The magazine welcomes letters for publication in the Feedback department. Contributions should be of general interest to the control systems community. All letters should be sent to the editor, preferably by e-mail.

McKibben Actuators and Tugger Technology

We have just read the article by Bertrand Tondu and Pierre Lopez titled "Modeling and Control of McKibben Artificial Muscle Robot Actuators" in the April 2000 issue of the *CSM*. This feature article highlights aspects of a resurgence in a very promising technology.

Although this class of muscle-like actuators is truly important, this article unfortunately fails to mention certain relevant background facts. Indeed, the cover illustration and other diagrams in the article immediately reminded us of similar items from Henry Paynter's work extending over the past three decades. His work is quite familiar to us because, besides reading his papers on the subject, we have attended several of his MIT and IEEE lectures and demonstrations on what he calls "Tugger Technology." Readers can find much of the history of this on his Web site (www.hankpaynter.com) through the link "Pneumatic Tug-&-Twist Technology," which contains four published papers, much other data, and patent references. Prof. Paynter's patents are currently available at the U.S. Patent and Trademark Office (USPTO) Web site.

The authors state that since the invention of the McKibben muscle in the late 1950s, a recent interest has emerged, citing publications including Bridgestone's Rubbertuator (1984) and Soft-Arm (1987), Imega's ROMAC (1986), and others in the late 1980s and 1990s. However, notably absent is any reference to the inventions of Richard Gaylord and John Yarlott, both of whom independently pioneered the application of rubber "muscles" to industrial automation.

Prior to McKibben, Gaylord's actuator was covered by a patent originally filed in 1953, issued in 1958, and assigned to Clevite Corporation. Here Gaylord pioneered the pantograph concept, basing his design on the earlier cross-braid technique used in reinforcing high-pressure hoses, with the knowledge that hoses of this type would shrink on pressurizing unless the braid was set at a critical angle. Some two decades later, Bridgestone cited and improved upon Gaylord's by-then-expired patent, without reference to McKibben's orthotic device. In this day of recognized intellectual property rights, it is important to point out that the Rubbertuator is protected by current U.S., Japanese, and European patents, yet appears strikingly similar to that shown in Fig. 4.

On the other hand, the first commercially produced Tugger was Yarlott's Ampflex, introduced in 1970 under patents applied for in 1969 and issued in 1972 (United States) and 1975 (Japan). Yarlott conceived the device explicitly as an "artificial muscle," having been led to his bladder-fold design following an earlier research assignment at United Technologies to explore the behavior of living antagonistic muscle pairs. Paynter was then inspired by Yarlott's actuators to invent unique multi-Tugger-driven, patented air motors sold through his Dynacycle Corporation. After acquiring Yarlott's Trish Energetics as a subsidiary of Dynacycle, Paynter improved upon the Ampflex with the later Dynaflex and Dynax actuators. These were designed so as to be able to operate the motors and other devices at shop air pressures of 6-8 bar. It is also important to emphasize that motor operating efficiencies and speeds exceeding 4000 rpm required accurate determination of both static and dynamic characteristics, as well as assured actuator life.

Although much of the above story is now told at Paynter's Web site, we believe that Prof. Paynter has made significant contributions to the field of Tuggers and Twistors over the last three decades. His contributions include publications, patents, and products manufactured by his company.

—Kamal Youcef-Toumi
—Dave Gossard
—Dave Hardt
—Neville Hogan
Cambridge, MA, U.S.A.

—Mark Nagurka
Milwaukee, WI, U.S.A.
25 April 2000

Author's Reply

Research into new actuators for robotic applications has brought to light the very promising technology of braided pneumatic artificial muscles. As both the comments above and our article indicate, this artificial muscle technology has undoubtedly been inspired by the technology of tire textile carcasses.

J.L. McKibben is generally acknowledged as being the first to have applied braided pneumatic artificial muscles for assistance to the disabled—both in the popular press (see [1] of our article) and in specialized journals (see [3] and [4] in our article). An increasing number of robotics researchers have since employed the term "McKibben artificial muscle" as a scientific term for this type of braided pneumatic artificial muscles; see, in particular, the work of the Washington University biorobotics team managed by Blake Hannaford ([26] of our article and their Web site: http://rcs.ee.washington.edu/BRL/).

Furthermore, several reports and articles from the 1960s indicate that J.L. McKibben is the inventor of the braided pneumatic artificial muscle based on the pantograph concept; see, for example, the basic McKibben muscle modeling article by H.F. Schulte published by the American Academy of Sciences in 1961 ([2] of our article). We also can quote the two following reports, not mentioned in our article, in which the terms "McKibben artificial muscle" and "braided pneumatic actuator" are given as synonymous:

- G. Paskusz, G. Gwynne, and J. Lyman, "Braided Pneumatic Actuators: Preliminary Analysis and Some Test Results," Biotechnology Laboratory, Technical Note No. 16, Department of Engineering, University of California, Los Angeles, August 1960;
- G. Paskusz and G. Gwynne, "Braided Pneumatic Actuators: Dynamic Test Results and Extension of Previous Analysis," Biotechnology Laboratory, Technical Note No. 19, Department of Engineering, University of California, Los Angeles, July 1961.

The origin of the McKibben muscle retains a certain mystery, however, because J.L. McKibben, to our knowledge, has never published any article describing his artificial muscle. The actual robotics studies concerning the McKibben artificial muscle, essentially aimed at controlling these highly nonlinear actuators, have not addressed the question of its origin. Consequently, I can well understand the commentators' indignation. However, I want to emphasize that, in a 1990 article titled "Actuator Properties and Movement Control: Biological and Technological Models," published in *Multiple Muscle Systems: Biomechanics and Movement Organization* (J.M. Winters and S.L.-Y. Woo, Eds., Springer Verlag), Blake Hannaford and J.M. Winters report that the braided pneumatic artificial muscle was patented for the first time by A.H. Morin in France in 1947, then in the United States in 1953 (Elastic Diaphragm, U.S. patent 2,642,091). In this relative confusion, Prof. Paynter's expert opinion could help us all better understand the origins of braided artificial muscles.

—**Bertrand Tondu**
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A Simple Test for Pole Placement Implementation in the MATLAB Control Toolbox

A nice point made by Mäkilä (*CSM,* Dec. 1999, p. 84) is that "there is nothing as practical as a good theory," because using prior knowledge from theory is always a wise thing to do. In his example, by simply using the fact that the absolute value of the sine function of any angle is less than one, you can quickly realize that an earlier version of the sine function implemented in MATLAB gave incorrect results for very large angles. This correspondence presents another example, a simple test for the implementation of robust pole assignment using `place` in the MATLAB Toolbox. The test problem is given by Dickman ("On the Robustness of Multivariable Linear Feedback Systems in State Space Representation," *IEEE Transactions on Automatic Control,* vol. 32, pp. 407-410, 1987), where the system is described by a controllable couple *(A, B),* with

$$A=\begin{bmatrix}-5 & 1 & 0\\ 0 & 0 & 1\\ 1 & 1 & 1\end{bmatrix},\quad B=\begin{bmatrix}0 & 0\\ 0 & 1\\ 1 & 1\end{bmatrix}.$$

We know that for *any* given self-conjugate eigenvalue set $\{\lambda_1, \lambda_2, \lambda_3\}$, we can assign the closed-loop eigenvalues of the system to this set. Unfortunately, using `place`, we fail to assign the eigenvalue set $(-1+i, -1-i)$ for this system, where i is sqrt (-1), with an error message "Can't place eigenvalues there." (Actually, one can find more eigenvalue sets that are not assignable by using `place`.) Clearly, the error message contradicts some well-known prior knowledge. We have developed a better algorithm/implementation (see A.L. Tits and Y. Yang, "Globally Convergent Algorithms for Robust Pole Assignment by State Feedback," *IEEE Transactions on Automatic Control,* vol. 41, pp. 1432-1452, 1996). This implementation, `robpole`, also uses MATLAB. Using `robpole`, we successfully assign the prescribed eigenvalues with the following feedback matrix

$$K=\begin{bmatrix}-16 & 4 & 1\\ 17 & -3 & 1\end{bmatrix}.$$

In addition, `robpole` is more efficient in many tested problems; it usually finds more robust feedback, and it is guaranteed to be globally convergent in some sense (a good theoretical result for control engineering practice). This MATLAB code can be obtained from its authors (see reference above).

—**Yaguang Yang**
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