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Automation of Drilling as Orthopaedic Manipulation

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Introduction

Recently the scientific investigations increase where the subject is the robot application in medicine. This can be understood also as a direct subsequence of fast development of an actual scientific research field – the force control strategies and methods for robot-manipulators as well as their successful application in specific contact task solution.

Robots in surgery

There are known various cases of successful adopting of robots as direct participants in separate steps of surgery intervention – for instance, prostatic adenoma treatment [2], kidney stones[3], tissue cutting, artificial knee-joint implantation [4], etc. Taking into account the specifics of robot-doing tasks, i.e. the objects under manipulation are human being organs, the main requirement here is to assure maximal reliability. All this leads to the understanding that the most expedient thing for surgery operation purposes is the usage of robots that are especially designed to do exactly determined manipulation. In this way it is possible to simplify maximally the robot mechanic system, to minimize its degrees of freedom, etc. [5]. The force effect level which must be achieved and applied on the object under manipulation is precisely weighed for every concrete case. This requirement needs excluding the possibilities of unknown deviations and unexpected trouble appearances. The mechanical system simplification to the possibly largest extent allows the adequate simple software and sensor system application what gives the surgeon the possibility to control the robot-made manipulation efficiently.

Control strategies

Two main approaches exist for robot application in surgery. They are determined according to the way the robot takes part in the operation step. The first one is based on entirely autonomous active robot system and the second – on entirely passive mechanic system. The first approach supposes maximal reliability functioning of the robot system since it does part of the operation by itself. The mechanical system motion control has to guarantee the working trajectory execution excluding the possible wrong deviations. But the passive mechanical system usage has much lower risk since the motion is executed and controlled directly by the surgeon doing the operation. The passive-hand role is to eliminate the working instrument oscilations during a concrete manipulation time. The lack of actuators in the mechanical structure makes it inapplicable in the cases where the specific trajectory has to be executed.

A third possibility is proposed [4], which consists of active and passive approach combination for robot system control. During a working regime the operation surgeon leads the robot mechanic system motion which is limited in preliminary determined region. The method of implicit force control [1,4] is used for permitted robot motion trajectories where the force applied by the surgeon on the mechanic system during its motion is taken into account.

Peculiarity of drilling as orthopaedic manipulation

The treatment of various bone system trauma often supposes the orthopaedic screw implantation. This requires drilling (in part or at all) of the corresponding bones. The main problems when hand-drilling takes place can be described as follows:

- probability of excessively large outgoing outlet for the drilling hole;
- necessity of tissue removing on both bone sides (which additionally involves complexities during the rehabilitation after operation);
- bone overheating caused by inappropriate drilling velocity;
- hole diameter variations for the reason of instrument oscilation during drilling process.

The problems above mentioned are discussed and clarified with the help of surgeons working in the Emergency medical institute "Pirogov". These problems are entirely caused by the fact that the bone drilling is made by hand as well as that subjective surgery behaviour is decisive for the final result quality of the operation. So that the drilling automation can neutralize (to some extent) the subjective factor and solve the problems mentioned until now.

The mechanical system choice and its mathematical model

Taking into account the working task – the drilling of the human being bone as well as the maximal reliability requirement of the manipulation, it is expedient to choose the mechanical system consisting of tree-like structure with two degrees-of-freedom realized by fifth-class joints (one translational and one rotational) having colinear axes [Fig. 1]. For mathematical model derivation other two joints are considered which role will be clarified later but here their state will be reckoned as fixed on the system basement.

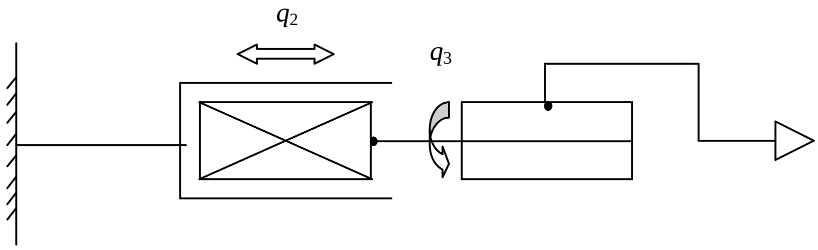

Fig. 1. The mechanic system kinematic structure

The mathematical model is derived by graph theory and the Orthogonality principle [6]. The structure is associated with the structure graph G_h , consisting of two connected elements G_{tr} and G_r is shown in Fig. 2 (in Fig.2 only G_{tr} is shown; in this case G_r is coinciding with G_{tr} where the difference between them is in the associated with the arcs other parameters, named fundamental across and through variables).

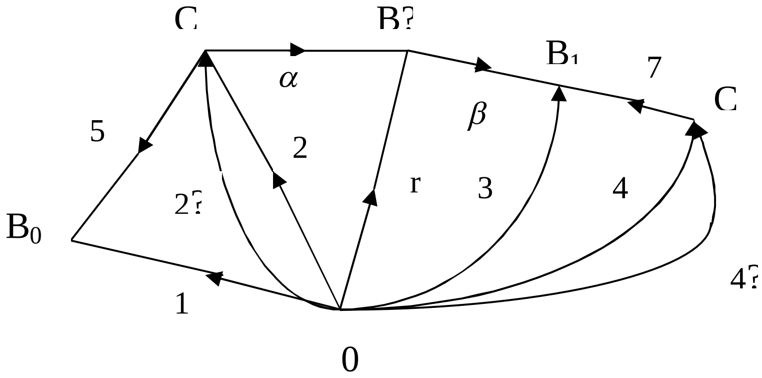

Fig. 2. Graph assigned to the mechanical system

The numbers of the graph edges interpret the following variables [6]:

For graph G_{tr}

A) Through variables:

1) D'Alamber forces F_{2k}, $k = 1, 2$, associated with the arcs $2k$;

2) External forces $F_{(2k)}$, $k = 1, 2$, acting on body k;

3) Forces F_{2k-1}, $k = 1, 2$, acting on the terminal points B_{ij} and the beginning 0 of the inertial system. Only $F_1 = 0$;

4) Forces F_l^c, $l = 2n + 1, \dots, 4n - 1$; $n = 2$, presenting the interaction between contiguous body.

B) Across variables.

Radius-vectors of the mass-centers and the terminal points B_{ij} are the across variables for all arcs with beginning 0 and the local radius-vectors of the points B_{ij} compared to the mass centers C_i for the remaining arcs.

For the formulating tree arcs with numbers from 1 to $2n$ ($n = 2$) are chosen and all other arcs are chords.

For graph G_r

A) Through variables

1) D'Alembert torques T_{2k}, associated with arcs $2k$ ($k = 1, 2$);
2) External torques $T_{(2k)}$, $k = 1, 2$, acting on body k;
3) Torques T_{2k-1}, $k = 1, 2$, for interaction between the terminal points and the inertial beginning;
4) Torques T_l^c , $l = 2n - 1, \dots ,4n - 1$; $n = 2$, for interaction between contiguous bodies.

B) Across variables.

For arcs beginning with 0, across variables are the absolute angle speeds of the bodies, to which points those arcs are directed (points B_{jk} are considered as points of body with number j). Across variables for arcs with number from 5 to 7 describe the relatively angle speeds, as well as across variables with odd numbers are zeros according to the admission for points B_{jk} to be regarded as appliance to the body with number j.

In our case the differential equations have the form

$$\begin{bmatrix} m_2 & 0 \\ 0 & J_{33}^2 \end{bmatrix} \begin{bmatrix} \ddot{q}_2 \\ \ddot{q}_3 \end{bmatrix} = \begin{bmatrix} F_6 - F_{4''} \\ T_7 - T_{4''} \end{bmatrix},$$

where

m_2 is the second link mass of the mechanical structure;

$$J_{33}^2 = \frac{3}{80} m \left(4r^2 + h\ \right),$$

$m = m_2$,
r – the radius of the cone (the cartridge-chamber),
h – the height of the cone,
F_6 – translation joint actuator force,
T_7 – rotation joint actuator moment,
F_4 – external force,
T_4 – external moment,
q_2, q_3 – joint variables.

The notations are in correspondence with the system graph edges numbering which is used for the differentiation equations derivation.

The control law synthesis

The control law synthesis is done on the basis of the mathematical model and the Servocontrol method by standard corrections [7]. The forces of interaction appearing during the drilling process due to variable bone density are taken into account.

Conclusion

Summarizing, it can be said that the problem discussed here is a very interesting practical task which is under development. Its successful solution will definitely affect the precision of operations connected with orthopaedic screw implantations as well as hole drilling in human being bones.

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Автоматизация пиления как ортопедическая манипуляция

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(Р е з ю м е)

Обсуждается применение роботов в хирургии, и более специфично – при ортопедической манипуляции пиления костей в человеческом организме. Проблем является очень интересным и актуальным в связи со современном увеличением применения роботов в медицине.