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Investigation of tribological interactions influence on dynamics of optimal surgical robot with DC motor and PID controller taking into account inputs from in vitro experiments on cardiovascular tissue

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Abstract Tribological interactions are one of the basic reactions affecting the course of the drive torque in surgical robot joints. It is interesting to test out what is the impact of friction on its dynamics because it gives the possibility to effective control. Inputs from two in vitro experiments on cardiovascular tissue were added to optimization model. For the optimal obtained geometry, a model of dynamics of driving torques was constructed by using the block diagram method, taking into the account the inertia tensors and the locations of masses centers. The electromechanical DC motor model was added to each joint. PID regulator models were also added to them and step response with optimal indicators of the regulation quality was received using gradient descent method. For a specific mechatronic system of the surgical robot, dynamic friction model was formulated based on the Lund-Grenoble model.

Keywords: surgical robot, LuGre, NSGA-II, optimization, FEM, PID, in vitro.

1. Introduction

Medical robots belong to the latest devices in the area of robotics. These devices are used in a variety of medical specialties. Since 1992, the ROBODOC robot has been used in the bone tissue surgery to replace joints into artificial, while in soft tissue surgery the American structure da Vinci has been used since 1996. Currently, a particular importance has a conduction of scientific research about a construction of a medical robot with an open kinematic chain, due to their large possibilities in the operating field for manipulating the tissue of the organ's rear walls and servicing of artificial organs.

The research area addressed in this article covers the fields of: mechanics, control theory and medicine. However, numerical methods are used to obtain the results progress of physical quantities, not the experimental methods. Such a procedure allows to simulate complicated numerical systems enabling to take into account various influences, often those that are even impossible to obtain experimentally. This can be interesting for researchers because of the ability of achieving results without having a proper laboratory. Author can also experiment with models in a relatively simple way, by forcing them to act and observing the effects under the accepted restrictions. At the same time, the formulated numerical models provide a promising basis for their modernization, adding new influences, determining the progress of physical impacts that are needed for that moment. From the process point of view of constructing a biomechatronic layout of a medical robot and from the applicability of the adopted research methodology, such an approach is necessary and makes it possible to obtain optimal documentation on calculation on the basis of which the prototype of the device is built. It should be noted that the criterion of overriding importance is met, i.e. safety of using a medical robot in any situation, the system has the functionality to perform medical procedure, for example it is characterized with the required accurate positioning of the effector. On this kind of a basis, a prototype of the device is built, which should faithfully behave like a predefined numerical model.

In this article, it was decided to fill the research gap which is the lack of a model based on the block diagrams method for solving differential equations related to the LuGre friction model. Additionally, model of the dynamics of driving torques, DC motor model, PID controller model with the aforementioned LuGre friction model are synthesized.

2. Literature review

Until now, a numerical model of a medical robot with a similar complication has not been found in literature, while researchers in various study centers around the world conducted researches in the field developed in this article. For example, in work [1], a dynamics model of a medical robot was built, based on the Lagrange's equations, where friction in the robot's joints was not taken into account, but the friction combined with trocar tool was simulated. The creation of optimal models due to various criteria by using the finite element method is shown in works [2 - 4]. Whereas, the method of creating a dynamical model of medical robot by using a block diagrams method is shown in works [5]. The method of creating a numerical model of dynamics accepted in this article is based on the transformation of mathematical equations: DC motor, tribological interactions in a block diagram, while in [6, 7] works, mathematical models in matrix and iterative forms are used. This is an alternative approach allowing for a quick modification of a model and finding easily the errors during the checking of the simulation model activity. However, the programming is not set aside because the block diagram is just a skeleton of the model and must be completed with the appropriate pats of the code written in a high level C++ language. In [8 ,9] works, the Coulomb friction model was used, however due to the inability to determine physical phenomena between rest and motion, dynamic model of LuGre based on differential equations is used in joints of a medical robot. The Dahl and LuGre models also take into the account the pre-sliding phenomenon. In addition, the LuGre model includes the Stickbeck's effect [10-13]. These models are more accurate than the outdated Coulomb model.

3. The aim of the article

The article allows to study the dynamics of a mechanically optimal surgical robot from the point of view of such criteria as: mass, displacement of the scalpel end, and the safety factor and also first natural frequency and buckling coefficient. The dynamics model also includes a drive with a DC motor and a PID controller, the settings of which have been selected in the optimal gradient descent method. Investigating the influence of friction on the model of dynamics of the surgical robot makes it possible to understand the nature of the robot's structure movement in conditions close to reality.

4. Materials and methods

The finite element method was used and the optimizing calculation model was specified based on a mesh discrete model. The Solid185 tetrahedral elements were used to create a discrete model. The mesh model of the open kinematical chain surgical robot is illustrated in the Fig. 1. The model of surgical robot has six degrees of freedom.

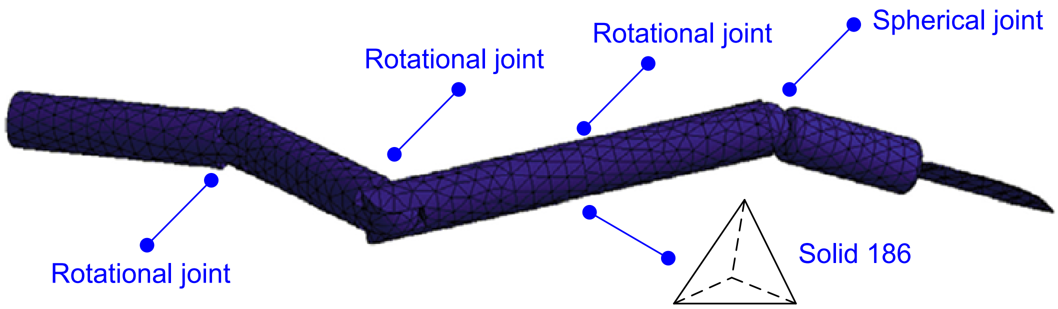

Figure 1. Mesh model of the surgical robot with the open kinematic chain. The robot model is completed with the scalpel.

Two eigenvalue problems for linear buckling and natural vibrations given by equations $([\boldsymbol{K}] - \boldsymbol{\omega}^2[\boldsymbol{M}]) \cdot \{\boldsymbol{u}\} = \{\boldsymbol{0}\}$ and $([\boldsymbol{K}] + \boldsymbol{\lambda}[\boldsymbol{K_G}]) \cdot \{\boldsymbol{\delta u}\} = \{\boldsymbol{0}\}$ are solved using the finite element method where: $\boldsymbol{\omega}$ – eigenvalues being as natural frequencies, $\mathbf{u}$ – eigenvector describing the displacement functions during resonance, $\boldsymbol{\lambda}$ – eigenvalue vector describing the load factors, $\boldsymbol{\delta}\mathbf{u}$ – eigenvector describing the buckling shapes.

The optimization computational models are defined by the following equation:

$$f_1(\{\mathbf{d}\}) = \left\{f_1\{\mathbf{d}\}, f_2\{\mathbf{d}\}, f_3\{\mathbf{d}\}\right\} \tag{1}$$

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where: d_1 – inner diameter (hole) of the first link, d_2 – inner diameter (hole) of the second link, $4 \leq d_1 \leq 9$ mm, $4 \leq d_2 \leq 9$ mm, $f_3\{d\} \geq 4$.

$$f_2(\{\mathbf{d}\}) = \{f_4\{\mathbf{d}\}, f_5\{\mathbf{d}\}, f_6\{\mathbf{d}\}, f_7\{\mathbf{d}\}\} \tag{2}$$

where: d_1 – inner diameter (hole) of the first link, d_2 – inner diameter (hole) of the second link, $4 \leq d_1 \leq 9$ mm, $4 \leq d_2 \leq 9$ mm, $f_5\{d\} \geq 40$ Hz, $f_6\{d\} \geq 30$, $f_7\{d\} \geq 4$.

Optimization equation for the problem of dynamics (1) contains three criteria. The mass $f_1\{\mathbf{d}\}$, which should be minimal after finding the optimal solution. The second criterion is the displacement of the scalpel end $f_2\{\mathbf{d}\}$, which should not exceed 0,1 mm. The third criterion is the dynamical safety factor $f_3\{\mathbf{d}\}$. The aim is also to ensure that the safety factor has a value greater than or equal to 4. Optimization equation for the problem of statics (2) contains four criteria. The mass $f_4\{\mathbf{d}\}$ should be minimal. The first natural frequency $f_5\{\mathbf{d}\}$ should be greater than 40 [Hz] and the buckling coefficient $f_6\{\mathbf{d}\}$ should be greater than 30. Dynamical safety factor $f_7\{\mathbf{d}\}$ whereas should be greater than 4. Other multi-criteria optimization and dynamical models of surgical robots are considered in the articles [14-16]

The established optimization model is based on the so-called meta-model (surface response), which is built with the usage of Kriging method [17-19]. The solution of the optimization model is obtained by the NSGA-II genetic algorithm, obtaining the optimal geometry with the adopted restraints based on the received Pareto fronts. The chart of Pareto front for dynamical safety factor in relation to two dimensions of surgical robot for vectorial function (3) is illustrated in the Fig. 2.

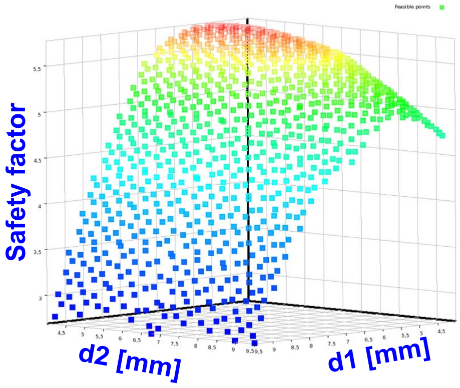

Figure 2. Pareto front for dynamical safety factor.

The NSGA-II genetic algorithm is ideal for searching for the extremes of global course of physical phenomena, which appear in the construction of the surgical robot. For the obtained optimal geometry, the tensors of inertia and the position of the mass centers are determined, which as physical parameters are imported into the Matlab environment, where a simulation model of dynamics of a driving torque was created, including the drive model in the form of a DC motor, PID controller, LuGre friction model.

4.1. Experiments on cardiovascular tissue

In order to find inputs for numerical models two experiments on cardiovascular tissue were done. The first experiment was carried out using four CMOS sensors [20]. The experiment is illustrated in Fig. 3. The velocities of minimally invasive tools were determined, which were used as inputs to the transient dynamics model. The second experiment was carried out using an electronic dynamometer, where the forces generated by the contact of the endoscopic instrument with the heart tissue were measured.

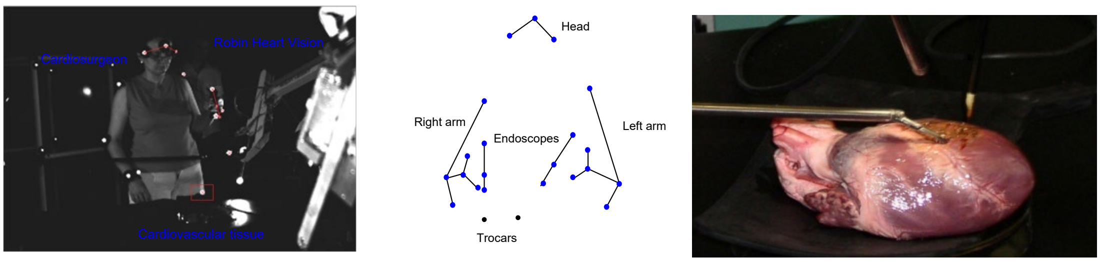

Figure 3. Experiment on cardiovascular tissue with using surgical robot Robin Heart Vision, tissue during electro coagulation, and kinematical chain of cardio surgeon in the APAS motion analysis system.

The maximum force value of 23 [N] was obtained. The normal distribution of measurement data was confirmed by the Kolmogorov-Smirnov statistical test.

4.2. Model of drive system and PID controller

The analytical equations of the DC motor have the following form:

$$\frac{d}{dt}\cdot\begin{bmatrix}\frac{d\omega}{dt}\\ i\end{bmatrix}=\begin{bmatrix}-\frac{b}{J} & \frac{k}{J}\\ -\frac{k}{L} & -\frac{R}{L}\end{bmatrix}\cdot\begin{bmatrix}\omega\\ i\end{bmatrix}+\begin{bmatrix}0\\ \frac{1}{L}\end{bmatrix}\cdot U, \tag{3}$$

$$y=\begin{bmatrix}1 & 0\end{bmatrix}\cdot\begin{bmatrix}\omega\\ i\end{bmatrix}, \tag{4}$$

where: k - back electromotorical force coefficient, i - current, L - inductance, ω- rotational velocity, R - resistance, b - viscous coefficient, U - voltage.

The block diagram, which was created based on equations (3) and (4), describing the DC motor model is illustrated in the Fig. 4.

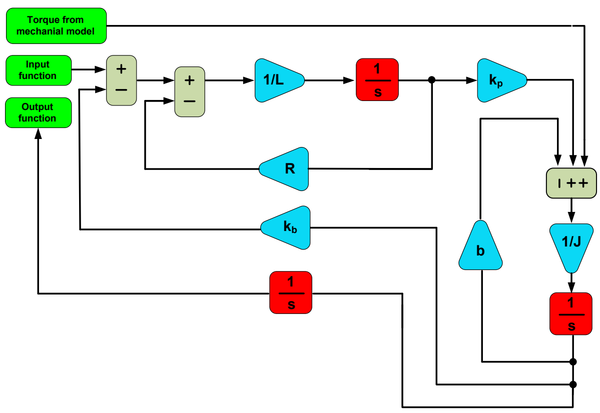

Figure 4. Block diagram of the DC motor model. Signal line connection from a mechanical model is illustrated.

The PID controller was added to the system with a feedback in each connector. The PID controller model is described by the equation:

$$u(t)=k_p\left(\varepsilon(t)+\frac{1}{T_i}\int_0^t\varepsilon(\tau)d\tau+T_d\frac{d\varepsilon(t)}{dt}\right) \tag{5}$$

where: $u(t)$ −control, k_p − proportional gain, T_i − integration time, T_d −derivative time, $\varepsilon(t)$ −error time.

The block diagram, which was created on the basis of equation (5), describing the PID controller model is illustrated in the Fig. 5. The control from the PID controller is sent via the signal line to the input of the mechanical model.

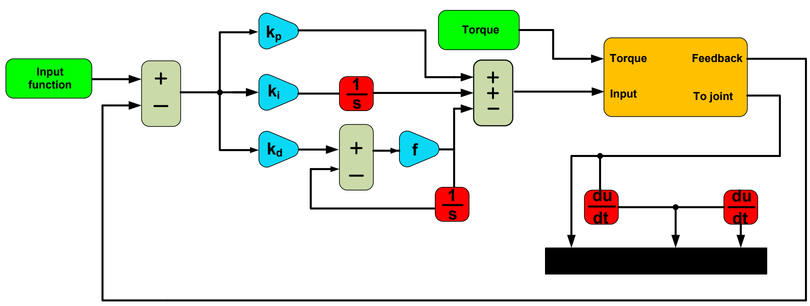

Figure 5. Block diagram of the PID controller, subsystem of surgical robot and derivative part as input to joint.

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The selection of regulator's settings was made with the usage of gradient descent optimal method.

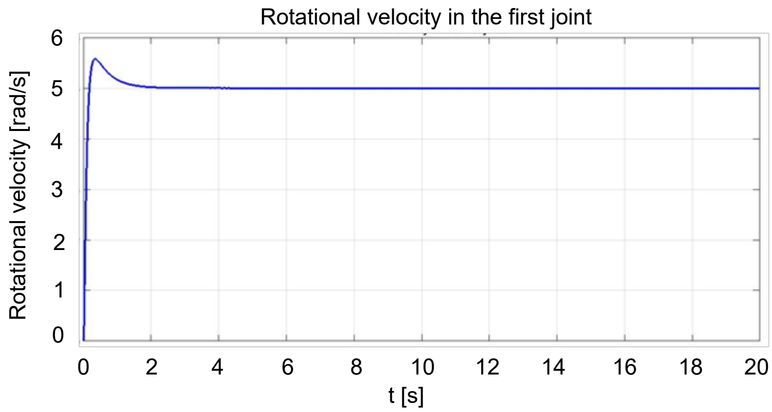

Figure 6. Step response in the first joint.

The testing of a step response for the first joint of surgical robot is illustrated in the Figure 6. The shape of the response indicates that the indicators of quality regulation achieve correct values.

4.3. LuGre model of friction

The differential equation of dynamics including the LuGre's friction model is stated as:

$$\sigma_0 \cdot z + \sigma_1 \cdot \dot{z} + \sigma_2 \cdot \dot{x} = F, \tag{6}$$

where: σ_0 – surface stiffness, σ_1 –fiber suppression, σ_2 – viscous friction, z – average deflection of adjoining surfaces. We also know that:

$$\frac{dz}{dt} = \dot{x} - \frac{\sigma_0}{g(v)} \cdot \dot{z} \cdot |\dot{x}| \ . \tag{7}$$

The Stribeck effect describes the equation:

$$g(v) = F_c + (F_s - F_c) \cdot e^{\left(-\frac{\dot{x}}{v_S}\right)^2}, \tag{8}$$

where: F_c – Coulomb friction, F_s –Stribeck friction, v_s – Stribeck's velocity.

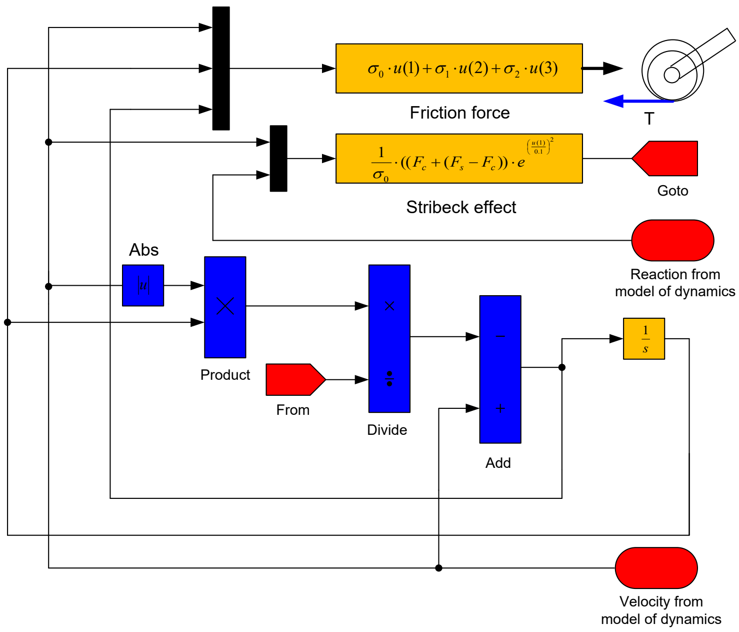

Figure 7. Block diagram of LuGre's friction model.

To determine the value of the friction force, a velocity line $v = \dot{x}$ calculated in the robot's joint is led into the block diagram describing the LuGre's friction model shown in Fig 7.

5. Results

The solution of dynamics model was made by using the Runge-Kutta method of the 4th order. For the optimal geometry of the kinematic chain, courses of drive torque with friction in next joints of a surgical robot were obtained as shown in Figs 8-10.

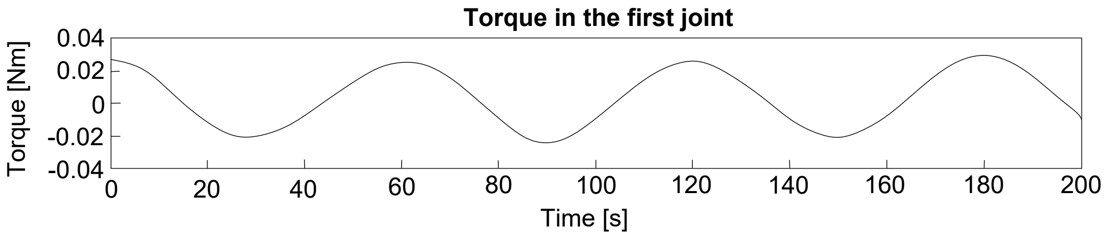

Figure 8. The driving torque in the first joint of the surgical robot.

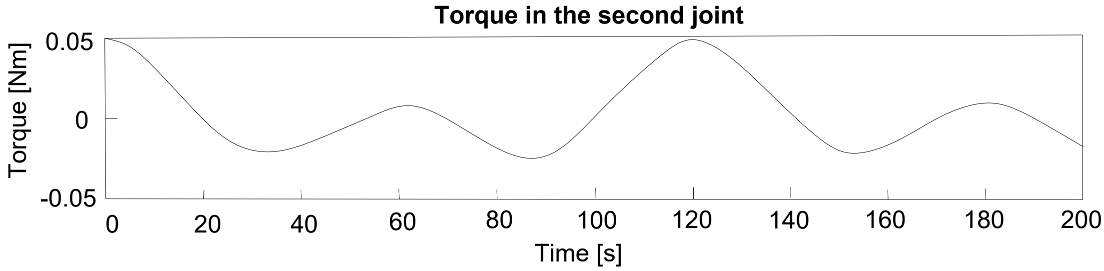

Figure 9. The driving torque in the second joint of the surgical robot.

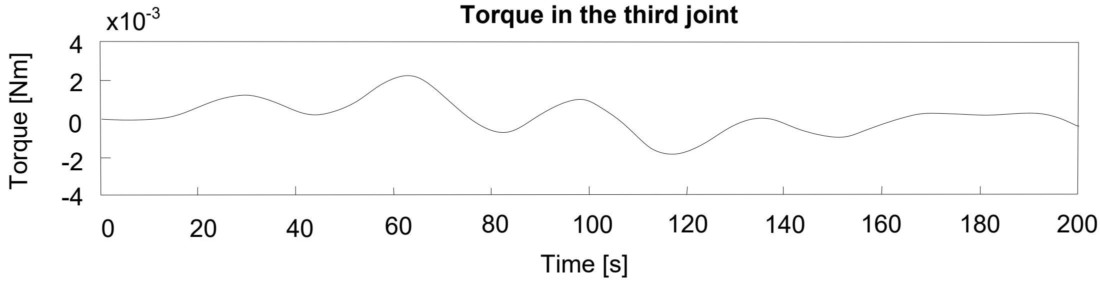

Figure 10. The driving torque in the third joint of the surgical robot.

The obtained results of the driving torques, taking into account the impact of friction determined by the LuGre model, allow the selection of DC motors characteristics close to reality due to the fact that the solved model gives an answer to the question of how large are the friction values in the joints of a surgical robot with an open kinematic chain.

6. Conclusions

The goal of the work was to create a dynamics model of a surgical robot, taking into the account the resistance movement, with significant complications. The obtained research results are of a great importance in the area of mechatronics and biomechanics because they describe the behavior of a medical robot structure close to real, due to the fact that a numerical model assumes most of the interactions occurring during the movement in the operating field. The methodology of creating a dynamical model of a medical robot illustrated in this work, including the frictional interactions of LuGre model, is characterized by a high applicability. The applied method of block diagrams enables in a simple way to replace any mathematical equations describing the course of physical phenomena appropriate blocks in the Simulink program and their effective solution. The solution of the numerical model was made by using the Runge-

Kutta method of the 4th order. The application of the finite element method enabled to obtain the optimal geometry of the medical robot for given limitations. Based on the finite element method, the response surfaces were determined, which served as a continuous input data functions for the genetic algorithm, which in the iterative process, based on the Pareto fronts, made it possible to obtain an optimal solution. In further works, it is planned to investigate the effect of the Dhal, Dupont and Maxwell (GMS) models of the friction on the dynamics of a medical robot with an open kinematic chain.

Additional information

The author declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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