Force control of cable-driven robotic segment

Uroš Mali **Marko Munih**
Laboratory of robotics
Faculty of electrical engineering
University of Ljubljana
Tržaška 25, 1000 Ljubljana
urosmali@robo.fe.uni-lj.si marko@robo.fe.uni-lj.si

Abstract

This work considers the problem of force control for robot manipulators without direct measuring of contact force. Ironless rotor and precious metal brushed DC motor was used. The current vs. torque characteristic of the selected motor is linear. For that purpose one degree of freedom robotic segment with tendon driven transmission system and pulleys was built. Two different brushed DC motors were compared.

1 Introduction

The force generating actuator is a key element in creation of a haptic environment [4]. Often an actuator (i.e. electric motor) must exhibit high force bandwidth. Use of motors with large inertia or high cogging (i.e., preferred orientation of the rotor magnets in relation to the stator windings - magnet locking) can decrease effectiveness of a haptic device to simulate "real" environments. While many other aspects of haptic design contribute greatly to successful simulation, no control algorithm can completely compensate for a poorly chosen actuator/motor.

Several aspects have to be addressed when choosing a motor for a haptic feedback device. Concerns include: commutation method, cogging, inertia, position feedback sensors, size, output power, and required torque. The remaining motor characteristics (i.e., commutation method, cogging, inertia, and feedback sensor) are often the deciding factors in final motor selection and contribute greatly to the motor's ability to supply the desired force at the end effector.

An important property of electric DC motor is torque ripple defined as fluctuation around desired output torque during motor rotation. Torque ripple is caused by: 1) design of the motor and 2) excitation of the system. For ripple reduction, motors need to be designed with skewed magnets on the rotor or even ironless rotor as shown in the following sections. Magnet skewing is toward to reduction preferred orientations between the magnets and the windings. The second possible way of torque ripple reduction (i.e., control of the system) includes commutation of the motor. To obtain no torque ripple, excitation of the motor must exactly match the motor's back electromotive force (back EMF).

2 Methods

2.1 Motor selection

In our experiment were used two types of DC motors though many haptic devices [1] use brushless DC type motors. First is standard DC motor with expressed poles. Second is DC ironless rotor motor combined with a commutation system using precious metals for brush gear.

Due to absence of an iron core in the second motor, rotor inertia is very low and with no cogging [2]. The rotor can stop at any angle. The rotation speed is not limited by iron losses but rather depends only on supply voltage and load torque. The stator consists from cylindrical two-pole permanent magnet that fits inside a steel tube closing the magnetic circuit. This construction leads to a distinct advantage in numerous applications, where high performance drive and servo system are required.

Unlike the brushed motor, which relies upon metal contacts for commutation, the brushless motor relies on non-contact sensors. The difference in commutation methods comes from the physical distinction between the two motor types. With brushed motors, the current carrying windings are held on the rotating shaft/rotor and the magnets are wound in the motor housing/stator. As the shaft spins, contacts are made with different current carrying brushes resulting in commutation. In brushless motors, the windings are in the stator and permanent magnet is placed on the shaft. Because the rotor rotation can no longer take advantage of commutation, the motor must be electrically commutated. This electrical commutation is performed by a separate electronic controller which reads rotor position and causes current flow in the necessary direction for sustained rotation. While these controllers add price and complexity, the benefits of low inertia, low friction, and flexible commutation schemes makes brushless motors an excellent option for haptic use. But price and simplicity in the control of ironless DC motors take advantages in our case.

2.2 Pulleys

In most cases pulley is used for redirecting force while pulling up loads. Furthermore, system of pulleys can be efficient also in reduction of exerted force. Relation between input and output force depends upon layout of pulley system [3].

There are two basic types of pulleys: parallel and serial, as shown on Figure 1.

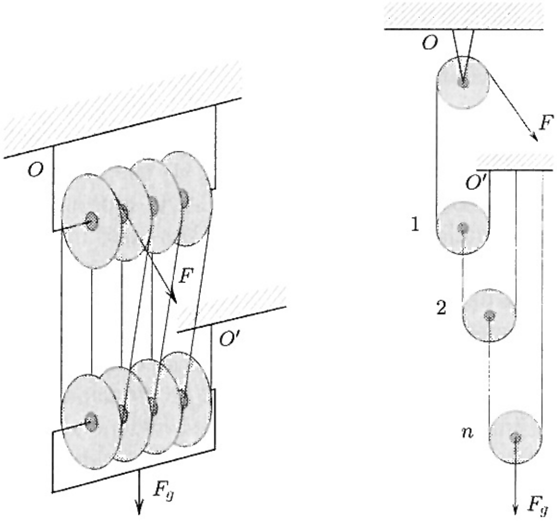

Figure 1: Parallel (left) and serial (right) type of system of pulleys

Parallel pulleys consist of upper nonmoving axle and lower moving axle. All moving pulleys are attached on the same axle. The transmission ratio is defined as

$$\frac{F}{F_g} = \frac{1}{n} \tag{1}$$

where F is input force, F_g is output force and n is number of cables which hold moving axle with pulleys. All the cables carry the same quantity of force F_g.

Serial type of pulleys consists of n moving axles with one pulley on each one of it as shown on Figure 1 right. Equation for such system is

$$\frac{F}{F_g} = \frac{1}{2^n} \tag{2}$$

where n is number of pulleys on moving axles. Not all cables are at the same tension. The length of the system is its main disadvantage.

2.3 Tendon drive

Tendon drives can be in generally classified into two categories: *closed-loop* and *open-loop tendon drives* [6]. The segment arrangement that was studied uses closed-loop tendon drive. Such type of transmission system with one motor drives a closed-loop belt in both directions as shown on Figure 2. The power transmission relies on friction generated between the pulley and the belt. To increase efficiency at low tension, toothed belt known as the *timing belt* or *chain-and-sprocket device* can be used. In a closed-loop drive, half of the tendon will be under high tension while is the other portion not loaded. Although, torque can be transmitted in both directions, pretension is often necessary to prevent slipping [5]. As side effect, pretension can introduce significant amount of friction as well as backlash due to the elastic effect of tendons. The property that a tendon can be driven in both directions means that number of actuators needed is equal to the number of degrees of freedom of a manipulator.

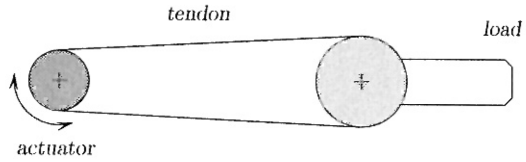

Figure 2: Single-stage closed-loop tendon drive

Figure 3 shows schematics of our closed-loop experimental setup with pulleys. Main parts of the segment are: (1) motor with a small driver wheel (1a), (2) nonmoving pulleys, (3) moving pulleys, (4) upper part with a driven shaft and wheel, (5) handle (next segment), (6) main cable and (7) two auxiliary cables.

Wheel on the shaft is driven by DC motor mounted in the base of the segment together with nonmoving pulleys. Driver wheel pulls the main cable placed

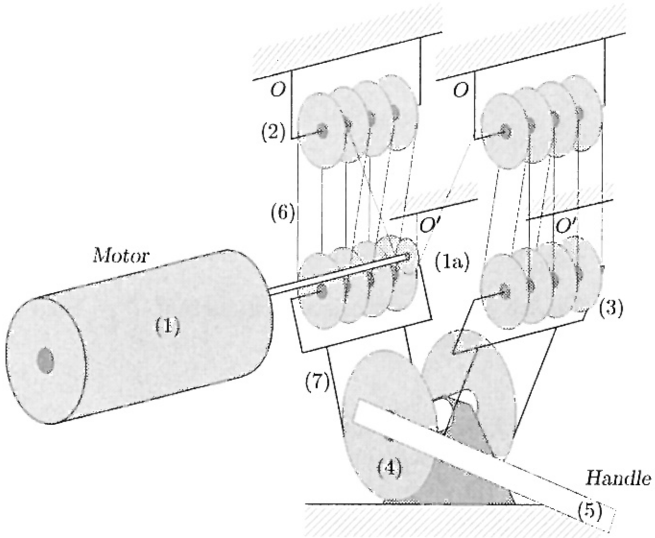

Figure 3: Used principle of tendon driven segment

across moving and nonmoving pulleys in both directions. Each end of the main cable is placed over on its moving pulleys. Both auxiliary cables are placed across driven wheels.

3 Results

The setup as described above was built to verify transmission and motor functioning. Moment on handle is acquired indirectly via Mettler balance (model *Mettler, PC 2000*) placed on the table. Experimental model was mounted on the top of Motoman SK6 industrial manipulator, which enabled adjustment of 90-degree angle between the handle and the balance.

Experiments with DC and DC ironless rotor motor analyzed dependence of force ripple on top of handle while rotating rotor in small increments with constant current through the rotor windings. The handle length is 34cm and gravity force about 0.3N.

3.1 Experiment with standard brushed DC motor

In this experiment was used standard DC motor with expressed poles. Transmission ratio was approximately 18. Generated moment of permanent magnet motors tend not to be completely smooth during a rotation. Cogging can be encountered as the magnet locks into the rotor poles during the revolution. Steel cable was used here for driving the system with pretension to prevent slipping. Acquisition control scheme (Figure 4) was realized within *Matlab-Simulink* software environment. The current control was realized within software environment.

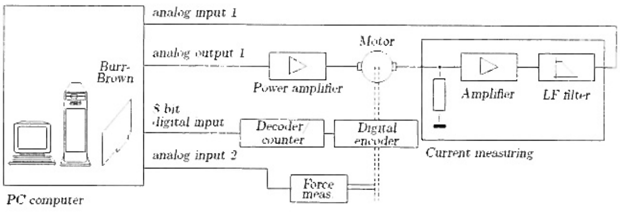

Figure 4: Connecting circuit

Figures 5 and 6 (right) show almost linear characteristic of output force vs. current through the rotor windings. Main problems here are static friction and force ripple which take approximately 35% at current 0.6A.

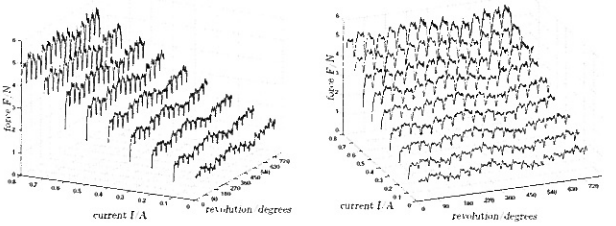

Figure 5: Force dependence of current and rotor revolution. Magnet locking into the rotor can be well noticed.

Theoretically was expected during rotor revolution nearly straight line force vs. current. Figure 5 shows measured characteristic which clearly demonstrate deviation from expectations. Locking of the magnet into the rotor during a revolution was the main disadvantage of the motor used in this experiment (Figure 6 left).

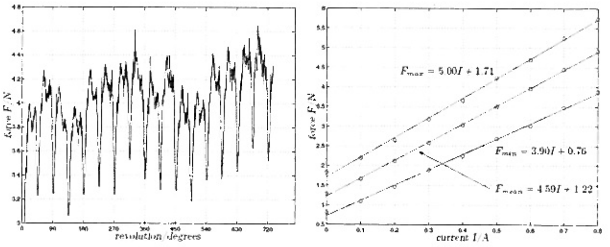

Figure 6: Characteristic for current $I = 0.6A$ (left) and regressive lines current vs. force (right)

Figure 6 right shows regressive lines for measured data. All lines are close to linear with very small deviation.

3.2 Experiment with ironless rotor and precious metal brushed DC motor

In this experiment was used ironless rotor and precious metal brushed DC motor with no magnet locking. Special steel cable with three and a half turns around driver wheel which prevent slipping on it was used for main cable. The toothed belts substituted two auxiliary steel cables requiring less pretension to prevent slipping on driven wheels. Achieved transmission ratio was 24. In this case was the current control not realized within software environment, but rather as a power operational amplifier with 4A maximum available output current (L456A).

Figures 7 show measured characteristics. Less force ripple can be noticed than in previous case. The cogging is approximately 8% of mean value at current 1.4A (Figure 8, left).

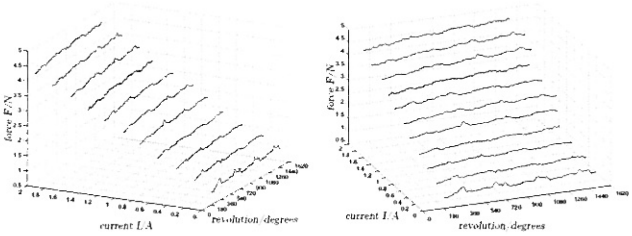

Figure 7: Force dependence of current and rotor position

Figure 8 right shows regressive lines for characteristics presented in Figures 7. As before in Figure 6 and as expected deviations from linear lines are very small. Also less difference between F_{mean} and other two lines can be encountered. The value of force ripple also remain rather constant while increasing supply current. The ripple as seen in Figure 8 demonstrates similar (periodic) shapes at different revolutions. Origins are coming from the rotation of motor rotor axis.

4 Summary and Conclusions

Experimental results with force control while using direct current motors are presented in this work. Two different DC motors were compared. Improvement while using ironless rotor DC motor is obvious. In this case smaller friction and low torque ripple were measured. The origins of torque ripple differ in both cases. In the first case the major reason for cogging is the locking of the magnets into the rotor poles and no further improvements possible here. The reason for torque ripple in the second case while using ironless rotor motor was misalignment of the driver wheel's axis and the motor's axis. Improvements are possible with use of modified design.

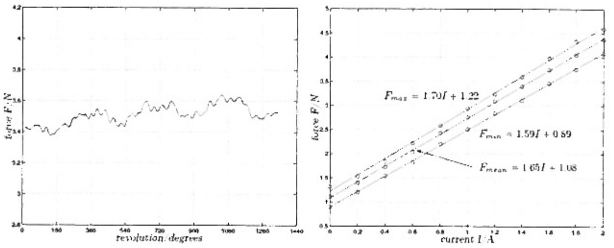

Figure 8: Characteristic for current $I = 1.4A$ (left) and regressive lines (right)

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