To appear in the Journal of Intelligent Material Systems and Structures

Closed-Loop Feedback Control of Magnetically-Activated Gels

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ABSTRACT: Polymer gels that exhibit a change in volume in response to a small change in an environmental parameter such as temperature have been fabricated and studied for several decades. We have developed gels that change volume in response to an applied alternating magnetic field. These gels could serve as actuators in servomechanisms. This paper presents practical techniques for using closed-loop feedback to control the position of magnetically-triggered polymer gels. Experimental results are presented, which demonstrate position control of two different types of magnetically-triggered gels using prototype power electronic drives.

INTRODUCTION

POLYMER gels are composed of cross-linked polymer networks immersed in a solvent. Carefully fabricated gels exhibit reversible changes in volume that can be triggered by variations in any of a number of environmental factors, including temperature, solvent pH, and applied light intensity (Tanaka, 1981). This and other properties of gels make them exciting and unique materials for potential application as fundamental components in servomechanisms, sensors, optical memories, controlled chemical release systems, and selective absorbents. A volume-phase transition is a result of the gel's ability to retain and exchange large amounts of fluid with the external environment. Microscopically, a phase transition is a reversible folding or unfolding of the polymer chains that constitute a network in a gel.

Polymer gel actuators could provide direct linear motion quietly, swiftly, and with useful force densities. These actuators could be suitable for application in servomechanisms and sensors, ranging from micro-fabricated mechanisms to larger devices comparable in size and force density to biological systems. Gel actuators may enable design techniques and approaches that are different from those used for systems employing traditional electromagnetic actuators. Since gels could be layered and flexed or routed conformally with an underlying mechanical structure, gel actuators should lead to servomechanisms with a range and complexity of motion that is very difficult to attain with bulk electromagnetic actuators. Because the gel actuator mass can be distributed, gels may permit the construction of servomechanical systems with reduced moments of inertia and, therefore, improved dynamic performance. Broadly, the development of successful polymer gel actuators for practical engineering applications requires the precise control of a number of material properties, including response speed, form factor, tensile strength, and trigger mechanism.

The completion of a closed cycle of useful work by a gel actuator requires that energy be provided to the gel. Trigger energy is provided to change the balances of forces on the polymer network, thus inducing a phase transition. Energy must also be provided for part of the closed cycle to change the gel phase, i.e., "latent heat". For example, a gel that exhibits a volume transition in response to changes in solvent pH receives trigger energy by consuming or reacting strong acids and bases around the gel. From an engineering perspective, it is highly desirable to provide energy to a gel actuator in a manner that does not require the storage and manipulation of large, expendable chemical reserves or changes in the chemical composition and ion content of the gel solvent. Thermal activation is attractive, for example, but may be relatively slow and difficult to implement in a portable way. Jackson et al. (1996), Jackson et al. (1997) and Leeb et al. (1997) introduced new techniques for remotely triggering gels using alternating magnetic fields. This paper describes closed-loop position-controlled servomechanisms employing two different magnetically-activated polymer gels.

MAGNETICALLY-ACTIVATED GELS

Application of a quasi-static (Haus and Melcher, 1989) magnetic field can be used to excite losses in a ferromagnetic seed material (Haider et al., 1991). Jackson et al. (1996) and Leeb et al. (1997) developed magnetically-activated gels by implanting ferromagnetic seed materials in the polymer network. An external alternating magnetic field can then be used to initiate the volume-phase transition in these polymer gels. The trigger mechanism for this transition is not the applied field itself, but the heating induced within the ferromagnetic particles. The predominant heating mechanisms, illustrated in Figure 1, include

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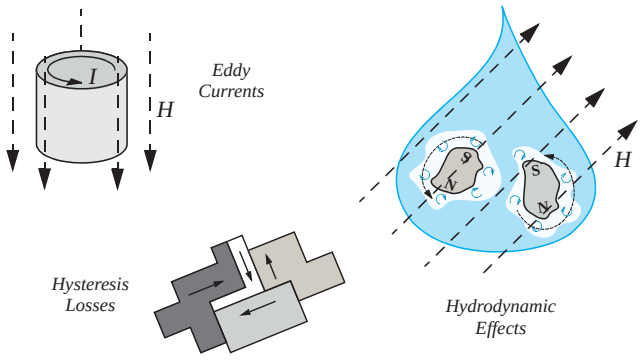


Figure 1. Loss mechanisms.

dissipation due to eddy currents, hysteresis losses, and hydrodynamic friction. The dominant loss mechanisms that serve to couple the magnetic field to the gel temperature are generally a function of field frequency, seed material, and geometry. The impact of the choice of seed material on gel design is briefly discussed here; a more complete overview is provided by Jackson et al. (1996).

Lumped-Seed/Powdered-Seed Gels

Our preliminary efforts to develop magnetically-triggered gels involved the use of a macroscopic seed material such as a steel pin (Jackson et al., 1996). The seed material could be inserted into the gel during or following gel fabrication. Lumped-seed materials can provide significant heating at relatively low frequencies.

Large-scale seed materials are easy to model accurately. They are excellent choices for developing magnetically-activated gels that respond to relatively low field strengths and frequencies. However, the bulk of these seed materials may significantly affect the flexibility and swelling ratio of the gel (ratio of largest to smallest equilibrium gel volume).

Experimentation with lumped-seed materials revealed that experimental design is a critical factor. For example, in our earliest experiments, a thermocouple was placed in the gel to measure gel temperature during induction heating experiments. This thermocouple was placed outside the bore of the solenoid used to apply magnetic fields, but not entirely outside of the fringing field just outside of the coil. The thermocouple junction was itself directly induction heated by the time-varying magnetic field, and therefore served as a significant and unwanted source of dissipation. Furthermore, the measurement provided by a typical thermocouple and thermocouple amplifier is skewed in the presence of high magnetic fields. To avoid these problems, all temperature measurements presented by Jackson et al. (1996), for example, were taken with a non-contact infrared pyrometer.

Unanticipated conducted heat can easily lead to erroneous conclusions about seed material performance. We have observed that great care must be taken to prevent heat, which originates from both ohmic dissipation and self-induction (proximity effect) in the induction coil, from transferring directly to the gel through conduction. Obviously, this conducted heat does not originate from direct induction heating of the seed materials in the gel. Accordingly, care was taken during the experiments described in the next section to ensure that thermal trigger energy is provided to the gel strictly through dissipation in the embedded seed materials.

Because lumped seed materials can restrict the swelling ratio of a gel, this seeding approach is not preferred for developing gel actuators with significant stroke. The distribution of a finely powdered seed material within the gel provides a practical alternative, which also yields relatively homogeneous heating. In the experiments presented here, the physical size and shape of the metal particles resulted in significant loss contributions from both eddy currents and hysteresis losses (Jackson et al., 1996). A gel was fabricated with 5%-by-weight nickel "leafing-grade" flakes provided by Novamet corporation[1]. These flakes have a typical thickness of 0.4 μm and a typical diameter of 30 μm. The gel was formed in a cylinder 0.51 cm in diameter and 7.37 cm in length. Because the relative dimensions of the flakes are small in comparison to those of the gel, the linear stroke of the seeded gel, between its collapsed and swollen states, is comparable to that of a pure unseeded gel.

Ferrofluid Solvent

Another seed material that can couple the magnetic field to the temperature of the polymer matrix is a ferrofluid solvent. A typical ferrofluid is composed of ferromagnetic particles on the order of 100 Å (0.01 μm) suspended in an aqueous solvent by a surfactant. Solvents other than water may be used. Ferrofluids can yield significant heating when immersed in an alternating magnetic field (Jackson et al., 1996). The actual mechanism of ferrofluid induction heating, however, is apparently poorly understood. Even at field strengths and frequencies (around 3 MHz in Jackson et al. (1996)) where eddy current dissipation and hysteresis losses should be negligible, very substantial heating is observed. Physical models and experiments appear to implicate hydrodynamic friction between rotating magnetic domains and the ferrofluid solvent (Thompson, 1996). To investigate the properties of ferrofluid as a seed material, a second gel was synthesized using an aqueous ferrofluid as its solvent.

EXPERIMENTAL OVERVIEW

The experiments in this section were conducted to determine the magneto-mechanical properties of *N*-isopropylacrylamide (NIPA) gels seeded with induction heating targets, and to determine the suitability of these gels as actuators. Conventional NIPA gels exhibit a nearly discontinuous phase-transition curve around a phase-transition temperature of approximately 34 °C (Hirotsu,

[1]Novamet Specialty Products Corporation, 10 Lawlins Park, Wyckoff, NJ 07481 USA.

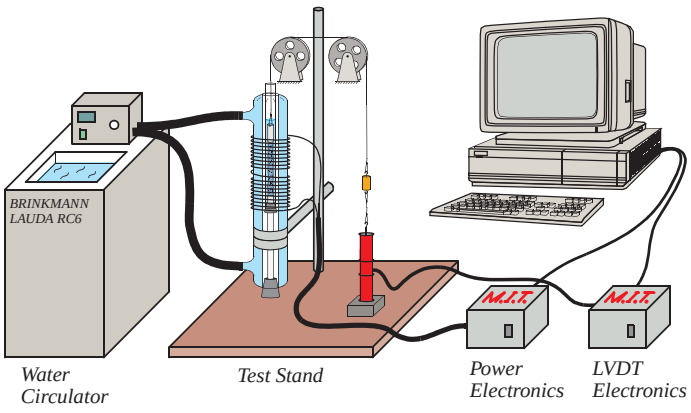


Figure 2. Experimental apparatus.

Hirokawa and Tanaka, 1987). Flake and ferrofluid seeded NIPA gels exhibit similar phase-transition curves (Jackson et al., 1996).

An apparatus was constructed to regulate the temperature, magnetic field, and mechanical load applied to the gel. A linear variable differential transformer (LVDT) was used to measure the length of the gel (Linear Technology, 1990). Figure 2 shows an overview of the experimental setup. The first set of experiments was conducted on a NIPA gel fabricated with Novamet nickel flakes implanted in the polymer matrix. The second set of experiments used a standard NIPA gel immersed in a ferrofluid solvent.

Gel Preparation

Gels made from recrystallized *N*-isopropylacrylamide (NIPA, Kodak) monomer were prepared by free radical polymerization in water at room temperature. Ammonium persulfate (APS, Mallinckrodt) and tetramethyl ethylene diamine (TEMED, Bio-Rad) were used as the initiator and accelerator, respectively. The crosslinker used was *N,N'*-methylenebisacrylamide (BIS, Bio-Rad). Poly(vinyl alcohol) (PVA, Aldrich) polymer with 115,000 molecular weight was used to form a semi-interpenetrating polymer network (IPN) in order to increase the tensile strength of the gel (Mitwalli et al., 1994). In the case of the powdered seed gel, PVA also helped suspend the seed material until gelation occurred.

Powdered Seed Gel

The powdered seed material is composed of Novamet ferromagnetic nickel "leafing grade" flakes. In the powdered seed gel, the ferromagnetic particles are entrained in the matrix during polymerization. This is achieved by suspending the seed material in solution as gelation occurs, effectively trapping the ferromagnetic material in the gel network structure. The polymer gel formula described below is a variation on the NIPA gel formula described by Mitwalli et al. (1994). The preparation steps for this gel are:

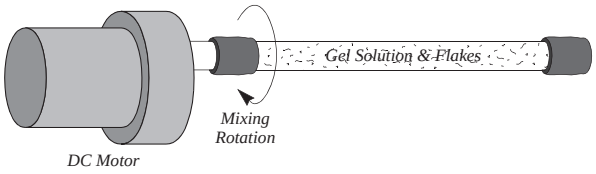


Figure 3. Spinning solution to maintain the nickel flakes in suspension.

1. PVA (5 g) was dissolved in 500 ml of deionized water at 50 °C for approximately 20 hours.
2. APS (0.2g) was dissolved in 5ml deionized water at room temperature. This solution was degassed in a vacuum chamber.
3. Nickel flakes (0.5 g) were mixed in 5 ml of the PVA solution from step 1.
4. NIPA monomer (0.78 g), and BIS (0.013 g) were dissolved in 5 ml of deionized water at room temperature. This solution was mixed with the mixture of PVA and nickel flakes from step 3. The resulting 10 ml solution was degassed.
5. TEMED (24 μL) and 100 μL of the APS solution from step 2 were mixed with the solution from step 4. The new mixture was then vigorously shaken with a vortex mixer.
6. The solution in 5 was immediately poured into a glass cylinder 0.51 cm in diameter. It is important not to let the nickel flakes settle before transferring the solution.
7. The cylinder was sealed at both ends and mounted onto the shaft of a DC motor. The motor serves to spin the cylinder at approximately 100 rpm horizontally (with the glass cylinder parallel to the ground) to keep the nickel flakes suspended in the solution as gelation occurred. This is illustrated in Figure 3. When gelation was complete, the gel was extracted from the glass tube and immersed in deionized water.

PVA serves a dual role in the preparation of this gel. In addition to enhancing the tensile strength of the formed gel, PVA also helps to suspend and coat the nickel particles in solution during the transfer into the glass cylinder and while gelation occurs. Coating the nickel flakes with PVA prior to gelation appears to enhance the efficiency of the polymerization initiator, APS.

Ferrofluid Gel

In the ferrofluid gel, the ferromagnetic material is suspended in the solvent around the gel network. The preparation protocol for the ferrofluid solvent gel is essentially the same as that given for the nickel flake gel in the previous section. However, for the case of the ferrofluid gel, the addition of nickel flakes in the third step is eliminated. The gel was formed in a cylinder 0.51 cm in diameter and 6.67 cm in length. When gelation was complete, the gel was extracted from the glass tube and immersed into the ferrofluid.[2]

Electromechanical System

The magneto-mechanical properties of the seeded NIPA gels were determined with the apparatus illustrated in Figure 4. The NIPA gel was mounted vertically in a tube recessed within the Liebig condenser (See Figure 5). The base of the gel was fixed with a mechanical support. The water temperature within the outer jacket of the condenser was regulated with a Lauda RC 6 water circulator,

[2]Lignosite FML made by Georgia Pacific

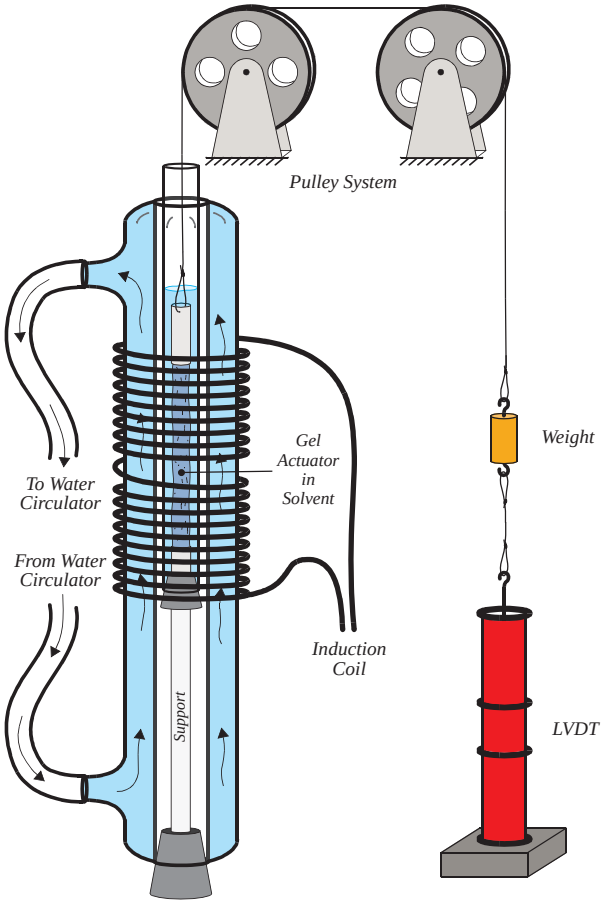
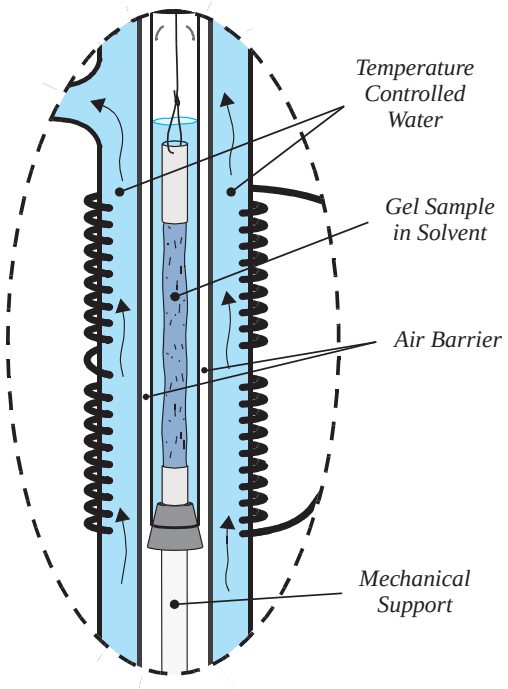


Figure 4. Liebig condenser and suspended gel.



(*The induction coil has been removed for clarity.*)

Figure 5. Closeup of the Liebig Condenser.

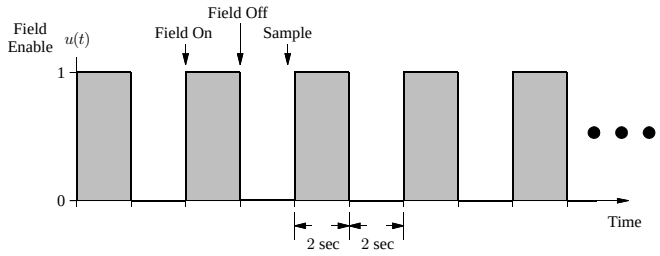


Figure 6. Timing sequence for heating and data acquisition.

which prevented any direct heat transfer from the excitation coil to the gel. In the series of experiments with the nickel seeded gel, an air barrier was left as a buffer to help further stabilize the temperature of the inner glass cylinder. The circulating Lauda water was set to 30 °C to "bias" the gel near to, but below, its transition temperature (34 °C). In the second series of experiments with the ferrofluid gel, the air barrier was filled with water to increase the coupling with the thermal bath. In addition, the circulating water bath was adjusted to 15 °C to increase the cooling rate of the gel temperature.

A silk fiber was attached to the top of the NIPA gel with epoxy. The fiber passed over a low-friction pulley system to an adjustable weight and light steel rod. The rod was suspended within a LVDT that sensed the relative position of the gel. The LVDT was driven at 1 kHz and the output was demodulated with a synchronous detector. The synchronous detector, coupled with a 12-bit AD converter, allowed for low-noise measurements sensitive to displacements of under 100 microns. The output of the synchronous detector was sampled and incorporated directly into the MATLAB processing environment (Mathworks, 1997). MATLAB also provided the command signal to the power electronics (described by Jackson et al. (1996)) that drive the excitation coil surrounding the Liebig condenser. The use of MATLAB as a control and computation environment allowed for relatively easy synthesis of different feedback compensation schemes.

When the power electronic inverter was active and applying a magnetic field to the gel, significant electromagnetic interference occurred in the LVDT position measurement. To ensure accurate position measurements, the inverter was disabled during the sampling of position. A typical operating scheme is illustrated in Figure 6. A magnetic field is applied to the gel for two seconds by the inverter. Then, the inverter is disabled for two seconds to allow the synchronous detector following the LVDT to stabilize. The position voltage was then sampled, and the cycle began again. This four second switching period was found to be substantially shorter than the dominant dynamic time constants of the gels.

Control Implementation

In order to close a feedback loop on the gel's position, a means of controlling the energy (induced thermal dissipation) delivered to the gel was required. One obvious scheme is to adjust the amplitude of the magnetic field. Another is to adjust the frequency of the excitation, since the heat dissipation is generally a function of frequency. The simplest control scheme given our apparatus, however, was to adjust the duty cycle of the applied field. As mentioned previously, an experimental period in the open-loop experiments consisted of a two second window of applied magnetic field, followed by a two second window to allow the synchronous detector to stabilize before sampling. The MATLAB interface facilitates adjustment of the duration of the magnetic excitation during the first two second window. Varying the duty cycle d of the applied field interval varies the average heat flow into the gel. A full experimental period is always four seconds long, and always has at least two seconds at the end of the period when the field is off in order to facilitate accurate position measurement. This constrains the maximum duty cycle to a value of 0.5 in our experiments.

RESULTS

With the experimental setup and data acquisition scheme described above, both the nickel-seeded NIPA gel and the ferrofluid NIPA gel were placed in an alternating magnetic field. In all of the experiments, the field frequency was 2.46 MHz, and the field strength was 2640 A·T/m. The dynamic response of the gel length in each experiment was recorded by the data acquisition system.

Open-Loop Response

A magnetic field was applied to both the nickel-seeded and ferrofluid swollen gels to induce a shrinking transition. In each case, the gels were loaded with a 5.1 g mass. Responses for both gels are shown in Figure 7. Note that the lengths indicated in the plots are the lengths of the segment of the steel rod in the bore of the LVDT, not the absolute lengths of the gels. For the time between the "Field on" and "Field off" markers in each subplot, the magnetic field was applied to the gels according to the scheme illustrated in Figure 6. For the time after the "Field off" marker in each plot, the magnetic field was disabled and the gels expanded. The dynamic profiles of both gels exhibit two distinct time constants. This is qualitatively consistent with observations made by Tanaka (1986).

Dependence on Load

Figure 8 plots the open-loop dynamic responses of the nickel-seeded gel under different loading conditions. Loads of 5.1 g and 10.19 g were used, and in each case the magnetic excitation was as illustrated in Figure 6. The static equilibrium points of the gel volume or length will vary with load due to the gel's elasticity. The gel

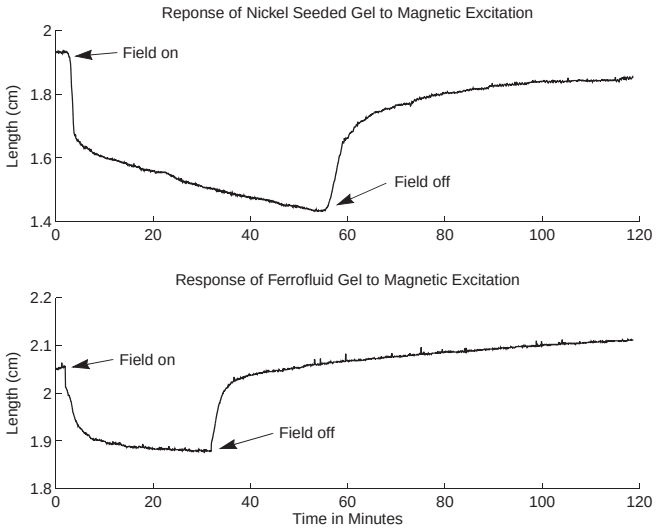


Figure 7. Gel responses.

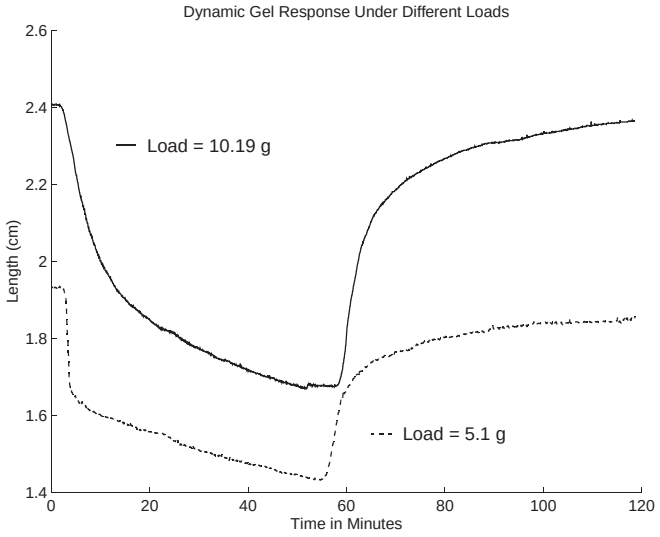


Figure 8. Magnetic gel response under different loading conditions.

in Figure 8 is longer in both the shrunken and expanded states when it is more heavily loaded. Other properties of polymer gels are known to change under mechanical load. Starodubtsev (1985) and Hirotsu (1989) show the effects of mechanical tension to have an effect on the transition temperature of thermo-sensitive gels. The experiments in Figure 8 demonstrate that the shape and rate of the dynamic response of the gel can also change with the variation of mechanical load. This change appears more pronounced in the shrinking transition.

Active Control

A closed-loop controller can be implemented by developing a compensator to modify the duty cycle as a function of the error between the measured gel length and the desired gel length. A well-designed compensator commands a corrective excitation profile for the magnetic field to minimize the position error. Figure 9 illustrates this

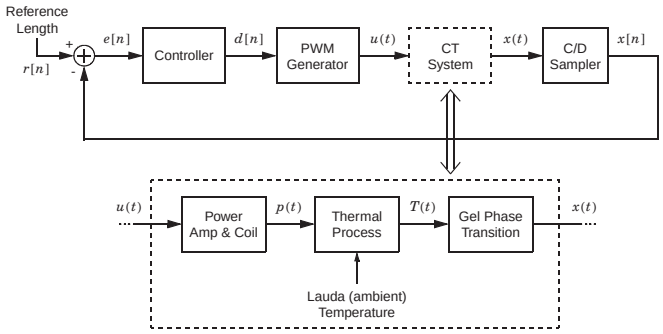


Figure 9. Block diagram.

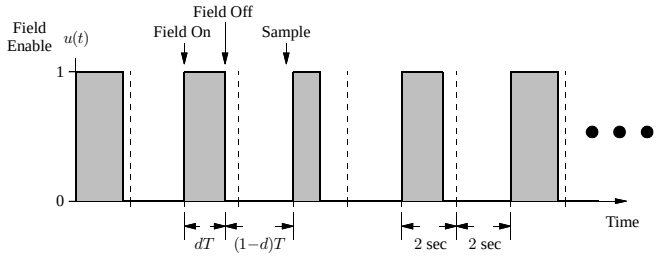


Figure 10. Pulse-width-modulation.

scheme.

The length of the gel $x[n]$ is sampled every $T = 4$ seconds by the MATLAB-based digital data acquisition system and controller. The discrete-time index n increments once each period T. The measured error $e[n]$ is the difference between this measurement and the reference input $r[n]$:

$$e[n] = r[n] - x[n]. \tag{1}$$

To adjust the input to the gel system based on this error signal, a pulse-width-modulation (PWM) scheme was used (Kassakian, 1991). This technique is illustrated in Figure 10. At the beginning of every n-th four second period, the magnetic field is turned on. The field will remain on for a fraction $d[n]$ of the period T, but not longer than two seconds, and then switch off. That is, the maximum duty cycle is again limited to $d[n] = 0.5$. By increasing $d[n]$, more heat is delivered to the gel over one switch period and its temperature rises. Decreasing $d[n]$, on the other hand, permits the ambient cooling from the circulating water in the outer jacket to lower the temperature of the gel. The closed-loop controller can therefore modulate the value of $d[n]$ to drive the gel position in the right direction to minimize the position error. The compensator was implemented as a digital controller in MATLAB. To design a stable compensator with adequate dynamic performance, a model for the continuous-time system in Figure 9 is needed.

Gel Model

The process of volume change in the gel is determined by the collective diffusion of the polymer network in the solvent (Tanaka, 1986). The collective diffusion coefficient is defined as the ratio of the elastic modulus of the polymer network k and the frictional coefficient f between the network and the solvent (Tanaka, 1986):

$$D = \frac{k}{f}. \tag{2}$$

The kinetics of a polymer gel as it undergoes a full volume-phase transition are generally nonlinear. The factors determining the diffusion coefficient, and therefore the dynamics, depend on the actual volume of the gel as well as its final equilibrium state in response to the environmental conditions. The response of the gel is described by nonlinear partial differential equations that generally require numerical solutions. When the total volume change is small, however, the equation of motion for a spherical NIPA gel with final equilibrium radius a and total radius change Δa_o can be reduced to a diffusion equation (Matsuo and Tanaka, 1988) with solution:

$$u(a,t) = \frac{6\Delta a_o}{\pi^2} \sum_{n=1}^{\infty} \frac{e^{(-n^2 t/\tau)}}{n^2} \tag{3}$$

where $u(a,t)$ is the displacement of a fixed point on the gel network from its equilibrium location a at time t. The time constant τ is defined as

$$\tau = \frac{a^2}{\pi^2 D} \tag{4}$$

for the diffusion coefficient D. For further detail on this formulation and its origin, see Matsuo and Tanaka (1988). Similar results have been obtained for cylindrical gels.

According to Equation (3), the radius of the gel changes rapidly for times smaller than τ and follows a single exponential profile for the rest of the time as it approaches its final value. This dominant single exponential $e^{(-t/\tau)}$ is a function of the dimensions of the gel as well as its diffusion coefficient. Observed dynamic behavior of polymer gels exhibits this two time scale property as seen in Figure 7. If the "fast" response of the gel for times before τ is approximated by one exponential, a second-order model can be developed that describes the behavior of the polymer gel under small signal conditions.

A second-order system transfer function with two poles on the real axis and one zero is shown by Mitwalli (1998) to be a reasonable model for the kinetics of small changes in the volume of cylindrical NIPA/PVA gels under constant mechanical load:

$$\frac{X(s)}{T(s)} = \frac{b_1 s + b_2}{(s + a_1)(s + a_2)} \tag{5}$$

where the input $T(t)$ is the gel temperature and the output $x(t)$ is the gel length. Ignoring the effects of the nickel particles and the ferrofluid solvent on the dynamics of the gel, this model can be used to describe the NIPA/PVA magnetic gels. This assumption is justified by qualitative analysis of the open-loop experiments, which indicate that the general two-time constant behavior of the gel is

unchanged by the ferromagnetic particles. For the purpose of control design, therefore, we assumed the transfer function in Equation (5) as the form of a model for the polymer gel.

The dynamics of both the magnetic field power amplifier and coil and also of the temperature diffusion from the seed targets to the gel were ignored in the control design, because these dynamics are both faster than the dominant gel kinetics. This approximation is valid only because of the large size and concomitant slow response of the polymer gel used in the experiments presented here. With faster gels, the thermal dynamics should not be ignored. We are working to develop models that incorporate all of the relevant dynamics for different time-scale separations. In general this can be challenging. The partial differential equations that describe the diffusion of heat into the gel, for example, can be quite complex. Fortunately, for the particular case of thermal activation through induction heating, the homogeneous dispersion of nickel flakes or the ferromagnetic particles in the ferrofluid solvent facilitate the development of lumped parameter models for the thermal system.

Control Design

Two kinds of discrete-time controllers were implemented in MATLAB and tested. A proportional controller commands a duty cycle proportional to the error:

$$d[n] = k(r[n] - x[n]). \tag{6}$$

A proportional-accumulator controller commands a duty cycle proportional to the error and an accumulated error term:

$$d[n] = k_1(r[n] - x[n]) + k_2 \sum_{i=0}^{n} r[i] - x[i]. \tag{7}$$

Stability, settling time, and tracking error can all be influenced by closed-loop control. We sought to construct a stable system with good tracking performance, or small steady-state error, in response to step inputs. Methods for identifying the coefficients of the gel model (Equation (5)) and its use in control design are discussed further by Mitwalli (1998); the discussion is beyond the scope of this paper. The parameterized structure in Equation (5) can be used along with a zero-order hold mapping (Astrom and Wittenmark, 1984) to see that the proportional and proportional-accumulator discrete-time compensators can both be configured to yield stable closed-loop systems with reasonable transient and tracking performance.

The performance of the closed-loop controllers is illustrated in Figures 11 and 12. Rising and falling step references were provided as trajectories to the closed-loop gel system. Figure 11 plots the closed-loop responses of the nickel-seeded gel. In the top portion of the figure, the higher gain proportional controller forces the gel to settle at a length that is closer to the reference signal. The proportional-accumulator controller eliminates

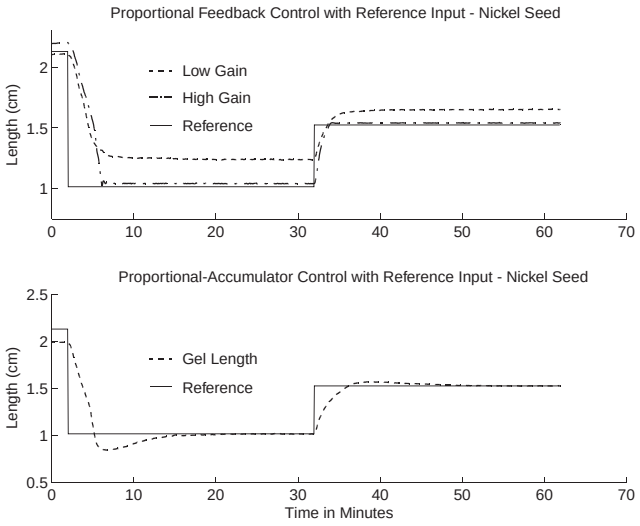


Figure 11. Closed-loop control – nickel-seeded gel.

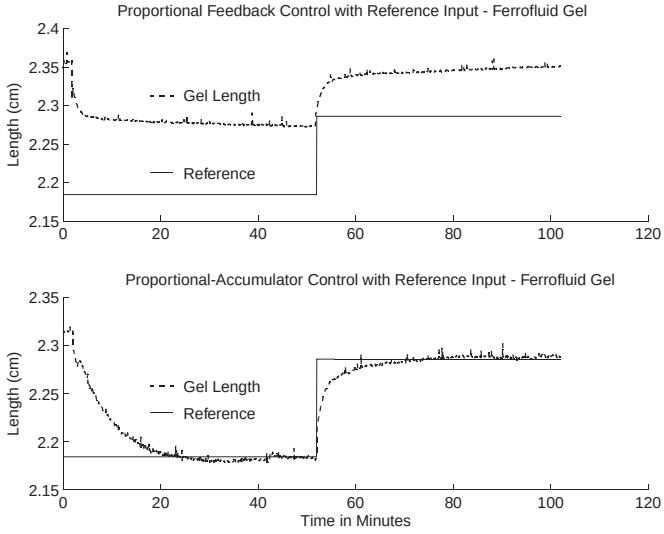


Figure 12. Closed-loop control – ferrofluid gel.

the steady-state error as the gel length settles to the value specified by the reference trajectory.

Similar experiments were carried out on the ferrofluid gels. In Figure 12, the proportional controller yields a non-zero steady-state error while the proportional-accumulator controller exhibits perfect tracking in equilibrium. Note also that the closed-loop dynamics are all different than the open-loop dynamics in Figure 7.

CONCLUSION

We have investigated two types of magnetically-triggered polymer gels. The powdered-seed gel was fabricated with nickel flakes embedded in the polymer matrix. The ferromagnetic particles in the ferrofluid gel were suspended in the gel solvent. Successful remote triggering of the volume-phase transition of both gels by application of an external alternating magnetic field was demonstrated.

In order to utilize polymer gels in mechanical applications, it is important to be able to regulate the length or volume of the gel. In some cases the length may need to follow a trajectory with predefined position and velocity as functions of time. Since the behavior of the gel varies with loading conditions, an "open-loop" scheme, which attempts to control the system using a predetermined magnetic field profile, would clearly fail in the face of this among other disturbances, including changes in ambient temperature. More robust techniques for regulating the length of the gel were developed using classical control theory and demonstrated in this paper. Closed-loop controllers using proportional and proportional-accumulator compensators were successfully implemented.

One challenge in robotics is to develop a flexible multilink manipulator that is capable of a range of motion similar to that of the human arm (Hirose and Ma, 1991; Hemami, 1985; Hirose, Kado and Umetani, 1983). The ideal actuator for this system might be an analog of the human muscle. A soft, flexible material like a gel could be shaped into an actuator with a mass distribution that enhances the dynamic behavior of the system beyond what might be achievable with lumped-mass actuators. The demonstrated ability to track desired trajectories highlights the potential utility of polymer gels as mechanical actuators.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the invaluable assistance of the MIT Physics Department Lecture Demonstrations Group for their help with constructing the experimental apparatus described in this paper. The authors also acknowledge the valuable advice and support of Dr. E. C. Lupton and Professors Markus Zahn, James Kirtley, and Marc Kastner. Steven Shaw, Dennis Evangelista, and Dahlene Fusco provided essential assistance with the experiments presented. Materials were provided by Novamet and Ferrofluidics. Test equipment for this work was made available through generous grants from the Intel Corporation, Hewlett-Packard, and Tektronix. This work was supported in part by the MRSEC Program of the National Science Foundation under Award Number DMR-9400334. Additional support was provided by MIT's Carl Richard Soderberg Career Development Chair, an NSF CAREER award, and by a New Venture Grant from AT&T.

REFERENCES

Astrom, K. and B. Wittenmark. 1984. *Computer Controlled Systems*, Englewood Cliffs, New Jersey: Prentice-Hall.

Dusek, K. 1993. *Responsive Gels*, New York: Springer-Verlag.

Haider, S., T. Cetas, J. Wait and J. Chen. 1991. "Power Absorption in Ferromagnetic Implants from Radio Frequency Magnetic Fields and the Problem of Optimization", *IEEE Trans. on Microwave Theory and Techniques*, 39(11):1817–1827.

Haus, H. and J. Melcher. 1989. *Electromagnetic Fields and Energy*. Englewood Cliffs, New Jersey: Prentice-Hall.

Hemami, A. 1985. "Studies on a Lightweight and Flexible Robot Manipulator", *Robotica*, 1:27–36.

Hirose, S. and S. Ma. 1991. "Moray Drive for Multijoint Manipulator", *Fifth International Conference on Advanced Robotics*, 1:521–526.

Hirose, S., T. Kado and Y. Umetani. 1983. "Tenser Actuated Elastic Manipulator", *Proceedings 6th IFToMM World Congress*, 2:978–981.

Hirotsu, S. and A. Onuki. 1989. "Volume Phase Transition of Gels under Uniaxial Tension", *Journal of Physical Society of Japan*, 58(5):1508–1511.

Hirotsu, S., Y. Hirokawa and T. Tanaka. 1987. "Volume-Phase Transitions of Ionized N-isopropylacrylamide Gels", *Journal of Chemical Physics*, 87(2):1392–1395.

Jackson, D., S. Leeb, A. Mitwalli, P. Narvaez, D. Fusco and E. Lupton. 1996. "Power Electronic Drives for Magnetically Triggered Phase Transition Gels", *IEEE Power Electronics Specialists Conference*, June 23-27, Baveno, Italy, pp. 302–309.

Jackson, D., S. Leeb, A. Mitwalli, P. Narvaez, D. Fusco and E. Lupton. 1997. "Power Electronic Drives for Magnetically Triggered Gels", *IEEE Transactions on Industrial Electronics*, 44(2):217–225.

Kassakian, J., M. Schlecht and G. Verghese. 1991. *Principles of Power Electronics*, Reading, Massachusetts: Addison-Wesley.

Leeb, S. et al. 1997. "Electromagnetically Triggered, Responsive Gel Based Drug Delivery Device", U.S. Patent #5,643,246, July 1, 1997.

Li, Y. and T. Tanaka. 1992. "Phase Transitions of Gels", *Annual Review of Material Science*, 22:243–277.

Linear Technology. 1990. *LTC1043 Data Sheet*, Linear Databook, pp. 11-15 – 11-30.

Mathworks. 1997. *MATLAB Student Version 5.0*, Englewood Cliffs, New Jersey: Prentice-Hall.

Matsuo, E. and T. Tanaka. 1988. "Kinetics of Discontinuous Volume-phase Transition of Gels", *Journal of Chemical Physics*, 89(3):1695–1703.

Mitwalli, A. 1998. Ph.D. Thesis anticipated January 1998, Massachusetts Institute of Technology.

Mitwalli, A., S. Leeb, T. Tanaka and U. Sinha. 1994. "Polymer Gel Actuators - Status Report", *Universities Power Engineering Conference*, Galway, Ireland, pp. 871–875.

Starodubtsev, S., A. Khokhlov and V. Vasilevskaya. 1985. "Collapse of Polyacrylamide Gels: Effect of Mechanical Deformation of the Sample and the Type of Solvent", *Akademia Nauk SSSR, Proceedings of Physical Chemistry Section 280-282*, pp. 484–486.

Tanaka, T. 1986. "Kinetics of Phase Transition in Polymer Gels", *Physica A*, 140A(1-2):261–268.

Tanaka, T. 1981. "Gels", *Scientific American*, 244(1):124–138.

Thompson, M. 1996. "Magnetically-Induced Heating Effects in Ferromagnetic Fluids", EECS Department Area Examination Report, Massachusetts Institute of Technology.