Electromagnetic Actuator Across Abdominal Wall for Minimally Invasive Robotic Surgery[1]

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1 Background

In the last decade, surgical advances have focused on techniques to minimize the invasiveness of such operations in order to reduce the resulting trauma, such as advances in laparoscopic techniques [1]. Current promising approaches are developed in robotic surgery for reducing access trauma using laparo-endoscopic single site surgery [2]. In these cases, the robotic manipulators are actuated through on-board motors. However, the performance of the motors that can fit through the small (20 mm) incision is limited.

In one of the most recent studies, the authors in Ref. [3] proposed a novel approach called local magnetic actuation (LMA) to transfer mechanical power across the abdominal wall by magnetic coupling which eliminates the need for embedded actuators and wired connections. As shown in Fig. 1, LMA is composed of an anchoring unit to support the instrument during surgery and an actuation unit to transfer power to internal driven magnet (IDM) via rotating external driving magnet (EDM).

The thickness of abdominal wall has an inverse relation with the magnetic field linkage between two permanent magnets in LMA. Therefore, in larger distance, the provided torque will be small. In addition, increasing the load torque can cause pole slipping between EDM and IDM and consequently reducing the amount of transferred torque significantly. In this paper, the work in Ref. [4] is extended by replacing the EDM with electromagnets to provide more control variables to enable better performance.

In variable local magnetic actuation (VaLMA), as shown in Fig. 2, the magnetic flux linkage is produced by a pair of electromagnetic coils and is transferred across abdominal wall and interacts with the magnetic field of permanent magnet. The magnitude of magnetic fields can be controlled via changing the magnitude of current in the coils. As a result, in the case of large distance or high load torque, the magnitude of currents in the coils can be increased to compensate for the reduction of torque in permanent magnet inside the abdominal wall. Two electromagnetic coils were used to produce a unique motion (speed and direction of rotation) of the rotor, located across the abdominal wall. Additionally, the ability to vary the actuation command to the electromagnetic coils would allow the software compensation of mechanical uncertainties and inaccuracies, such as the misalignment of rotational axis suffered by the LMA.

2 Methods

Figure 2 shows a schematic of the proposed VaLMA scheme that consists of at least two coils and one permanent. Altering the polarity of the coils causes the rotation of permanent magnet inside the abdomen. The rotor torque is the consequence of the interaction between of the permanent magnet field and the flux linkage (λ) of the electromagnetic coils that can be obtained as follows:

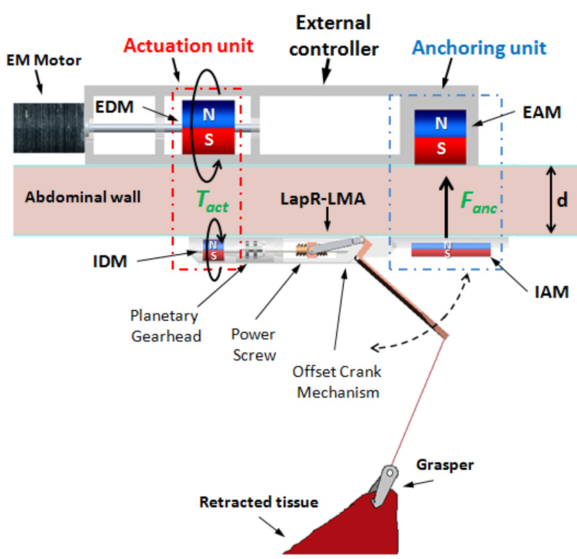

Fig. 1 The schematic of the LMA system reported in Ref. [3]

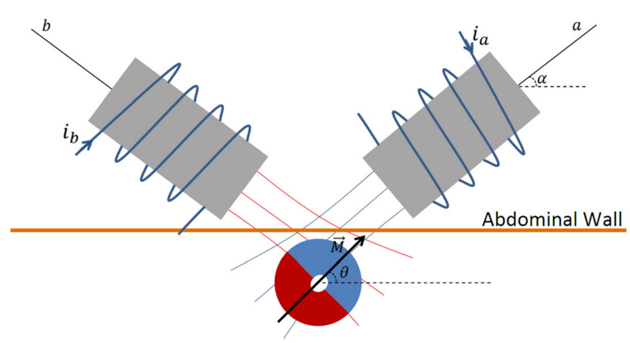

Fig. 2 The schematic of VaLMA

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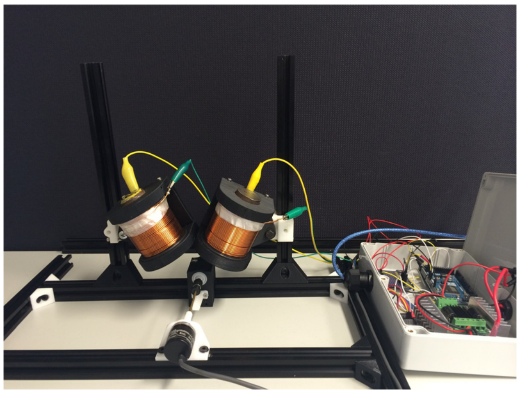

Fig. 3 Experimental setup of VaLMA

Table 1 Model parameters of VaLMA

Model parameters	
Resistance (R)	2.8 Ω
Inductance (L)	2.7 mH
Back-emf coefficient (K_b)	0.0042
Friction coefficient (B)	0.00008 N m s
Moment of inertia (J)	0.0005 kg m^2

$$T_e = (e_a i_a + e_b i_b)/\omega \tag{1}$$

where T_e is the rotor torque, i_a and i_b are the coil currents, e_a and e_b are the back electromotive forces (back-emfs), ω is the angular velocity of the permanent magnet at the rotor, and back-emf of each coil can be considered as $e = \lambda\omega$.

The magnitude of T_e can be regulated by the current of the coils, which is related to the voltage across each coil using the following equations:

$$\begin{aligned} v_a &= Ri_a + L\frac{di_a}{dt} + e_a \\ v_b &= Ri_b + L\frac{di_b}{dt} + e_b \\ J\frac{d\omega}{dt} + B\omega &= T_e - T_l \end{aligned} \tag{2}$$

where v_a and v_b are the coil voltages, R is the coils resistance, L is the self-inductance of coils, J is the total moment of inertia, B is the friction coefficient, and T_l is the load torque.

The experimental setup is shown in Fig. 3. It consists of two coils, one permanent magnet connected to a rotary incremental encoder. Note that in real operation case, the encoder will be replaced by a Hall effect sensor to measure the angular position and velocity of the rotor. These measurements will be used as a feedback to the controller. The coils are driven by Sabertooth drivers controlled by Arduino Due microcontroller.

In order to design a controller for VaLMA, we need to identify the parameters in the electromechanical model. Using multimeter (for R and L), algorithms based on oscilloscope measurements (for K_b) and algorithms based on torque measurement (for B), the VaLMA system parameters are identified as shown in Table 1.

In addition, to verify the kinematic model of the VaLMA, we consider the VaLMA as a synchronous motor. Therefore, there should be a linear relation between frequency of input signal to the coils (f) and angular velocity of permanent magnet (ω)

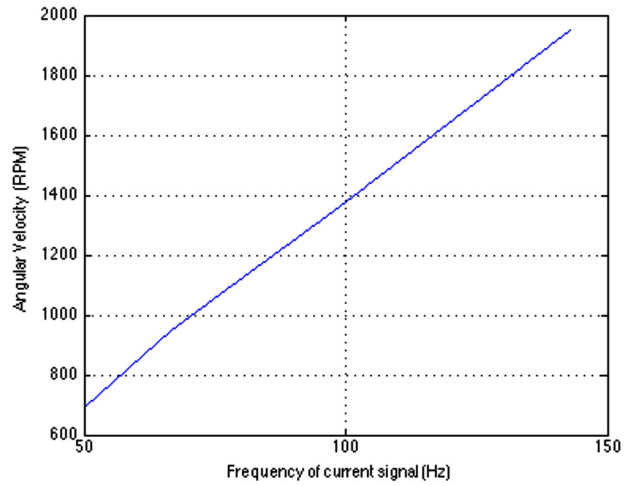

Fig. 4 Relation between f and ω

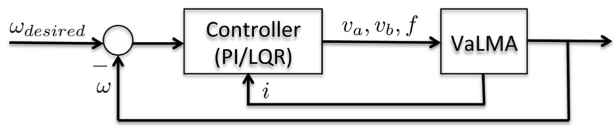

Fig. 5 Schematic of the controller implementation

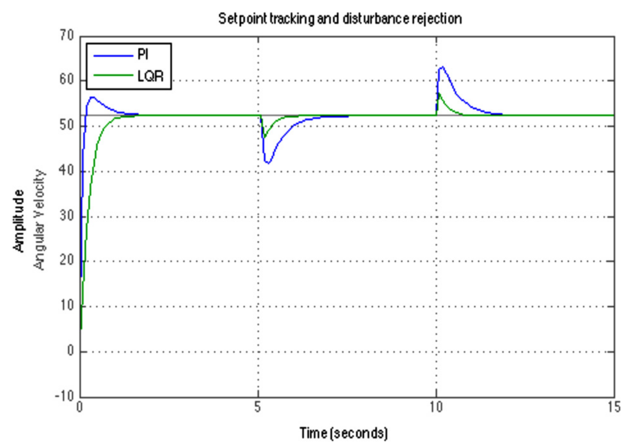

Fig. 6 Simulation results of two controllers: PI and LQR

$$\omega = 2\pi f/K \tag{3}$$

where K is the number of pairs of poles of the rotor permanent magnet. The angular velocity is measured experimentally in different frequency of input signal and has been shown in Fig. 4. As expected, there is a linear relation between frequency of coil voltage and angular velocity.

3 Results

Using dynamic model of the VaLMA, two speed control schemes are designed: the conventional proportional–integral (PI) and linear–quadratic regulator (LQR) (Fig. 5). The proportional and integral gains in PI controller are 5 and 9, respectively, obtained using trial and error. However, LQR provides a systematic method based on optimal control algorithms to determine the feedback gains. The gains in LQR are obtained as 44, 712, and 32 for three states i, ω, and $(\omega - \omega_{\text{desired}})$.

Figure 6 shows simulation results for implementation of the designed controllers to the obtained model of the VaLMA. In this simulation, during the time (5–10 s), a load torque equal to 10 mN m is applied to model as an input disturbance.

4 Interpretation

The results show that both of controllers can track the desired angular velocity and reject the applied disturbance. LQR controller can reject the disturbance quicker than PI.

In the future work, a hysteresis brake will be attached to the other end of the permanent magnet shaft to impose load and disturbance torque and verify the robustness of the designed controllers.

References

[1] Mack, M. J., 2001, "Minimally Invasive and Robotic Surgery," JAMA, **285**(5), pp. 568–572.

[2] Fader, A. N., and Escobar, P. F., 2009, "Laparoendoscopic Single-Site Surgery (LESS) in Gynecologic Oncology: Technique and Initial Report," Gync. Oncol., **114**(2), pp. 157–161.

[3] Di Natali, C., Ranzani, T., Simi, M., Menciassi, A., and Valdastri, P., 2012, "Trans-Abdominal Active Magnetic Linkage for Robotic Surgery: Concept Definition and Model Assessment," IEEE International Conference on Robotics and Automation (ICRA), St. Paul, MN, May 14–18, pp. 695–700.

[4] Garbina, N., Di Natalia, C., Buzzib, J., De Momib, E., and Valdastria, P., 2014, "Laparoscopic Tissue Retractor Based on Local Magnetic Actuation," ASME J. Med. Devices, **9**(1), p. 011005.