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DYNAMICS OF MULTIBODY SURGICAL ROBOTIC SINGLE INCISION LAPAROSCOPIC SURGERY TOOL

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Abstract: *The current paper introduces a method for modeling the dynamics of highly specialized robotic tools, used in the Minimally Invasive Surgery (MIS) or Single Incision Laparoscopic Surgery (SILS) operations. The method is based on an original approach presented in detail in (Wittbrodt et al, 2016). The kinematic model of the analyzed laparoscopic tool was presented earlier in (Leniowski et al., 2010). In the current paper the model is extended by including the dynamics of the tool and the flexibility of its links. Numerical results demonstrate the influence of loading conditions on accuracy of movements of the end effector.*

Keywords: Dynamics modelling, Flexible links modelling, Multibody system, SILS, MIS.

1. Introduction

Modern medicine is growing rapidly due to the use of modern mechatronic devices supporting surgeons in standard surgical interventions. Among different solutions, special attention is paid to technologically advanced surgical robots, dedicated to minimally invasive surgery (MIS) – laparoscopic surgery. Such treatments are performed with the introduction of tools (endoscopic cameras and other laparoscopic tools) through small incisions in the patient's abdominal wall. This method is used successfully since the early 90s of the twentieth century. An extension of the classical technique MIS operations is single incision laparoscopic surgery (SILS). This method is also referenced in the literature as single-port access (SPA) surgery or minimal access surgery through a single incision (MASTSI). With the SILS procedure, the cosmetic effect is even better than with the MIS technique. However, the SILS is much more difficult to implement than the MIS.

Usually, the dynamics of surgical tools is not analyzed. This is perhaps due to the prevailing popular opinion that surgical robots move so slowly that their dynamics may be neglected. However, the engineering practice indicates that there is a need to include the dynamics of flexible, multibody laparoscopic tools in order to improve the accuracy of their movements. The current paper introduces a method for modeling the dynamics of highly specialized surgical robotic SILS tool – multibody open kinematic chain with flexible beam-like links, dedicated to different robotic surgical procedures.

2. Materials and Methods

Modern surgical tools used in MIS techniques usually take form of a pipe with diameter of 5 or 10 mm and length of approximately 500 mm. The tool is equipped with a system of tendons routed inside the pipe for opening or closing the end effector (e.g. a gripper). The tendons are pulled by a system of levers driven by the operator's hand. The tool is also equipped with a locking clamp and a rotating head at the main arm. The tool has the interface to connect the apparatus to the pneumoperitoneum and to plug-in the electric system necessary to operate the coagulant. Surgical tools for SILS techniques are more complicated because they are equipped with multiple arms with different end effectors. In this case the tool diameter is usually greater due the fact that it may consist of two (or more) active arms in the operating field and an additional arm with an integrated endoscopic camera. Operating the part of the tool above the integument is very complicated and exhaustive for the surgeon. On the other hand, mounting

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the tool on an arm of a surgical robot is troublesome, as the robots are not usually equipped with multiple end effectors to operate several arms of the SILS tools.

Therefore, for the purposes of robotic minimally invasive surgery, a novel concept of a tool having the structure of an open kinematic chain with six degrees of freedom has been proposed. The kinematic chain is made of six links connected with rotary joints. The links are driven with integrated gears and micromotors installed at the joints of the mechanism. The tool is designed so that it can be attached not only to a specialized surgical robot, but also to an arm of a typical industrial robot adapted for an operating theater. This way the implementation costs of the robotic surgery system may be considerably reduced. The kinematic structure of the novel robotic tool has been adopted from the structure of a similar tool proposed by (Leniowski et al., 2010). The CAD model of the SILS robotic tool has been designed in SolidWorks (Fig. 1a) with all components of the system made of the targeted material. The kinematic chain is shown in Fig. 1b. The model has been used to test the possible mobility of the tool and decide how to manufacture its prototype. The model has been also used to evaluate inertia properties of the links: masses, mass moments of inertia, locations of centers of masses. These parameters have been included in the dynamical model of the tool developed with the rigid finite element method and implemented in Matlab.

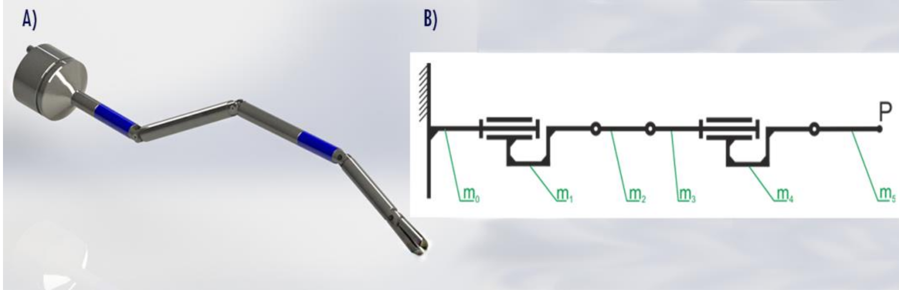

Fig. 1: Surgical robotic tool for SILS procedures (A) and its kinematic structure (B).

The original method of modeling the dynamics of open kinematic chains of multibody systems presented in this section is described in detail in works. The origins of this method go back to the scientific school created by Kruszewski (Kruszewski et al., 1999) and continued by Wittbrodt. The method was further improved and extended by Adamiec-Wojcik and Wojciech (Wittbrodt et al., 2006). The idea of this method consists in replacing a flexible link of a kinematic chain with a series of rigid finite elements, connected by spring-damping elements. In the so called primary division a single link of a multibody system modeled as a beam of length L_p and constant profile is divided into m_n sections of the same lengths. These sections are called *rigid finite elements* (*rfes*). In the secondary division the flexibility properties of the link are substituted in *spring-damping elements* (*sdes*) located at the middles of lengths of the *rfes*. This way the flexible link is divided into $m_p + 1$ rigid finite elements connected by m_p massless and dimensionless spring-damping elements. Coordinate systems are assigned to the *rfes* as follows: $\{0\}$ - inertial coordinate system, $\{p,0\}$ - coordinate system assigned to *rfe 0*, $\{p,i'\}$ - coordinate system assigned to *rfe i* in the undeformed state (the axes of this system are parallel to the principal, central inertial axes of *rfe i*), $\{p,i\}$ - local system assigned to *rfe i*, $\varphi_1^{(p,i)}, \varphi_2^{(p,i)}, \varphi_3^{(p,i)}$ - Euler angles ZYX. Index p denotes the considered flexible link of the kinematic chain. A detailed description of the discretization method is presented in (Kruszewski et al., 1999). Equations of motion of an open kinematic chain including the energy of spring deformation of flexible links can be presented as

$$\mathbf{A}\ddot{\mathbf{q}} + \mathbf{K}_R\mathbf{q} = \mathbf{Q} - \mathbf{G} - \mathbf{h} - \mathbf{S} \qquad (1)$$

where: $\mathbf{A}$, $\mathbf{h}$ are matrix and vector components of Lagrange's operator derived from the kinetic energy of the system, $\mathbf{G}$ is the vector of gravitational forces, $\mathbf{Q}$ is the vector of generalized external forces, $\mathbf{K}_R$ is the stiffness matrix, $\mathbf{S}$ is the vector of translational forces due to elastic deformation of the flexible link, $\mathbf{q}$ is the vector of generalized coordinates. The details on calculating the components of Eq. (1) using the rigid finite element method, generalized coordinates and Euler angles are described in (Wittbrodt et al., 2006).

For simulation purposes it has been assumed that the last link of the proposed tool is flexible. Therefore, it is presented as a system of three *rfes* of equal lengths connected with two *sdes*, following the discretization procedure described above (Fig. 2).

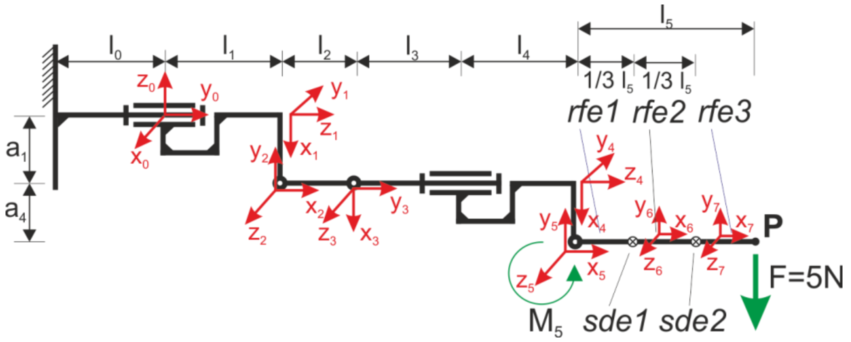

Fig. 2: Kinematic structure of the SILS tool after discretization of the last link.

Coordinate systems $x_1y_1z_1$, …., $x_5y_5z_5$ of the first five links are assumed in accordance to Denavit-Hartenberg notation used in the *rfe* method. Centers of the coordinate systems $x_6y_6z_6$, $x_7y_7z_7$ of the *rfes* are at their mass centers, and axes are at their principal, central inertial axes. Lengths of the links are as follows: $l_0 = 56$ *mm*, $l_1 = 51.09$ *mm*, $l_2 = 92$ *mm*, $l_3 = 56$ *mm*, $l_4 = 36$ *mm*, $l_5 = 150$ *mm*. The links are of equal diameter $D = 5$ *mm*. To reduce the total mass of the tool the links are made of the special, biomedical material called *PEEK* polymer (polyether ether ketone) of Young's modulus $E = 4$ GPa and density $\rho = 1320$ kg/m^3.

3. Results

Based on the mathematical model presented in the previous section, the simulation model of the SILS tool has been prepared in Matlab. The model contains of a set of seventeen nonlinear, time-variant equations of motion in the form given by Eq. (1). The vector of generalized coordinates q contains of five joint angles θ_1, ..., θ_5 about z_1, ..., z_5 axes, three linear and three angular deformations along/about x_6, y_6, z_6 axes of the first *sde*, and three linear/angular deformations along/about x_7, y_7, z_7 axes of the second *sde*. The equations are solved numerically using the implicit Newmark's integration scheme (Newmark, 1959). Rotations θ_1, ..., θ_5 at the joints are controlled with five proportional controllers in angular position closed-loop systems. During simulations the following test scenario has been assumed:

1) initial joint angles $\theta_{p|0}$ is defined in such a way that the axes of the first four links are aligned horizontally and the fifth link is directed vertically downwards;
2) proportional controllers maintain initial four angular positions θ_1, ..., θ_4 unchanged from their initial values by applying external force moments M_1, ..., M_4 to the links at the joints;
3) the 5th link changes its angular position from $\theta_{5|0} = 0°$ to $\theta_{5|f} = 90°$ by applying the external force moment M_5 (see: Fig. 3) generated at the 5th joint by the proportional controller;
4) the fifth link is loaded by an additional force $F = 5\ N$ applied at the end of the 5th link (at the tool center point, TCP) perpendicularly to x_7 axis (Fig. 3); the force simulates external loadings impacting the SILS tool due to the resisting action of tissues inside human's body;
5) the calculations are conducted twice: for the 5th link assumed as non-flexible (stiff), and for the 5th link assumed as flexible (non-stiff); for the stiff link, the 5th link is not divided into *rfes* and *sdes*.

Time histories of local joint angles θ_1, ..., θ_5 and vertical positions y_5, y_7 of the TCP in the global coordinate system are presented in Fig. 3. As can be seen, if the 5th link is assumed as stiff, the vertical position of the TCP changes smoothly from the initial $y_{5|0} = -0.15$ m to the final $y_{5|0} = 0$ m (Fig. 3b). If the 5th link is assumed as flexible, the vertical position of the TCP at the beginning changes in a similar manner (Fig. 3d). However, when the final position $y_{7|f} = 0$ m is attained, the oscillations of the tool tip appear. The amplitude of the oscillations is about 20 mm. Certainly, the oscillations would have a detrimental effect for the results of patient’s operation. Therefore, some technical measures should be undertaken to avoid them. The diameter of the tool links can be increased or the material of the links can be changed to be more stiff. However, not all of these solutions may be acceptable in a given design of the tool due to biomedical requirements of the SILS technique. It should be noted that these oscillations are not present in the time history of the θ_5 joint angle (Fig. 3c), which means that only the end part of the last link oscillates. Therefore, if only the angular position of the 5th link was measured, the positon controller would not react to these oscillations.

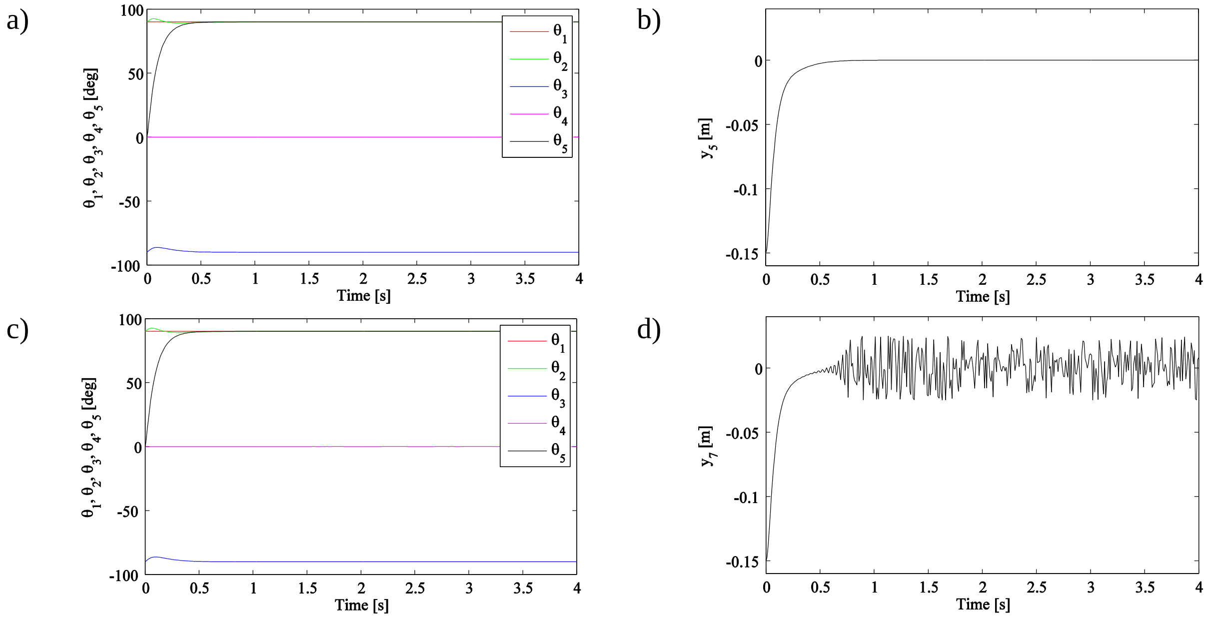

Fig. 3: Time histories of the manipulator: a) joint angles θ_1, ..., θ_5 (rigid 5th link), b) vertical position y_5 of the TCP in the global coordinate system (rigid 5th link), c) joint angles θ_1, ..., θ_5 (flexible 5th link), d) vertical position y_7 of the TCP’ in the global coordinate system (flexible 5th link).

4. Conclusions

The application of the presented rigid finite element method of modeling multibody systems can significantly accelerate the design process of novel laparoscopic tools for medical robotics. It has been demonstrated numerically that by using the method for the dynamics analysis of robotic SILS tools it is possible to evaluate their dynamic properties if the flexibility of links is assumed. This way the trajectory of the end effector can be tested in different loading conditions, for different geometric and material properties, etc. Control strategies for position controllers of the links can be also verified. The design process of the proposed SILS tool is underway and more accurate results will be presented soon.

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