THE PERFORMANCE OF A NEW TYPE OF PNEUMATIC MOTOR

Marco Aurelio Bossetto
DPM – FEM – UNICAMP – Cx. Postal 6122 – CEP 13083-970 – Campinas – SP – Brazil
marcoboss@fem.unicamp.br
URobotics Lab – School of Medicine – Johns Hopkins University – Baltimore – MD – USA.
marco@urology.jhu.edu

Doru Petrisor
URobotics Lab – Johns Hopkins University – Baltimore – MD – USA.
dpetris1@jhmi.edu

Dan Stoianovici
URobotics Lab – Johns Hopkins University – Baltimore – MD – USA.
dss@jhu.edu

Joao Mauricio Rosario
DPM – FEM – UNICAMP – Cx. Postal 6122 – CEP 13083-970 – Campinas – SP – Brazil
rosario@fem.unicamp.br

Abstract. *This paper presents the experimental results for the performance of a new type of pneumatic motor, the first pneumatic step motor (PneuStep). The motor was designed to be compatible with magnetic resonance medical imaging equipment (MRI) for actuating an image-guided intervention robot for medical applications. For this reason the motors were entirely made of nonmagnetic and dielectric materials. PneuStep is readily applicable to other pneumatic or hydraulic precision motion applications. Experimental results present the stall speed, torque capability, and air consumption of the motor as a function of the pneumatic hoses size (length and bore), and the pressure of the air supply. Stepping accuracy is also evaluated (error and hysteresis curves) to show that, similar to electric steppers, the position errors are non-cumulative. Experiments evaluating the time response of the pneumatic actuation system are included as well. Results show that the new motor can be efficiently and safely used for a class of slow but precise applications, including surgical robots.*

Keywords*: step motor, pneumatic motor, medical robot, MRI compatible.*

1. INTRODUCTION

Pneumatic actuation is commonly used in industrial and commercial applications for its low cost, compact size, high power-to-weight ratio, reliability, and low maintenance. In many cases these characteristics make it preferable over electric actuation, especially when a supply of air is readily available. The major limitation of classic pneumatic actuators, rotary or linear, has been their reduced precision in controlled motion (Choi et al, 2005). This is mainly caused by air compressibility and friction in the valve (Hagglund, 2002) and actuator which make the pump-line-actuator dynamic system highly nonlinear. Novel hardware (Bendov and Salcudean, 1995 and Butefisch et al, 2002) and pneumatic-servo control (van Varseveld and Bone, 1997 and Shen et al, 2000) solutions have been proposed to deal with these problems and impressive results have been achieved in force control (Richer and Hurmuzlu, 2000a and Richer and Hurmuzlu, 2000b) and speed regulation (Renn and Liao, 2004). Nevertheless, these complex solutions require special care so that most practical applications are still limited to unregulated pneumatic motion.

A new type of pneumatic motor has been developed, PneuStep, the first pneumatic step motor (Stoianovici, 2007a/b). We have also reported several other versions of hydraulic stepper motors (Stoianovici, 2005). One of those versions, the “Harmonic Motor” is somewhat similar to an earlier pneumatic motor reportedly applied to an industrial paper mill machine in the 1980’s (Cissell et al, 1991). Harmonic motors (Stoianovici and Kavoussi, 2006) use fluid power to deform the flex spline of a harmonic drive in place of the common mechanic wave generator. Another version that we previously reported, the “Planetary Motor” (Stoianovici, 2007c), is the latest precursor of the PneuStep design presented here.

This development was performed for medical applications, under a project for creating a robot that can precisely operate within the closed bore of high intensity magnetic resonance imaging (MRI) equipment. This allows for performing remote procedures within the scanner under MRI guidance. The diagnostic and therapy potential of the system is very significant because the MRI is the preferred method for imaging soft tissues and the addition of the robot could provide precise navigation of instruments based on the digital image. This could allow, for example, insertion of a needle precisely at the center of a small tumor visualized in the image for performing a tumor-centered biopsy. Today biopsy procedures are typically performed with randomized sampling techniques. The use of the robot could reduce the incidence of false-negative sampling. A robot actuated with PneuStep motors has been completed and is now under evaluation.

Creating MRI robotics is a very challenging engineering task. MRI scanners use magnetic fields of very high density (up to several Tesla) with pulsed magnetic and radio frequency fields. Creating passive instrumentation for MRI interventions involves careful material selection with nonmagnetic and preferably dielectric properties (Stoianovici, 2005). In the case of active instrumentation, ensuring MRI compatibility is a much more difficult task because it should not interfere with the functionality of the imager.

The electromagnetic motors typically used in robotics are incompatible by principle with the MRI scanners. Robotic research in the field has unanimously utilized ultrasonic (piezoelectric) motors (Masamune et al, 1995 and Louw et al, 2004). These are magnetic free but still present conductive components and use electricity creating image isocenter (Hempel et al, 2003). Pneumatic actuation is a fundamentally flawless alternative for MRI compatibility. Pneumatics has been used in handheld drill-like instrumentation (Neuerburg et al, 1998) and tested in robotic end-effector designs (Hempel et al, 2003), but could not yet be involved in precisely controlled motion.

All our PneuStep prototypes are fully MRI compatible (MRI translucent, safe, and precise), being constructed of nonmagnetic and dielectric material like Delrin, Nylon, Ceramic and Rubber, using air pressure for motion, and light for fiber optic encoding. In other applications the motor could be constructed of metallic components for increased mechanical performance and durability and may potentially be operated hydraulically for higher torque / size ratios.

2. THE MOTOR

The PneuStep invention is based on the simple remark that end-to-end motion of a piston within its cylinder is always exact. This can be achieved by simply pressurizing the cylinder which is much easier than positioning the piston in mid-stroke with pneumatic-servo control. The step motor is designed to successively collect small end-to-end motion strokes in a rotary motion. A step is made by an end-of-stroke motion.

A new kinematic principle (Stoianovici et al, 2007) is used to induce the step motion and demultiply it (gear it down) in the same mechanism. The basic motor is rotary, but the integrated gearhead can be configured for either rotary or linear output of various step sizes.

Two prototype motor sizes were constructed with overall dimensions of 70 x 20 x 25mm and a larger one, Fig. 1, with 85 x 30 x 30mm outside diameter, bore, and width, respectively. The large model has a step size of 3.33° angular and 0.055 mm linear when a built in screw is used on the rotary output of the motor.

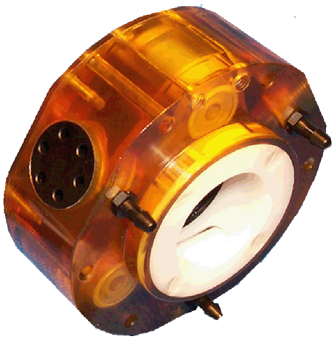


Figure 1 - PneuStep motor

3. CONTROL

A pneumatic distributor was constructed using three electric valves mounted on a manifold. The valves are normally closed, 3-way, 2-position direct-acting solenoid valves. A special electronic driver is used to control the new motor with electric stepper indexers and standard motion control cards. The driver directionally cycles the activation of the valves in the desired 6-step sequence, as controlled by the step and direction signals of the indexer. Among three valves tested, we found the fast-acting valve NVKF334V-5D by SMC Corp. to be best performing for our application, in terms of a well balanced response time/air flow capacity. This is a 24VDC, 4.3W valve with 0.2CV. The max cycling frequency is not rated, but the valve experimentally outperformed valves rated 50 cycles/sec and is very reliable.

Optical encoding was added to the motor to monitor or control its motion. For compatibility with the MRI environment we used fiber optic encoding so that all electric components are remotely located, keeping the motor electricity free. For simplicity, the existing hoop-gear part of the motor is also used for encoding in place of a traditional encoder wheel. Two fiber optic circuits are set so that in its motion the hoop-gear cyclically interrupts their beams generating quadrature encoded signals. The ends of the fibers are connected to two D10 Expert fiber optic sensors by Banner Engineering Corp., one for each fiber optic circuit. The digital output of these sensors is connected to the A and B encoder channels of a motion control card. The output shaft of the motor was connected to a dynamic torque measurement stand.

The motor accepts open-loop step operation as well as closed-loop control with position feedback from the enclosed sensor. A special control feature is implemented to adapt classic control algorithms to the new motor and is experimentally validated.

4. EXPERIMENTS

The test stand, Fig. 2, is composed by flow meters, pressure supply, driver optic sensor, PC, MCC, data acquisition and control, motor and dynamic torque generator and meter. The motor was connected to the distributor with 1/8" = 3.175mm or 1/16" = 1.587mm ID hoses. Experiments were performed with both hoses and electronic distributors for generating the commutation waves at various pressures. Figures 3 and 4 show the graphs of the speed vs. pressure and air consumption vs. speed, respectively, using 7m long hoses.

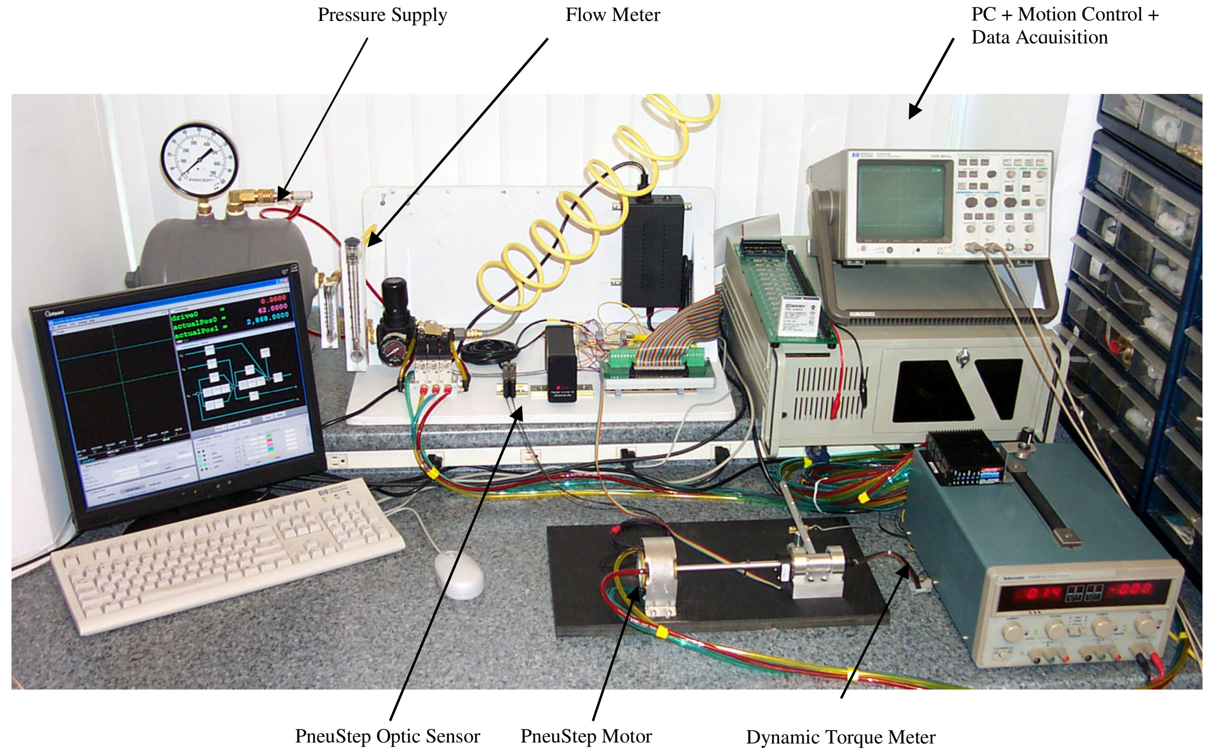
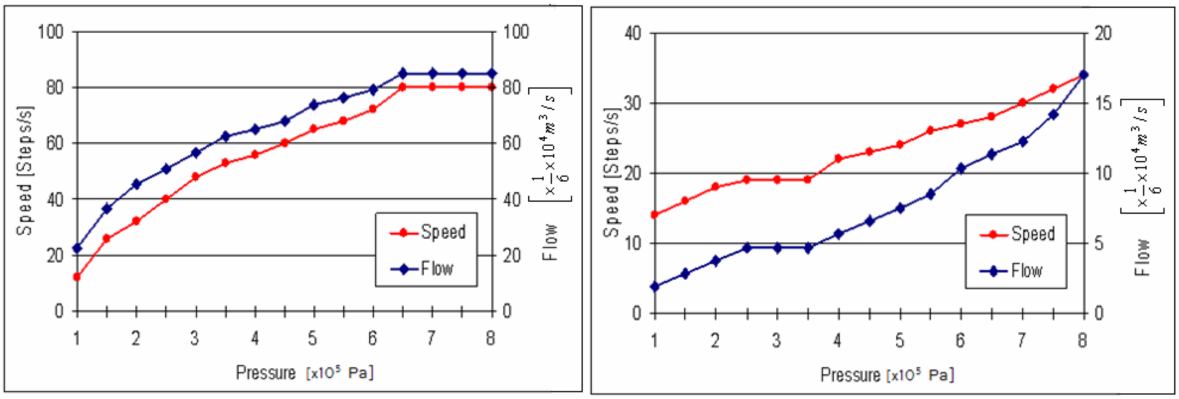


Figure 2 - Test stand



(a)

(b)

Figure 3 – Speed and Air Flow vs. Pressure – (a) 1/8" ID Hose and (b) 1/16" ID Hose

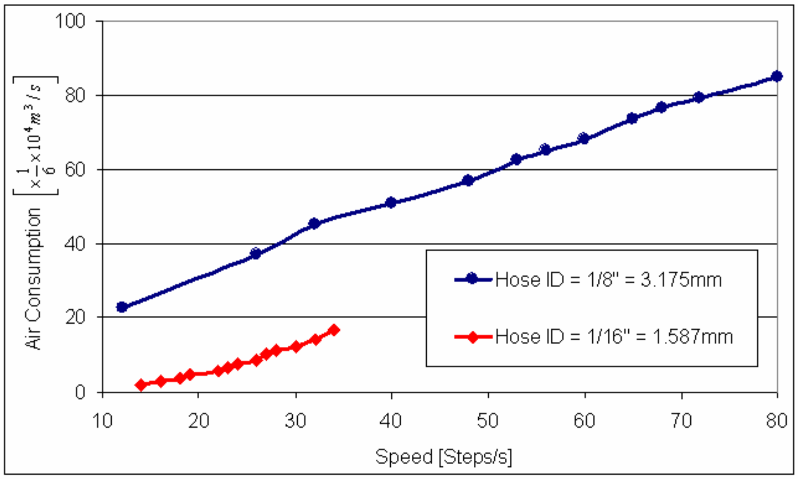


Figure 4 – Air Consumption vs. Speed for two hose sizes

The diagram, Fig. 5, depicts the air consumption vs. speed graphs with electronic distributors for various pressure levels when using 7m long hoses and 1/8” ID.

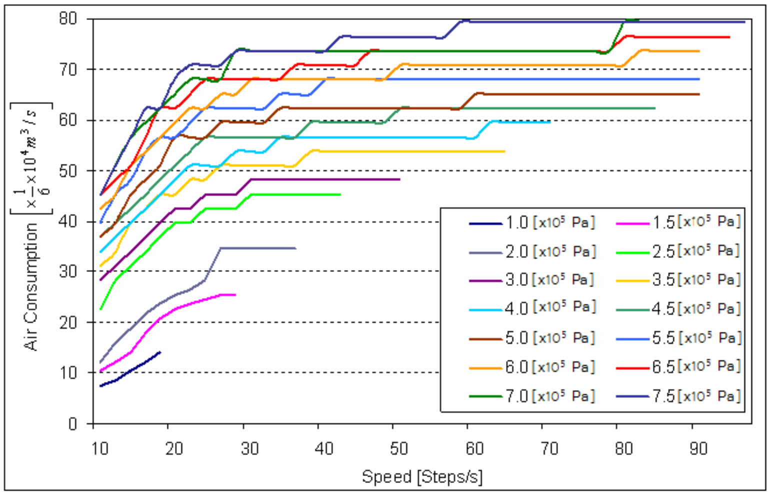


Figure 5 – Air Consumption vs. Speed at various levels of the supply pressure

Unlike servo motors, steppers may only achieve discrete positions. However, one of their advantages is that their position errors are non-cumulative. Stepping is like walking on tiles. Place the foot anywhere within a tile but not over the border line. In this case, when taking *n* steps the foot is always on the *n*th tile. As such, stepping precision refers to how precise the foot is centered within the *n*th tile, and does not accumulated with each step.

Experiments were performed to asses the stepping errors of PneuStep, as the difference between the actual and command motor positions over a large number of steps. The hysteresis error reflects the stepping error when taking the same steps in opposite directions of motion. The motor was commanded to slowly move, step by step for a full rotation (108 steps). The actual position of the output shaft was recorded at each step with a high count encoder connected to the output shaft. The resulting hysteresis error graphs, Fig. 6, show the stepping errors of the motor at different pressure levels, in a forward and backwards cycle.

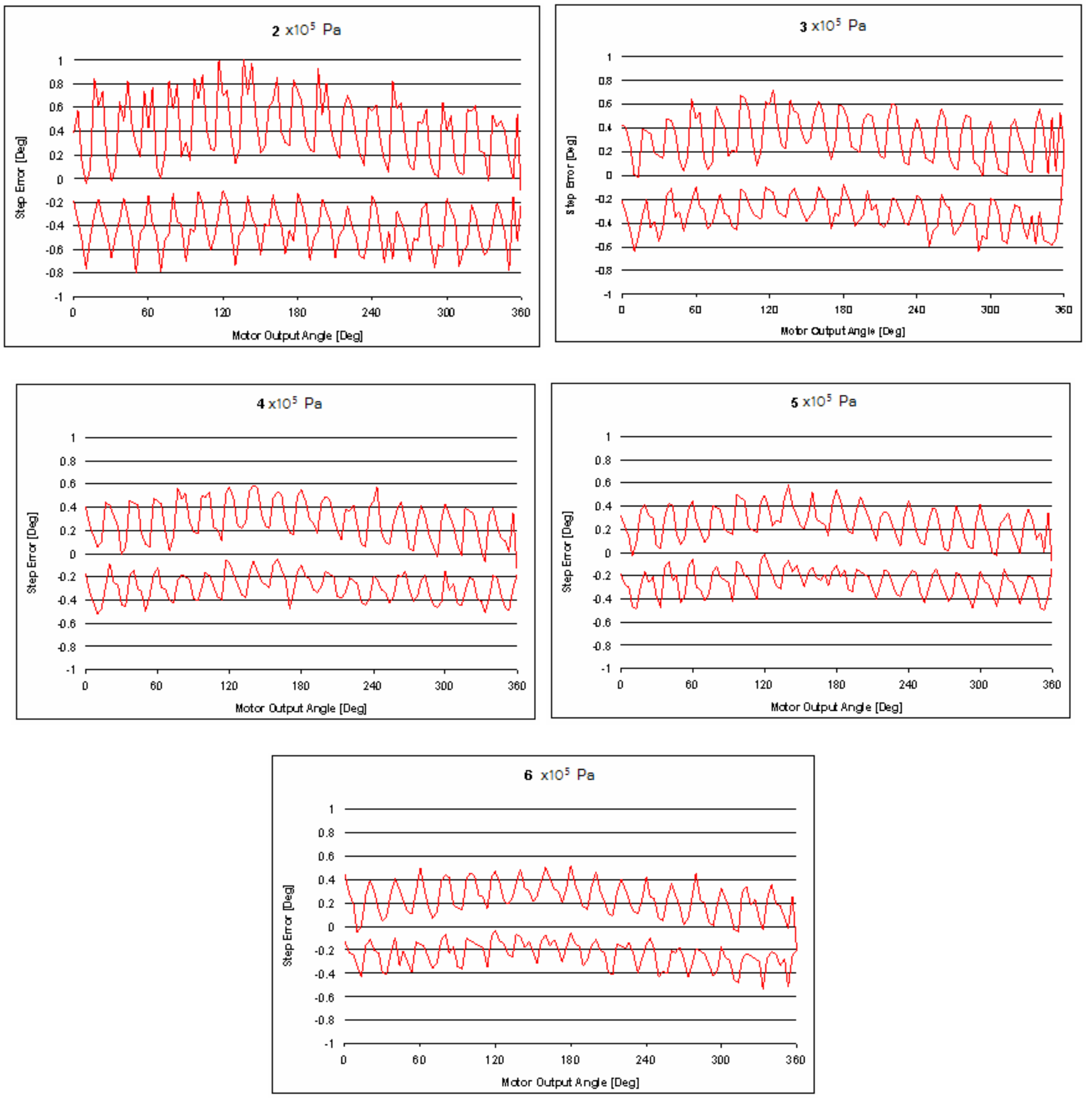


Figure 6 – Non-cumulative step errors

The graphs show that the errors are as high as 1° for low pressure levels, but diminish with the level of the pressure supply. The graph, Fig. 7, collects the results of the previous graphs to show the dependency of the stepping error on pressure. The average step errors and standard deviations are given at various pressure levels. At $6\times10^5\ Pa$ for example the motor step is 3.333° ± 0.24° with 0.20° standard deviation.

The same motor was used in all experiments and no repairs were needed. A comprehensive durability study was not performed, but during testing the motor was deemed reliable.

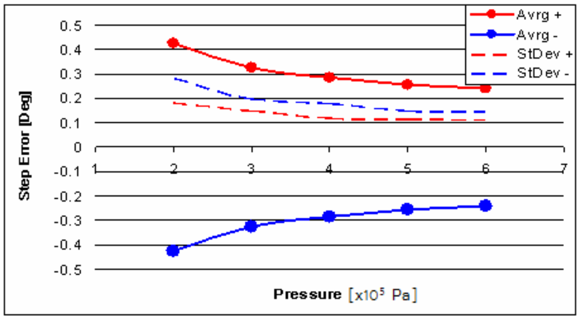


Figure 7 – Average Stepping Error as a function of the Air Pressure Supply

5. MRI COMPATIBLE ROBOT APPLICATION

Six PneuStep motors were used to actuate the first fully MRI compatible robot, Fig. 8, (Stoianovici et al, 2007a). Previously reported MRI robots had limited compatibility (Masamune et al, 2003 and Hempel et al, 2003), mainly due to their piezoelectric actuation. The robot was designed for performing transperineal percutaneous needle access of the prostate gland under direct MRI guidance. Its first application is for prostate brachytherapy (Muntener et al, 2006). The robot is positioned alongside the patient on the MRI table, as shown in Fig. 8. PneuStep performance matches the requirements of the clinical application for low speed (< 20 mm/sec), high accuracy (< 0.5 mm), and most importantly safety. The stepper is safer than servo-pneumatic actuation because in case of malfunction, it may only stall. Breaking a PneuStep hose, for example, may not unwind the mechanism potentially harming the patient.

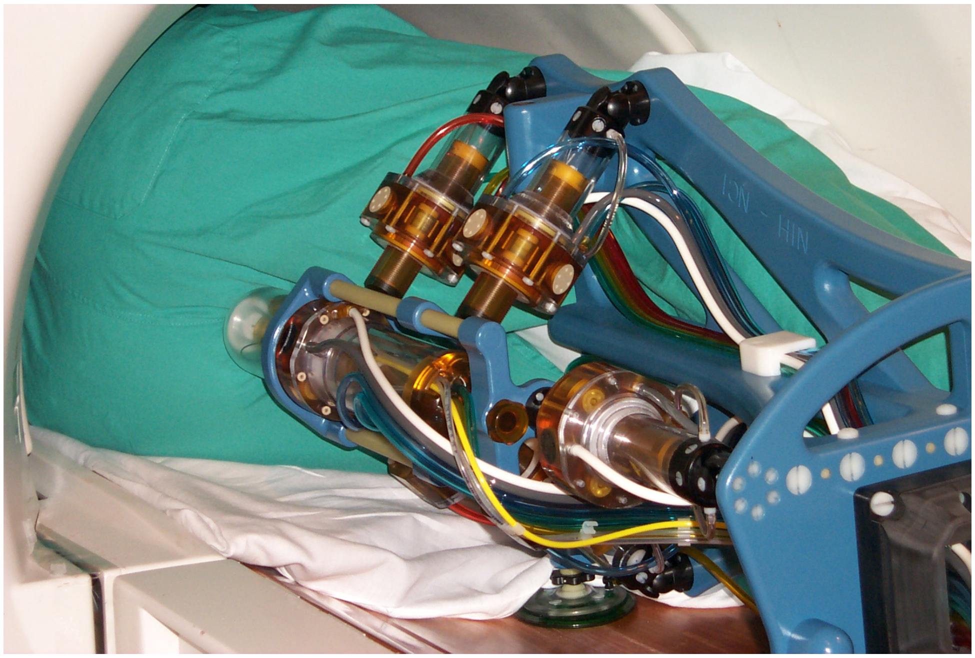


Figure 8 – MRI compatible robot with 6 PneuStep motors, MrBot

The robot is controlled from a remotely located cabinet through 7m hoses carrying air and fiber optics. The robot is entirely nonmagnetic and dielectric. Imager compatibility tests performed showed that the robot is unperceivable in MRI and does not interfere with the functionality of the imager, in motion or at rest. In fact the robot is multi-imager compatible because it is compatible with all other types of medical imaging equipment (MRI gives the most stringent constrains). Motion tests (Stoianovici et al, 2005a) showed the mean value of the robot's positioning repeatability to be 0.076mm with a standard deviation of 0.035 mm, which is highly adequate for a "plastic" construction. The PneuStep motor was also tested in a 7 Tesla MRI scanner (typical scanners go up to 3T), and no problems were encountered in its operation.

6. CONCLUSION

This paper reported several experimental results for the performance of the first pneumatic step motor (PneuStep). The main advantage of this motor is the simplicity of control in precise motion. The motor takes the same number of steps independent of the air pressure supply. A small error may appear in taking each step, but this does not add from one step to the other. Resonance was never detected in the experiments, but this could possibly occur with inertial loads as for all step motors. The air consumption of the motor may be reduced by using smaller cross section hoses; however, this is done in lieu of the maximum speed that the motor could achieve. The experiments also showed good reliability of the motor during extensive testing.

The main advantage of the PneuStep motor is that it can achieve easily controllable pneumatic motion. Unlike servo-controlled pneumatics which requires a very delicate pressure balance for driving the motor and complicated control algorithms to deal with the nonlinearities of the air-actuator-valve system, the PneuStep takes the same number of steps independent of the pressure levels by simply commutating some valves. This allows for applying pneumatics to precise motion.

ACKNOWLEDGEMENTS

M.B. author's work on this project was sponsored by the Brazilian Committee for Postgraduate Courses in Higher Education (CAPES) scholarship. The development of the PneuStep motor was supported by the National Cancer Institute (NCI) of the National Institutes of Health under Grant CA88232. Preclinical tests of the robot were sponsored by the Prostate Cancer Foundation (PCF) and the Patrick C. Walsh Foundation (PCW). The tests of the motor were sponsored by the Johns Hopkins Alliance for Science and Technology (TOP). The contents are solely the responsibility of the authors and do not necessarily represent the official views of the CAPES, NCI, PCF, PCW, or the TOP.

REFERENCES

Bendov, D. and Salcudean, S.E., 1995, "A Force-Controlled Pneumatic Actuator". IEEE Transactions on Robotics and Automation, vol. 11, pp. 906-911.

Butefisch, S., Seidemann, V. and Buttgenbach, S., 2002, "Novel micropneumatic actuator for MEMS". Sensor and Actuators a Physical, vol. 97-8, pp. 638-645.

Choi, H.S., Han, C.S., Lee, K.Y. and Lee, S.H., 2005, "Development of hybrid robot for construction works with pneumatic actuator". Automation in Construction, vol. 14, pp. 452-459.

Cissell, T., Doerschuk, D., Koester, K. and Reed, G., 1991, "Pneumatic Stepper Motor Actuator". USA Patent 5,060,539. ABB Process Automation Inc., Columbus, Ohio.

Hagglund, T., 2002, "A friction compensator for pneumatic control valves". Journal of Process Control, vol. 12, pp. 897-904.

Hempel, E., Fischer, H., Gumb, L., Hohn, T., Krause, H., Voges, U., Breitwieser, B., Gutmann, B., Durke, J., Bock, M., and Melzer, A., 2003, "An MRI-compatible surgical robot for precise radiological interventions", Comput Aided Surg, vol. 8, pp. 180-91.

Louw, D.F., Fielding, T., McBeth, P.B., Gregoris, D., Newhook, P. and Sutherland, G.R., 2004, "Surgical robotics: a review and neurosurgical prototype development". Neurosurgery, vol. 54, pp. 525-36; discussion 536-7.

Masamune, K., Kobayashi, E., Masutani, Y., Suzuki, M., Dohi, T., Iseki, H. And Takahura, K., 1995, "Development of an MRI-compatible needle insertion manipulation for stereotactic neurosurgery". J Image Guid Surg, vol. 1, pp. 242-8.

Muntener M, Patriciu A, Petrisor D, Mazilu D, Kavoussi L, Cleary K, Stoianovici D., 2006, "Magnetic Resonance Imaging Compatible Robotic System for Fully Automated Brachytherapy Seed Placement". Urology. Vol.68 (6) pp.1313-1317. http://urology.jhu.edu/urobotics/pub/2006-muntener-urology.pdf

Neuerburg, J., Adam, G., Bucker, A., Zilkens, K.W., Schmitz-Rode, T., Katterbach, F.J., Klosterhalfen, B., Rasmussen, E., van Vaals, J.J. and Gunther, R.W., 1998, "MR-guided bone biopsy performed with a new coaxial drill system". Rofo-Fortschr Rontg, vol. 169, pp. 515-520.

Renn, J.C. and Liao, C.M., 2004, "A study on the speed control performance of a servo-pneumatic motor and the application to pneumatic tools". International Journal of Advanced Manufacturing Technology, vol. 23, pp. 572-576.

Richer, E. and Hurmuzlu, Y., 2000a, "A high performance pneumatic force actuator system: Part I – Nonlinear mathematical model". Journal of Dynamic Systems Measurement and Control-Transactions of the ASME, vol. 122, pp.416-425.

Richer, E. and Hurmuzlu, Y., 2000b, "A high performance pneumatic force actuator system: Part II – Nonlinear control design". Journal of Dynamic Systems Measurement and Control-Transactions of the ASME, vol. 122, pp.426-434.

Shen, T.L., Tamura, K., Kaminaga, H., Henmi, N. and Nakazawa T., 2000, "Robust nonlinear control of parametric uncertain systems with unknown friction and its application to a pneumatic control valve". Journal of Dynamic Systems Measurement and Control-Transactions of the ASME, vol. 122, pp. 257-262.

Stoianovici D., 15 January 2005, "Multi-Imager Compatible Actuation Principles in Surgical Robotics". International Journal of Medical Robotics and Computer Assisted Surgery. Vol.1(2) pp.86-100. http://urology.jhu.edu/urobotics/pub/2005-stoianovici-MRCASJ.pdf.

Stoianovici D, Patriciu A, Mazilu D, Petrisor D, Kavoussi L., Feb 2007, "A New Type of Motor: Pneumatic Step Motor". IEEE/ASME Transactions on Mechatronics. Vol.12(1) pp.98-106. http://urology.jhu.edu/urobotics/pub/2007-stoianovici-tmech.pdf

Stoianovici D, Kavoussi L., Aug 8, 2006, "Planetary - Harmonic Motor". USA Patent 7,086,309 (DM-1736). http://urology.jhu.edu/urobotics/pub/2007-stoianovici-uspto-07086309.pdf

Stoianovici D, Kavoussi L., Feb 15, 2007, "Planetary Motor". USA Patent App. 20070034047 (DM-4783). http://urology.jhu.edu/urobotics/pub/2007-stoianovici-uspto-0034047.pdf

Stoianovici D, Patriciu A, Mazilu D, Petrisor D, Kavoussi L., Feb 15, 2007, "Pneumatic Stepper Motor". USA Patent App. 20070034046 (DM-4783). http://urology.jhu.edu/urobotics/pub/2007-stoianovici-uspto-0034046.pdf

van Varseveld, R.B. and Bone, G.M., 1997, "Accurate position control of a pneumatic actuator using on/off solenoid valves". IEEE-ASME Transactions on Mechatronics, vol. 2, pp. 195-204.