Controlling an MR Safe Robot Arm with Six Pneumatic Stepper Motors using Eight Tubes

Vincent Groenhuis[1], Matthias Bac[1], Stefano Stramigioli[1] and Kenan Niu[1]

I. Introduction

Magnetic resonance imaging (MRI)-guided interventions are difficult to perform by hand and may benefit from robotic assistance [1]. The MRI safety requirement excludes the use of electromagnetic motors; a suitable alternative is utilizing pneumatic stepper motors as these can be fabricated from plastic materials and do not use electricity. One such motor is typically actuated by three to six pneumatic tubes; a design with two double-acting cylinders generally uses four tubes [2]. Conventionally, the total number of tubes is $4n$ with n the number of joints. The total bundle of tubes takes up significant volume and mass, possibly interfering with the medical procedure, restricting range of motion and/or adding parasitic stiffness to joints [3].

The aim of this research is to control a six degrees of freedom (DOF) MR safe robot arm using only eight tubes. In the results, we show that $2k$ tubes can actuate $n = \binom{k}{2}$ joints in such a way that each joint can still be operated to its setpoint position with a deviation of at most one step.

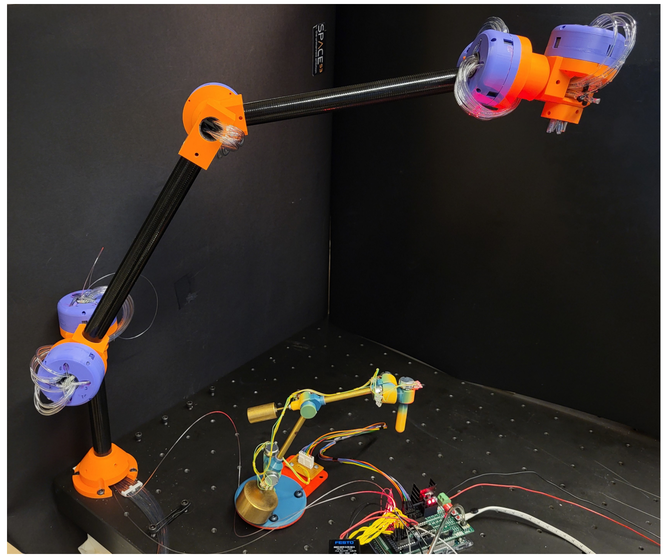

Fig. 1. Robot arm (top) and controller (bottom)

II. Materials and Methods

A robot arm is actuated by six identical pneumatic stepper motors with strain wave gear reductions. A hand-operated input device with the same kinematic configuration as the robot arm but at a smaller scale is used as an input device defining the setpoint joint vector for the robot arm.

A. Design of pneumatic stepper motor

One stepper motor houses two cylinders with pistons in cross-configuration [2], a 14-tooth hoop gear with 13-tooth cycloid gear and a compact strain wave gear with a transmission ratio of 33:1. The motor housing with cap and output flange (all $\varnothing 64\,\mathrm{mm}$) are printed in polylactic acid (PLA) while moving motor parts are printed in polycarbonate (PC). Acrylic rods are used for the roller bearings. Figure 2 shows an exploded view of the motor. Six identical actuators are connected by $\varnothing 23\,\mathrm{mm}$ fibreglass tubes of different lengths.

The ungeared motor step size is $\frac{360}{4 \cdot 13} = 6.92°$. With the strain wave gear, the step size is reduced to $\frac{360}{4 \cdot 13 \cdot 33} = 0.210°$. The cylinder bore size is $25 \cdot 15\mathrm{mm}^2 = 375\,\mathrm{mm}^2$ and the stroke distance is $2.86\,\mathrm{mm}$.

B. Sharing tubes among multiple motors

The six pneumatic stepper motors, numbered $J_1..J_6$, are connected to eight pneumatic tubes, labeled $A..H$. A cylinder is represented by the labels of the connected tubes, e.g. AC. The six motors $J_1, J_2, J_3, J_4, J_5, J_6$ are respectively driven by cylinders $(AC, BD), (EG, FH), (AE, BF), (CG, DH), (CE, DF), (AG, BH)$. The cylinder pressurization state is indicated by an overline, e.g. $AC = \overline{10}$ pressurizes chamber A and depressurizes chamber C, setting the piston state of AC to "down", while pressurization state $AC = \overline{01}$ changes the piston state to "up". Pressurization state $AC = \overline{11}$ and $AC = \overline{00}$ do not actuate the piston, although the state might still be influenced by the other cylinder of the motor. Not all combinations of piston states are achievable: the piston states of AC, CE and EA cannot be in the "down" state simultaneously, because if $AC = \overline{10}$ (setting piston state of AC to "down"), the piston in either CE or EA is moved to "up" state (depending on pressurization state of E). The consequence is that not all combinations of motor setpoints are achievable; the theoretical error in control is at most one step $(0.21°)$.

In order to operate joint J_1 the following cyclic waveform sequence can be used: $ABCDEFGH = [\overline{11001111}, \overline{10011111}, \overline{00111111}, \overline{01101111}]$. This puts the piston states of the AC and BD cylinders alternatingly to "up" and "down", resulting in step-wise motion of joint J_1. The pistons in all other cylinders remain stationary: there exist no AB or AD cylinders, and in AE and AG the piston state remains "up". This ensures that all non-operated motors are at stand-still. A state machine keeps track of all cylinder

[1]Vincent Groenhuis, Matthias Bac, Stefano Stramigioli and Kenan Niu are with Robotics and Mechatronics, University of Twente, 7500 AE Enschede, The Netherlands v.groenhuis@utwente.nl

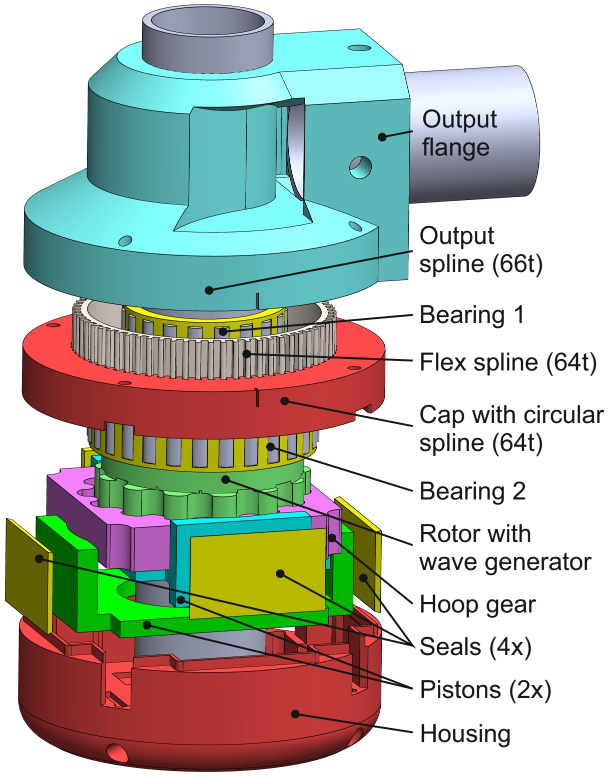

Fig. 2. Exploded view of geared pneumatic stepper motor. The housing has two cylinders with pistons acting on a hoop gear, which in turn drives a cycloid gear to which the wave generator of the strain wave gear reduction is attached.

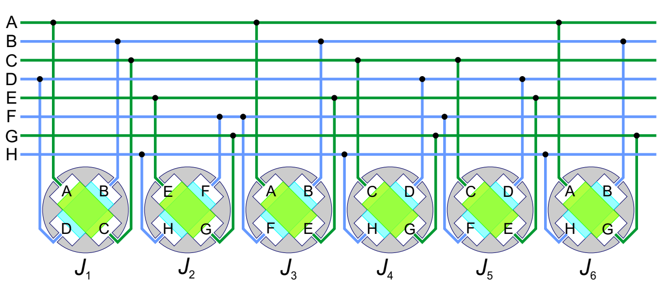

Fig. 3. Connection of eight tubes $A..H$ to six motors $J_1..J_6$. Each tube is connected to three different chambers. Tubes A, C, E, G exclusively connect to one set of cylinders (green), the other four tubes to the complementary set of cylinders (blue).

and the piston states, and ensures proper transitions between different waveform sequences. It is also possible to use more complex cyclic waveforms which act on multiple motors; such cyclic waveforms are typically to be pre-generated and stored in a look-up table [4].

C. Control with input from hand-operated input device

A hand-operated input device has been created with the same joint configuration as the robot arm, but at a smaller scale. This device is gravity-compensated using counterweights and each joint houses a potentiometer of which the voltage is measured by a microcontroller and used as setpoint angle for the respective joint in the robot arm. A controller calculates the required waveforms to iteratively bring each joint to its setpoint, with an error of at most one step.

III. Results

Actuator torque measurements show that without reduction gear, the maximum torque is $3.53\,\mathrm{N\,m}$ at a pressure of $0.7\,\mathrm{MPa}$. With 33:1 reduction gear, the maximum torque is $16.2\,\mathrm{N\,m}$ at a pressure of $0.27\,\mathrm{MPa}$. At higher torques the output shaft skips steps due to plastic deformation of the cap with 64-tooth circular spline. The maximum stepping frequency (with reduction gear) is $35\,\mathrm{Hz}$, corresponding to an angular speed of $7.3\,{}^\circ\,\mathrm{s}^{-1}$ or 49 seconds per revolution.

After proper calibration, the robot arm was able to accurately follow the motions of the hand-operated input device, with some delay due to the relatively low speed and sequential operation of joints. This demonstrates the correctness of the control method by eight pneumatic tubes.

IV. Conclusion

A six-DOF robot arm driven by identical MR safe pneumatic stepper motors has been developed. Through the bench-top testing, it demonstrated that it can be effectively controlled using eight pneumatic tubes in total, by sequentially operating the different joints until all have reached their setpoint (with at most one step error). The maximum stepping frequency is $35\,\mathrm{Hz}$ and the maximum output torque of the geared actuators is $16\,\mathrm{N\,m}$. Future steps include simultaneous control of multiple joints using complex waveforms [4], and designing end-effectors for specific clinical interventions under MRI guidance.

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References

[1] D. Stoianovici, C. Jun, S. Lim, P. Li, D. Petrisor, S. Fricke, K. Sharma, and K. Cleary, “Multi-imager compatible, MR safe, remote center of motion needle-guide robot,” *IEEE Transactions on Biomedical Engineering*, vol. 65, no. 1, pp. 165–177, 2018.

[2] V. Groenhuis and S. Stramigioli, “Rapid Prototyping High-Performance MR Safe Pneumatic Stepper Motors,” *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 4, pp. 1843–1853, 2018. [Online]. Available: https://doi.org/10.1109/TMECH.2018.2840682

[3] H. Ranjan, M. Van Hilten, V. Groenhuis, J. Verde, A. Garcia, S. Perretta, J. Veltman, F. J. Siepel, and S. Stramigioli, “Sunram 7: An MR Safe Robotic System for Breast Biopsy,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Detroit, USA: Institute of Electrical and Electronics Engineers (IEEE), 10 2023, pp. 10 281–10 288. [Online]. Available: https://doi.org/10.1109/iros55552.2023.10342425

[4] V. Groenhuis, F. J. Siepel, and S. Stramigioli, “Magnetic Resonance Pneumatic Stepper Motor With Multiple Concentric Shafts Output,” *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 4, pp. 2379–2389, 8 2022.