GEER HEAD

by David Geer

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Using Hot and Cold Running Water to Flex Nickel-Titanium Robot Muscles

It Sounds Simpler Than It Is

Make a Muscle!

Dr. Stephen Mascaro and his research team in the department of mechanical engineering at the University of Utah are making robot muscles, working in a vein of research called Wet Robotics. Rather than the fascinatingly technical explanation you might envision, they are simply actuating a metal that contracts in response to hot water and expands in response to cold water. But there is where the simplicity ends.

They are making artificial muscles for robots that work much the same as our muscles do. The technology uses shape memory alloys (SMAs), which are nickel-titanium alloy strands or poles with one of the rarest traits among all metals — the capacity to contract in response to heat.

SMAs

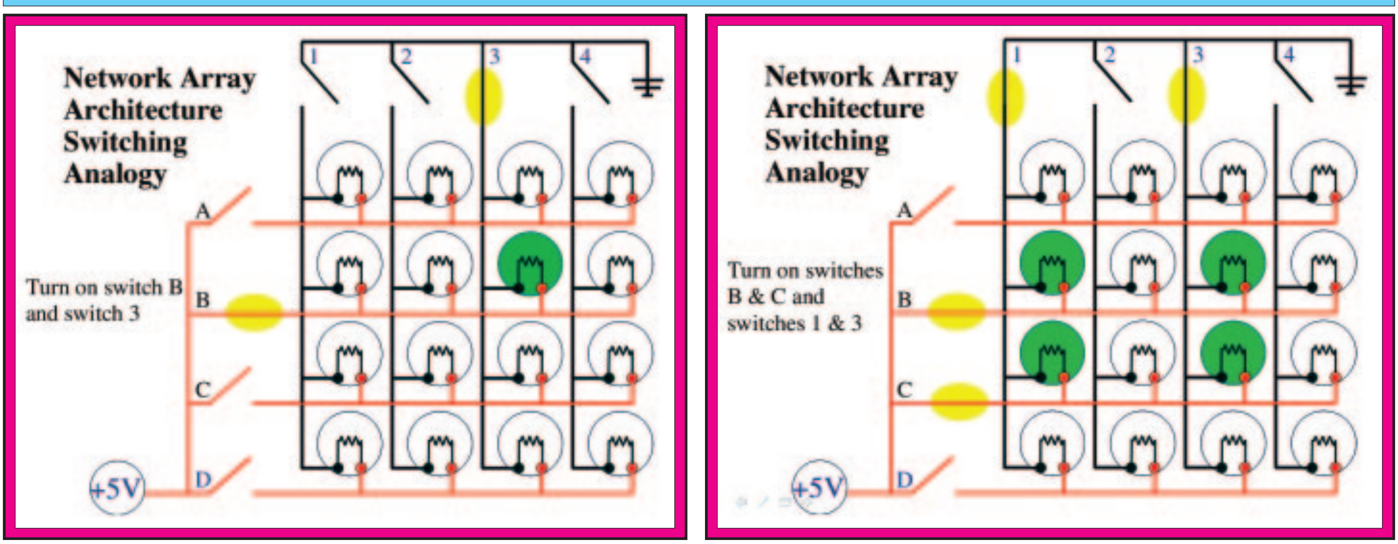
Most metals tend toward expanding in response to the application of heat. Nickel-titanium does just the opposite. "What's going on is that they [the nickel-titanium strands] are actually realigning their crystal structure when you heat them up. So, the crystals of nickel and titanium realign into a more compact orientation," says Dr. Mascaro.

Experimentation is ongoing into practical, scalable, and efficient ways to heat up and contract SMAs to make them act like muscles in order to apply them as a robot muscle technology in humanoid robots.

Some researchers (for other applications) heat SMAs by filling them with electric current. This is called Joule or Resistive heating, according to Dr. Mascaro. "You heat them up (to temperatures) above their transition (contraction) temperature. This varies depending on the concentration of nickel vs. titanium," says Dr. Mascaro.

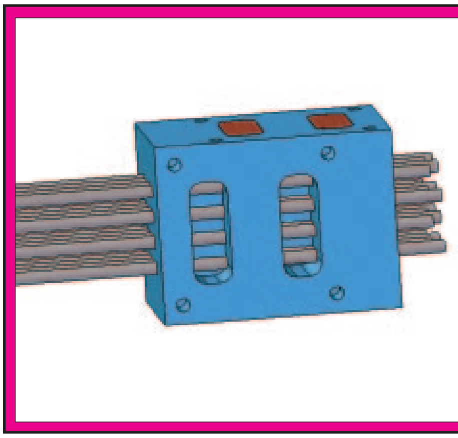
Above their transition temperature, the SMAs are in a "super elastic state" in which they are quite pliable. You can actually heat these wires up and stretch them like a rubber band.

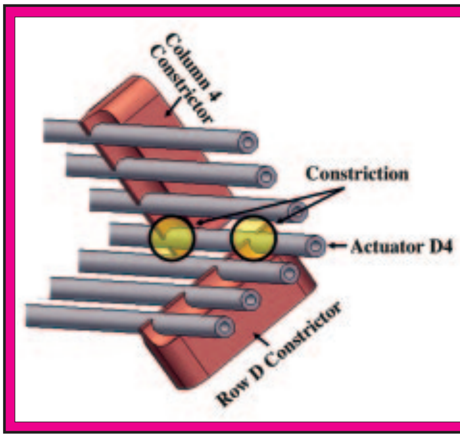
Figures 1 and 2. Demonstrates the Matrix idea of the Matrix Manifold and Valve system (MMV) whereby a particular muscle can be activated based on the column and row that it's in inside the matrix.



You can see the advantage of being able to manufacture SMAs with the balance of nickel and titanium that gives you contraction at the most desirable temperature for a given application.

Some SMAs have transition temperatures at "room temperature" so that you can "grab them" barehanded and "stretch them out" — a very unusual experience the first time around! They use these particular SMAs for dental applications, "to stretch onto the teeth to hold them in place where your dentist wants them," explains Mascaro.





Figures 3 and 4. Details the parts of the Matrix Vasoconstriction Device (MVD), including the housing and water vessel tubing and the constrictors used on the Matrix to constrict and open the flow of water.

Other SMA Properties, Limitations, and Problem Solving

As actuators [potential robot muscles], SMAs are about 1,000x as strong as human muscles for the same size muscle. They don't, however, contract as much as the human muscle. Human muscle contracts 20 percent whereas the SMAs only contract about four percent.

While you can heat up and contract SMAs as fast as you would like using electricity — fast enough to approximate human muscle contraction speeds — they don't cool down fast enough to expand with the speed of human muscle.

How do you cool these SMAs down quickly enough to solve this problem? Some researchers accomplish this by putting the SMAs in a cooling fluid. This introduces another problem: "Now you have the weight of this fluid added to your system and you've lost the original advantage of these actuators — that they are tiny, lightweight, and give you a lot of strength without having the bulk of an electric motor," says Dr. Mascaro.

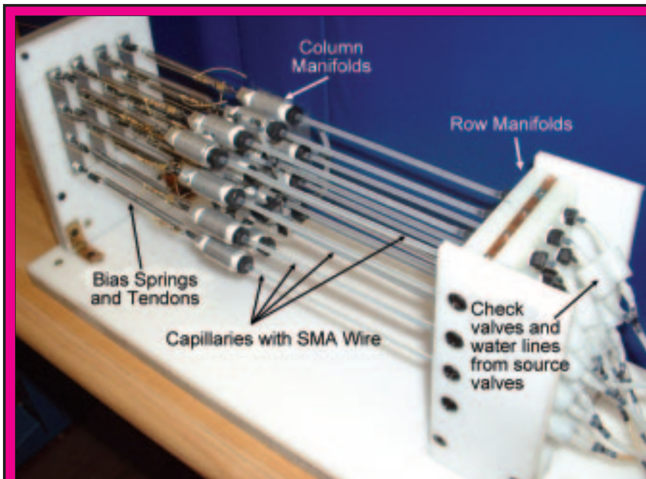
This is the problem that lead Dr. Mascaro to his idea of how to use SMAs as muscles. With Dr. Mascaro's technology, you embed the SMA wires within tubes of flowing fluid for cooling purposes. This gives your robots their own sort of blood vessels. In the human body, energy is carried to and from the muscle groups via blood vessels. With the robot muscles, you have cold fluid removing heat, and as we will discuss, hot fluid producing the artificial muscle contractions.

When you use electricity, the energy it produces is lost in the cooling fluid. Dr. Mascaro uses hot fluids, in this way the hot and cold fluids are both recycled back into hot and cold reservoirs. This produces better energy efficiency than using electricity.

Actuating in Dr. Mascaro's Array Design

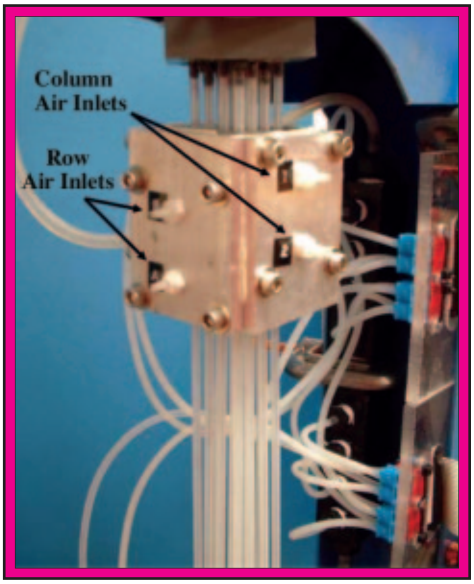
How do you put large arrays of these muscles into a compact area like a robot arm? The advantage

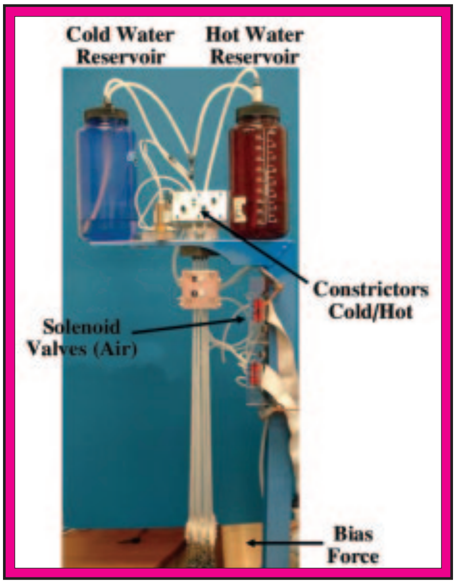
Figure 5. According to Dr. Mascaro, this figure shows the MMV prototype, which exposed new challenges in the form of fluid resistance from the solenoid valves and parasitic behaviors such that if the device tried to deliver hot water to one of the actuators, later on in the sequence the hot water might leak into one of the other actuators at a time when they didn't want to activate that muscle.



LEAKY, RESISTIVE MUSCLES

This valve-based attempt at actuating heat-responsive contracting nickel-titanium alloy metal strands for robot muscles had some issues: The hot water leaked into tubing that contracted strands the researchers didn't want to contract at the time, taking away some control of the muscles; and the valves were resistive to the water flow, costing some energy (see Figure 5).





Figures 6 and 7. Photos of the prototype MVD and the completed MVD, respectively.

maintains so long as you have a high-strength to low-weight ratio. How does this scale so that you can have, say, 100 muscles in a robot arm, and control them all without having to have 100 separate controls for each one?

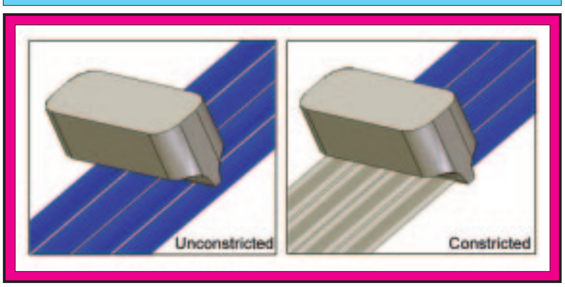
This is where Dr. Mascaro's Matrix Manifold and Valve (MMV) system comes into play. The system arranges the artificial muscles into rows and columns so that only one switch is needed for each matrix manifold and so for several muscles, as well.

In production, a robot limb that would need to extend or leverage something would have matrix manifolds with a hundred muscles in 10 x 10 arrays. The current proof of concept model has 4 x 4 arrays.

A NEW LEASE ON SMA ROBOT MUSCLE LIFE

Constricting and opening the vessels/tubing directly removed the need for valves. This removed the resistance and provided greater control over where the water flowed (see Figure 8).

Figure 8. Demonstrates the new muscle system, which constricts the vessels transporting water to the SMA muscles or "unobstructs" them, rather than using solenoid valves, which presented their own problems in the form of fluid resistance.



Manufacturing

Dr. Mascaro expects that manufacturing techniques and processes will be key in going beyond even the 10 x 10 robot muscle scenario. Connecting the actuators as an integrated array with more than 100 SMA muscles is a scalable manufacturing issue; something that can't feasibly be practical as the work of a few human scientists working by hand in the lab. Manufacturing should take the potential muscle count to hundreds at first, eventually even thousands.

A scalable manufacturing method hasn't been addressed yet, but this will be addressed in the lab, so that it can be taken to production.

Power, Force, and Speed

In the big picture, Dr. Mascaro has figured out how to make the muscles forceful while maintaining their light weight. The trick here is to make them fast while maintaining light weight, to get high-power-to-weight ratio, rather than just high-force-to-weight ratio.

Wet Robotics/Human Body Muscle Comparisons

The cardiovascular system in the human body has many functions:

1. Delivering chemical energy to the muscles.

2. Thermal regulation of the body.

"When your body gets hot during a workout, your blood starts flowing faster, so the heat is transported by your blood stream out from the core of your body to the extremities where sweating removes the heat," says Dr. Mascaro.

Controls in the body constrict and open the blood vessels to regulate your core temperature. With fluid flow in the robot muscles, temperature regulates the muscle contraction and expansion.

MMV

The MMV uses a valve on each row and column of the array. By opening the correct row and column valves in combination, you send hot or cold fluid to the correct SMA.

While the row and column arrays passed muster, the valve system had to go. The valves are standard solenoid valves and while they are common and predictable, the water has to flow through a small hole in the valve. "This introduces fluidic resistance. We can turn the flow off and on to any of the muscles, but when it's on, we don't want any resistance at all, which you can't do with solenoid valves," explains Dr. Mascaro.

Solution: Rather than putting valves in inline with the flow of fluid, why not try to constrict the vessels used to transport the fluid? Dr. Mascaro has developed a Matrix Vasoconstrictor Device (MVD) to replace the MMV. Rather than using the solenoid valves, this device constricts all the rows and columns of the vessels using air pressure, so that they can completely collapse the vessel, stopping all of the fluid flow, or open it and fluid flows without any resistance, according to Dr. Mascaro.

As you might assume, the SMA muscle apparatus and MVD constitute a fully closed system in which the same fluid is used all the time, a fluid that doesn't dissipate. "The only energy input to the total system is keeping the hot water hot, the cold water cold, and some means to pressurize the system to keep the flow moving," says Dr. Mascaro.

You Gotta Have Heart

Dr. Mascaro and crew are now working on a robotic heart to pump the fluid in and out of the SMA muscles. The same SMA muscles — which are nourished by the hot and cold fluid pumped by the heart itself — will power the robotic heart, explains Dr. Mascaro. However, this work is just in the beginning stages and does not yet appear in any of Dr. Mascaro's papers as of this writing. **SV**

RESOURCES

Stephen Mascaro's Page
www.mech.utah.edu/~smascaro/research.htm

Wet Robotics, Image 1
www.mech.utah.edu/~smascaro/video/WetSMA2Hz.mpg

Wet Robotics, Image 2
www.mech.utah.edu/~smascaro/video/vastactuators.mpg

Mascaro paper on Wet Robotics
www.mech.utah.edu/~smascaro/pdf/Mascaro-2003-IROS-Wet SMA.pdf

Mascaro paper on Wet Robotics
www.mech.utah.edu/~smascaro/pdf/Mascaro-2003-ICRA-Wet SMA.pdf

Other University of Utah Robotics
www.cs.utah.edu/research/areas/robotics/robotics.html