore, this design of leg is well suited for adapting to changes in steady state operation, as the mechanically variable stiffness leg has been used.<sup>2</sup>

With the temperature control circuit in place, a prototype leg was attached to the loading head of a MTS Insight testing system (Fig. 4) and compressed onto a linear stage to measure the effective radial stiffness of the variable stiffness leg. The leg was tested at room temperature and in 5°C increments from 40°C to 85°C. As shown in Fig. 5, the leg stiffness ranged from a maximum value of 2310 N/m at room temperature to 650 N/m at 85°C, a change of approximately 350%.

## 5. Discussion and Future Research

In this work, we synthesized a shape memory composite material and developed an integrated temperature-based stiffness control policy. Based on this material, we fabricated a new shape memory composite mechanism and characterized its radial stiffness characteristics. The variable stiffness leg developed in this study was capable of over a 70% decrease in stiffness, a range encompassing the expected operational states for Edubot. Further optimization is required before this leg can be implemented on the robot operating in the field. The mechanical

strength and fatigue life need to be improved for an extended operational lifetime of the leg. A new layup, using a higher-grade carbon fiber, is expected to extend the lifetime of the component by increasing resistance to the micro-buckling failure mode. Once these improvements have been achieved, testing on a mobile robotic platform will demonstrate the utility of the new leg.

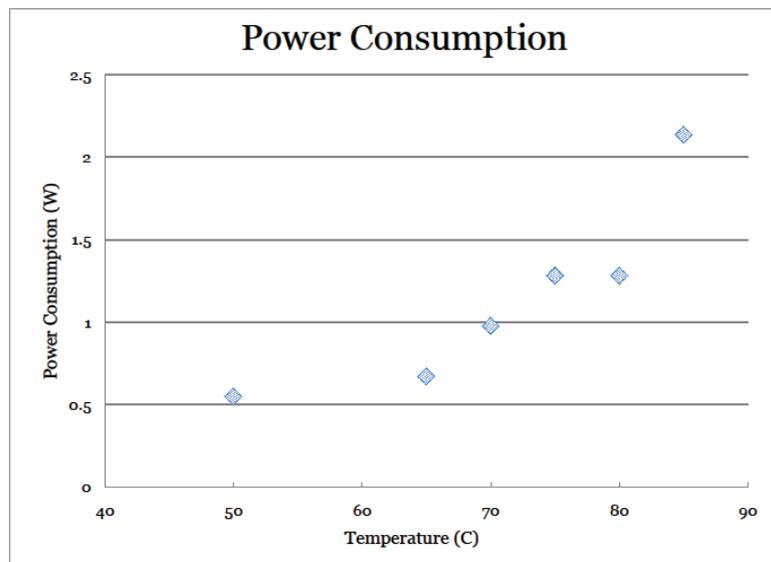


Figure 3: Power consumption of the variable stiffness leg as a function of specified flexure temperature.



Figure 4: Stiffness testing equipment

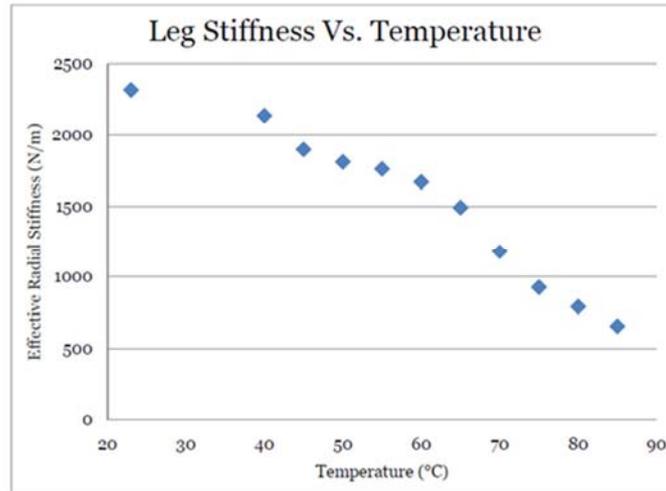


Figure 5: Experimental performance of the variable stiffness leg

## References

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