Tendon-Based Transmission for Surgical Robotics: Systematic Experimental Friction Modeling

R. Beira, A. Sengul, M. Hara, P. Schoeneich, H. Bleuler

***Abstract*— Increased miniaturization of surgical instruments is essential to successfully perform surgical procedures in restricted areas as in many applications of minimally-invasive surgery. Miniaturization permits increase in dexterity and decrease in access incisions which are required in many surgical procedures. Tendon-based transmissions provide several important advantages for the mechanical design of miniaturized surgical devices. Reflected mass and inertia are reduced since tendon-based transmissions allow to locate the motors far apart from the actuated joint. In spite of providing several important advantages, they introduce several non linear effects that must be considered and modeled to achieve suitable performance. In this paper tendon-based transmission system for surgical robotics is illustrated. And nonlinear friction, due to direct sliding of synthetic fiber cables over small fixed pulleys (pins) is discussed and models aiming at compensating these nonlinearities are presented.**

Keywords: Surgical Robotics, Tendon Transmission, Friction Compensation, Friction Modeling

I. INTRODUCTION

Tendon-based transmission systems are used in many robotic devices to transmit power from actuators to the joints. In some special cases in which, it is not possible to locate motors within the robot structure due to space and inertia constraints, tendon-based solutions usually is the only possible solution. Tendon-based transmission is often used in robotic hands and robotic fingers because of space and inertia limitations [1], [2], [3]. Tendon-based transmission is also often used in surgical robotics applications, where end effector operates inside the patient body and the actuators placed remotely for miniaturization, space, inertia and safety reasons [4].

This work is part of ARAKNES project, which is focused on innovative robotic system for endoluminal surgery. The project aims at bringing inside the patient body an advanced micro robotic surgical system. Tendon-based transmission is choosen because it enables miniaturization in terms of locating the motors far from the actuated joints. In Fig. 1 concept of the micro robotic surgical system is illustrated.

Due to the small size of the two arm structure, motors are remotely located and tendons have been chosen for motion/force transmission. Two actuator and two cables have been used per degrees of freedom (DoF) to provide an antagonistic actuation. The two arm structure has 6 DoF for each arm which means that large amount of individual tendons need to pass at axial joint, see Fig. 2. Synthetic fiber cables, Dyneema®, Spectra®, and Vectran® , might be chosen as the motion/force transmission media since they exhibit much lower flexural rigidity, providing a smaller bending radius. Another key advantage is related with their low friction coefficient with steel, enabling the direct sliding over small fixed pulleys (or pins), which is especially useful in miniature axial joints where the use of a idle pulley system might be too bulky and complex.

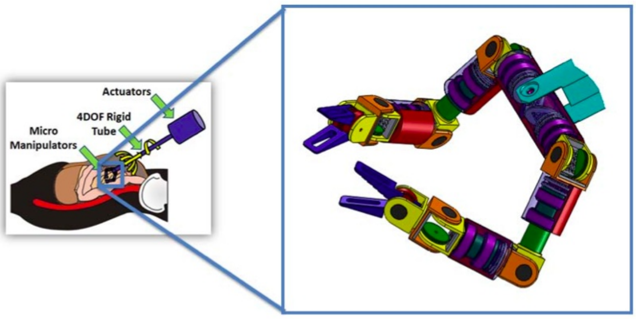

Fig. 1. Micro Robotic Surgical System

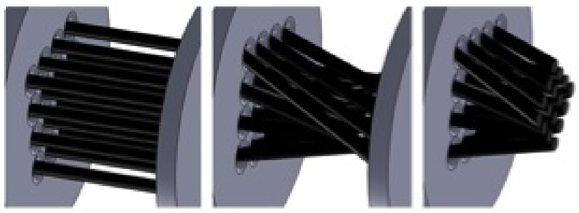

Fig. 2. Axial joint using Synthetic Fiber Cable Transmission

In spite of bringing several important advantages, those kinds of fiber cable driven systems often imply some drawbacks due to the friction along the tendon path and due to tendons compliance [5], [6], [7]. These introduce dead-zones and hysteresis in the force transmission, which might limit the transparency of forces at haptic-feedback teleoperator. Therefore, proper friction models and suitable control strategies need be developed in order to obtain satisfactory performance of the transmission system. For a tele-manipulator with tendon-driven joints, friction occurs at several stages of power transmission. It occurs in the actuator

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that moves the tendon, in the joint of the manipulator driven by the tendon, in the pulleys that support the tendon or in the areas of sliding movement between fixed pulleys and a synthetic fiber cables. Since the tendon is stretched during force transmission, the displacements of the friction surfaces of the tendon mechanism are different from the displacement input to the controller. These displacement lags are much larger than the pre-sliding distances of the friction surfaces of the transmission and should be considered in the design of compensators to ensure passivity of the teleoperator.

Ideally, force sensors could be used to eliminate resistant forces of the manipulators from being feedback to the human operator [8]. Due to the practical limitations of using force sensors in robot assisted surgery (geometry, size, biocompatibility, sterilization, and cost), we are studying force measurement methods that do not require force sensors. Thus, our idea is to use a position-tracking controller to provide haptic feedback and a feedforward strategy to cancel the friction forces. To do this, a model-based compensator will be used to cancel friction in teleoperators joints, in such a way that a feedforward force should be calculated based on a friction model and then added to the teleoperator control force to obtain the force that has be applied by the actuator [9], [10].

Inspite of having been extensively examined, the behavior of friction has remained an elusive phenomenon. Friction embodies an extraordinarily rich mixture of mechanisms which makes impossible the construction of a general friction model from physical principles. It is well known that the friction force on a cable driven system might depend on many factors such as cables tension, sliding velocity, angle of curvature, humidity, temperature, etc. The dependence of the friction force on these factors is treated in some technical publications [11], [12], however, only handful attempts present the dependence of friction force on more than one variable, having focused on the study of the effect of one variable at a time. The major disadvantage of this technique is that it does not include interactive effects among the variables and, eventually, it does not depict the complete effects of the factors.

This work introduces a systematic experimental approach to model friction losses in a cable transmission in order to build a mathematical model that takes into account the effect of different factors on the friction behavior, namely the cables tension, the cables sliding velocity, the cables total angle of curvature and temperature. The humidity was not considered in this analysis, due to the use of liquid lubrication on the cable transmission, however, its effect might be important for dry friction systems. The aim of this study is to find out the parameters (factors) from which the friction in a cable driven transmission is affected and to which factor of interactions it is related. This is usually done by means of Analysis Of Variance (ANOVA) [13]. Furthermore, a Response Surface Method (RSM) is used to establish the correlation between factors and responses. The appropriate degree of the regression equation is found which is thought to be useful assessment of the predictive equation.

II. EXPERIMENTAL SETUP AND FRICTION MODEL

A. Mathematical Model

Since many parameters might affect the total amount of friction loss in the system, it may be difficult by a mechanical analytical approach to find the parameters that most efficiently improve the process. Since there are many parameters effecting the friction and it is expected to have a non linear friction. Quadratic polynomials can be used to model non linear friction. Thus, statistical techniques may be used to model these computation-intensive processes in order to improve efficiency. Response Surface Methodology (RSM) is such an approximation method for replacing a complex model by an approximate one based on results measured at various samples in the design space [13], [14]. For most of the response surfaces, the functions for the approximations are polynomials because of simplicity, though the functions are not limited to the polynomials. For the cases of quadratic polynomials, the response surface is described as follow:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j \qquad (1)$$

where k is the number of variables, β is the coefficient, x is the measured value and y is fitted value. In the case that total number of experiments is n, the response surface can be expressed by matrix expression:

$$Y = X\beta + \varepsilon \qquad (2)$$

where

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad X = \begin{bmatrix} 1 & x_{11} & \dots & x_{1k} \\ 1 & x_{21} & \dots & x_{2k} \\ 1 & x_{31} & \dots & x_{3k} \\ \vdots & \vdots & \dots & \vdots \\ 1 & x_{n1} & \dots & x_{nn} \end{bmatrix} \quad \beta = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \dots \\ \beta_n \end{bmatrix} \qquad (3)$$

where ε is the residual vector.

The unbiased estimator b of the coefficient vector β is obtained using the well-known least square error method as follows.

$$b = (X^T X)^{-1} X^T y \qquad (4)$$

Statistical analysis techniques such as ANOVA can be used to check the fitness of a RSM model and to identify the main effects of design variables. Test for significance of the regression model is performed as an ANOVA procedure by calculating the F-ratio, which is the ratio between the regression mean square and the mean square error. The F-ratio, also called the variance ratio, is the ratio of variance due to the effect of a factor and variance due to the error term. This ratio is used to measure the significance of

TABLE I

LEVELS OF THE INDEPENDENT FACTORS AND CODING IDENTIFICATION

	Factor	Low Level (-1)	High Level (1)
θ	Angle (rad)	0	4π
V	Velocity (rad/s)	0	5
F	Force (N)	0	0.4
T	Temperature (^oC)	20	35

the model under investigation with respect to the variance of all the terms included in the error term at the desired significance level. Test for significance on individual model coefficients forms the basis for model optimization by adding or eliminating coefficients. It involves the determination of the probability value, usually relating the risk of falsely rejecting a given hypothesis. For example, a $Prob. > F$ value on an F-test tells the proportion of time you would expect to get the stated F-value if no factor effects are significant. The $Prob. > F$ value can be compared with the desired probability. In general, the lowest order polynomial would be chosen to adequately describe the system.

B. Experimental Design

The design layout is a central composite design (CCD) where the factorial portion is a full factorial design, the centre points have middle range values and the star points are placed at the face of the cube portion. This option was taken due to some physical and equipment limitations, which didnt allow us to reach values of the analyzed factors outside of the analyzed range (for instance, negative velocities or bending angles).
The studied parameters (factors) were the total bending angle of the transmission cable (θ), the actuators angular velocity (ω), the load carried by the joint (F) and the temperature of the environment (T). The response corresponds to the difference between the motors torque and the torque applied on the joint. All the factors were varied at three levels, ranging from their maximum and minimum values. Table I shows the factors and factor levels assessed in this study. All the main effects of factors and two-order interactions were desired to be considered in this study. The design matrix is established, Table I , based on the number of variables. The units of the independent variables differ from one another. Even if some of the parameters have the same units, not all of these parameters will be tested over the same range. Since parameters have different units or ranges in the experimental domain, the regression analysis should not be performed. Instead, one must first normalize the parameters before performing a regression analysis. Each of the coded variables is forced to range from -1 to 1, so that they all affect the response more evenly, and so the units of the parameters are irrelevant. The normalized parameter in Table I is designed to exit in the range -1 to $+1$. For a physical variable x, a normalized parameter I may be defined as follows:

$$I = \frac{2(x - x_{min})}{x_{max} - x_{min}} - 1 \tag{5}$$

where x_{min} is the low value of x and x_{max} is its high value.

C. Experimental Equipment and Setup

The experimental setup consisted of a velocity-controlled DC motor connected to a robot joint through a pin mount unit, on which the cable had been wound Fig. 3. On the tip of the robot joint, a weight of a known mass was suspended and allowed to move. The motor was then used to lift up the weight, with different speeds, cable tension, bending angle and temperature and the friction losses were experimentally estimated according to the required motor currents for different cable tensions and velocities. The actuator consists of a brushed DC motor without any gear reduction and containing a 500 pulses per revolution encoder. The robot joint consists of a bar, representing an articulation of the micro robot. The cable is attached from the actuators pulley to the joint in a pull configuration. It consist of 100% Dyneema® cable sliding through polished stainless steel pins.

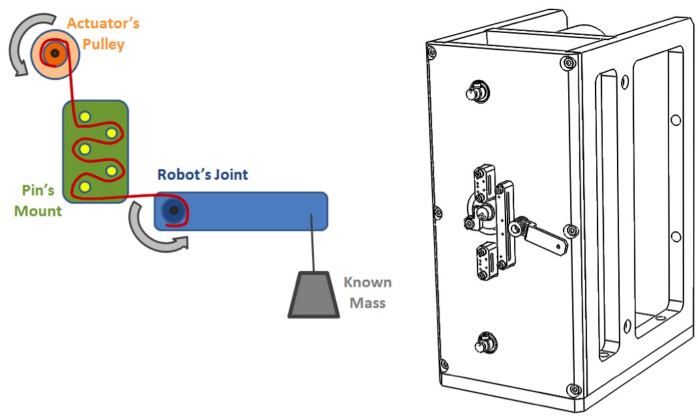

Fig. 3. Axial joint using Synthetic Fiber Cable Transmission

III. RESULT AND DISCUSSION

During the experiment, different parameters were monitored, displayed and stored in the computer for further analysis. Data was displayed in real time on the monitor. The motor currents were also recorded, from which the friction losses were computed. The results were then collected and analyzed using (ANOVA), where the main and interaction effects are computed. The effects that are statistically insignificant were screened out and the significant ones retained. Finally, a model was generated in terms of the significant main and interaction effects. Since in our analysis we consider that values of $Prob > F$ higher than 0.05 indicate that the terms are insignificant, models $Prob > F$ value of $2.40E^{-09}$ implies that it is significant, which means that the terms in the model have a significant effect on the response and therefore may be used for further analysis. Checking the values of $Prob > F$, it is seen that the main effects of θ and F, the two-level interaction θF and the quadratic terms TT

TABLE II

RESULTING ANOVA TABLE FOR REDUCED QUADRATIC MODEL

Source	SS	df	MS	F	*Prob.* $>F$
Model	0.0034	7	0.0048	3.80E+02	0
Mean	0.0219	1	0.022	1.70E+03	0
T	0	1	3.8E-05	3	0.097
θ	0.0027	1	0.0027	2.1E+02	4.2E-13
F	0.0069	1	0.0069	5.5E+02	0
θ **F**	0.0017	1	0.0017	1.3E+02	4.5E-11
TT	0.0003	1	0.00025	20	0.00018
FF	0.0001	1	0.00014	11	0.0032
Residuals	0	23	1.3E-05		
Total	0.034	30			

and FF are the significant model terms. By eliminating the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for surface roughness is shown in Table II. Results from Table II indicate that the model is still significant. The main effects v and F, the second-order effect vF and the quadratic terms TT and FF are still significant model terms. The main effect T was added only to support hierarchy. The main effect F is the most significant factor associated with the friction loss of the system. Finally, the mathematical model of the total friction loss in the robotic system is given by the following equation:

$$\Delta F(\theta,F,T) = -0.014528 + 0.001511T + 0.000304\theta + 0.011167F + 0.000835\theta F - 0.00003T^2 - 0.001636F^2$$

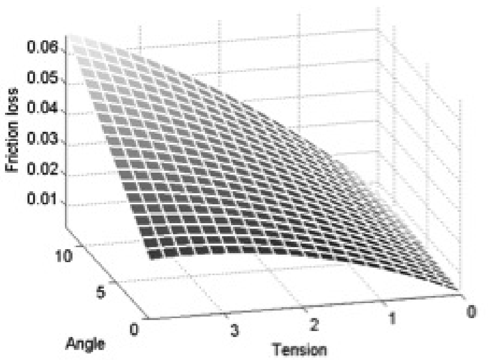

Fig. 4. 3D Surface of the Empirical Model

A three-dimensional surface, is plotted in Fig. 4 to point out the simultaneous effect of the independent variables F and θ on friction losses of the system. It shows a vaguely curvilinear profile in accordance to the quadratic model fitted. This is consistent with the fact that F term is significant. However, this increase becomes must more evident for higher values of θ, which is another significant effect.

IV. CONCLUSIONS AND FUTURE WORKS

This work applies a systematic experimental approach to model friction losses in a cable transmission in order to build a mathematical model, taking into account the effects of the cables tension, angle of curvature and temperature on the friction behavior of a robotic system. An ANOVA was performed to find where the measurement results had a common mean or not and to identify the significant factors. It is important to identify the factors that influence friction characteristics to improve the design or performance of frictional components and to compensate de friction losses through an active systems control. Friction force with the variation of the factor levels is investigated on an experimental setup.

The following conclusions were drawn from the results of the present investigation. A four-factor three-level RSM technique can be employed to develop a mathematical model for predicting the friction losses in cable driven robotic system. Comparison of experimental and calculated values for the friction losses shows that a good agreement has been achieved between them, showing the ad equability of the developed model to calculate the friction present on a robotic system. The friction losses are mainly influenced by the tension in the cable F, and the bending angle of the cable θ, being also slightly affected by their interaction and by the quadratic term of the temperature.

In this work, control other issues related to control such us stability, transparency are not considered. These topics will be object of future research activities, together with further analysis on the materials of both the tendon and the sliding surface, the effects of lubrication and the trade off between the tendon transmission characteristic (in terms of stiffness and hysteresis) and the system performance. Since this work is a preliminary study on the feasibility of employing these materials in the design of a surgical robotics, future developments will be centered also on the study of tendon behavior on the control of surgical robotics.

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