БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ • BULGARIAN ACADEMY OF SCIENCES

ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, **56**
PROBLEMS OF ENGINEERING CYBERNETICS AND ROBOTICS, **56**

София • 2006 • Sofia

Experimental Verification of the Control of Automatic Drilling Module in Surgery

Tony Boiadjiev[1], *Kazimir Zagurski*[1], *Vladimir Vitkov*[2], *George Boiadjiev*[2]

[1] *Central Laboratory of Mechatronics and Instrumentation, 1113 Sofia*
URL: http://www.clmi.bg
E-mail: Tonyboev@clmi.bas.bg
[2] *Institute of Mechanics, 1113 Sofia*
URL: http://www.imbm.bg
E-mail: George@imbm.bas.bg

1. Introduction

Various cases of successful adopting of robots as direct participants in separate stages of surgery intervention are known – for instance prosthetic adenoma treatment, kidney stones, tissue cutting, artificial knee-joint implantation, etc. [1, 2, 3, 5, 7, 8]. Taking into account that the objects under manipulation are human being organs, the main requirement here is the *maximal reliability* to be assured. All that leads to the understanding that most expedient thing for surgery operation purposes is the usage of robots that are especially designed to do exactly determined manipulation. This allows simplifying maximally of the robot mechanical system, the minimization of its degrees of freedom, etc. The force effect level, which must be achieved and applied on the object under manipulation, is precisely weighted for every concrete case. This requirement must exclude 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 allows the surgeon to control the robot-made manipulation efficiently.

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

- bone overheating caused by inappropriate drilling velocity,
- probability of excessively large outgoing outlet for the drilling hole,

• necessity of tissue removing at both bone sides (which additionally involves complexities during the rehabilitation after operation);

• hole diameter variations due to instrument oscillation during the drilling process.

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. Hence the drilling automation can neutralize (to some extent) the subjective factor and solve the problems above mentioned.

2. Recent research

The purpose of the work is: *Experimental results presentation showing the drilling execution according to the synthesized control law in different regimes taking into account the resistant force.*

2.1. Mathematical model

The mathematical model is derived by graph theory and the Orthogonality principle [9, 10, 18]. The system kinematics structure R⊥T||R is chosen for the drilling module interpretation and the graph G_h (Fig.1) is associated with this mechanical structure.

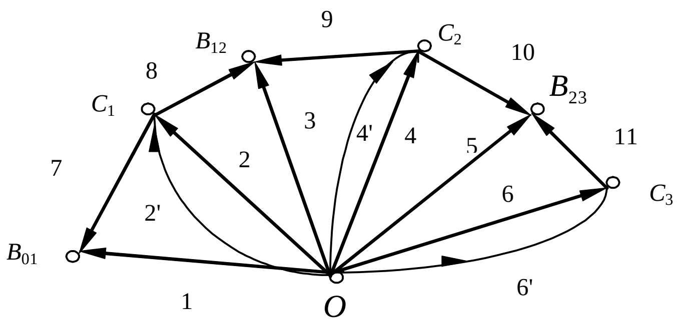

Fig.1. Graph assigned to the mechanical system

The differential equations are obtained in the form

(1) $$A\ddot{q} = B,$$

where

$$a_{11} = I_{33}^{(1)} + m_1 r_7^2 + m_2(h_2 + q_2)^2 + m_3\Big[r_7^2 + (r_8 + q_2)^2 + r_9^2 + r_{10}^2 + r_{11}^2 +$$
$$+ 2(r_8 + q_2)(r_7 + r_9 + r_{10} + r_{11}) + 2r_7(r_9 + r_{10} + r_{11}) + 2r_9(r_{10} + r_{11}) + 2r_{10}r_{11}\Big] +$$
$$+ I_{22}^{(2)} + s^2q_3 I_{11}^{(3)} + 2sq_3cq_3 I_{12}^{(3)} + c^2q_3 I_{22}^{(3)};$$

$$a_{12} = a_{21} = a_{23} = a_{32} = 0; \quad a_{13} = a_{31} = I_{32}^{(3)}; \quad a_{22} = m_2 + m_3; \quad a_{33} = I_{33}^{(3)}.$$

$$b_{11} = \dot{q}_1^2\left(s^2q_3cq_3 + s^2q_3cq_3 I_{31}^{(3)} - 2sq_3c^2q_3 I_{32}^{(3)}\right) - \dot{q}_3^2\left(cq_3 I_{13}^{(3)} - sq_3 I_{23}^{(3)}\right) -$$
$$- \dot{q}_1\dot{q}_3\left(sq_3cq_3\left(I_{11}^{(3)} - I_{33}^{(3)}\right) - I_{21}^{(3)} - cq_3sq_3\left(I_{33}^{(3)} - I_{22}^{(3)}\right) - m_3h_3 - 2I_{21}^{(2)}\right) +$$
$$+ 2\dot{q}_1\dot{q}_2\left(sq_3cq_3\left(I_{11}^{(3)} - I_{22}^{(3)}\right) - q_2(m_2 + m_3)\right) - 2\dot{q}_1^2\dot{q}_2\left(sq_3 I_{13}^{(3)} + cq_3 I_{23}^{(3)}\right) -$$
$$- g(h_1m_1 + h_2m_2 + h_3m_3 + q_2(m_2 + m_3))cq_1 + T_7;$$

$$b_{12} = -\dot{q}_1^2 r_9 - \dot{q}_2 \dot{q}_1^2 (m_2 + m_3) + (m_2 + m_3) g + F_{6'}^{(s)} + F_9;$$

$$b_{13} = -\dot{q}_1^2 \left[I_{21}^{(3)} (s^2 q_3 - c^2 q_3) + sq_3 cq_3 (I_{22}^{(3)} - I_{11}^{(3)}) \right] + 2\dot{q}_1 \dot{q}_2 (sq_3 I_{32}^{(2)} - cq_3 I_{31}^{(2)}) -$$

$$- \dot{q}_1 \dot{q}_3 (sq_3 I_{23}^{(3)} - cq_3 I_{13}^{(3)}) - \dot{q}_1^2 \dot{q}_2 I_{33}^{(3)} - T_{6'}^{(s)} + T_{11}.$$

In the equations the following notations are also made,

m_k is the k-th body mass of the mechanical structure k = 1, 2 , 3;

$I_{sp}^{(k)}$ – inertia tensor components of body k, k = 1, 2, 3;

$$J_{33}^{(3)} = \frac{3}{80} m_3 \left(4r^2 + h \right);$$

r – the radius of the cone (the cartridge-chamber);

h – the height of the cone;

F_9 – translation joint actuator force;

$F^{(s)}_{6'}$ – external resistant force;

T_7 , T_{11} – rotational joint actuator moments;

$T^{(s)}_{6'}$ – external resistant moment;

q_1, q_2, q_3 – joint variables;

h_i – the distance between O_0 and the mass centers C_i. The notations are in correspondence with the system graph edges numbering.

2.2. Synthesis of the control law

The dynamic control is stated on the basis of the motion equations written in the form [10-13, 17, 20].

(2) $$\mathbf{A}(\mathbf{q}(t))\ddot{\mathbf{q}}(t) + \mathbf{b}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) = \mathbf{u}(t).$$

The signal $\mathbf{u}(t)$ consists of three components:

(3) $$\mathbf{u}(t) = \mathbf{u}_{\text{fb}}(t) + \mathbf{u}_{\text{d}}(t) + \Delta\mathbf{u}(t).$$

The first one expresses the feedback for the joint variables:

(4) $$\mathbf{u}_{\text{fb}}(t) = (\hat{\mathbf{A}} - \mathbf{I})\ddot{\mathbf{q}}(t) + \hat{\mathbf{b}} - \mathbf{K}_2 \dot{\mathbf{q}}(t) - \mathbf{K}_1 \mathbf{q}(t).$$

The second one involves the information for the desired motion:

(5) $$\mathbf{u}_{\text{d}}(t) = \ddot{\mathbf{q}}_{\text{d}}(t) + \mathbf{K}_2 \dot{\mathbf{q}}_{\text{d}}(t) + \mathbf{K}_1 \mathbf{q}_{\text{d}}(t).$$

The third component is obtained from (3), after rewriting and taking into account both components – the first and second:

(6) $$\Delta\ddot{\mathbf{q}}(t) + \mathbf{K}_2 \Delta\dot{\mathbf{q}}(t) + \mathbf{K}_1 \Delta\mathbf{q}(t) = \Delta\mathbf{u}(t) - \Delta\mathbf{f}(t),$$

where $\Delta\mathbf{q}(t) = \mathbf{q}(t) - \mathbf{q}_{\text{d}}(t)$. The element $\Delta\mathbf{f}$ reflects the external force and torque influence. Its compensation is made exactly by the third component $\Delta\mathbf{u}(t)$, which is formed by the standard corrections for joint variables.

2.3. Experimental determination of the resistant force

The experimental setup [16, 18] used for data base creation about the resistant force, consists of translation module driven by a step DC-motor and a servo DC-motor executing the drilling process. The speed of the last motor is 800 cycles/min and the speed of the linear module is 1mm/s. The object under manipulation is fresh caw bones which are very similar to the human being ones.

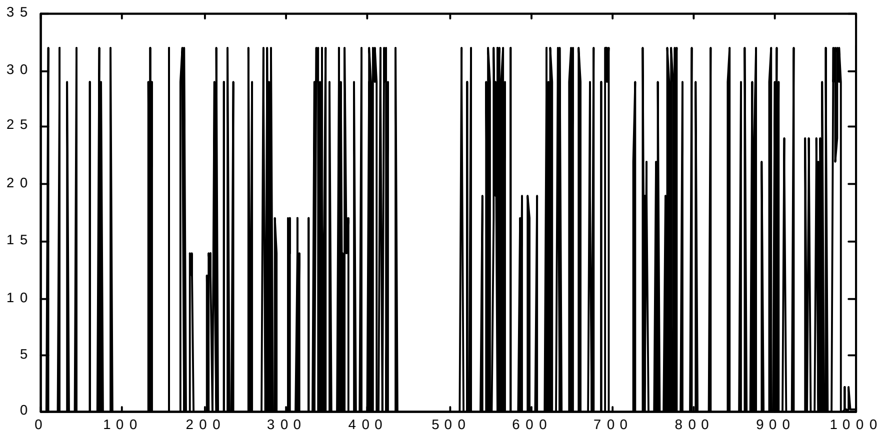

Fig. 2. Force sensor data during the whole drilling process for the tube-type bone

The sensor data are taken at every 5 ms time-interval. They are changed up to 25-35 N in a jumping-style manner. The maximal force and the existence of “long zero” values [16, 18] can be taken as a criterion to change the control of the process according to a different regime.

3. Experimental results and graphic visualization

The results bellow concern the translation module only because the second drive differs just by the concrete numbers describing the joint positions and speeds executing the same control task. The desired motion is given according to the working task formulation and the standard corrections are obtained by numerical integration.

The system control includes:

- constant speed of the two module’s subsystems motion (linear and angular);
- smooth regulation of both speeds from their current values to zero.

Below the experimental results are shown concerning the actuator speed and position during constant velocity maintaining as well as in the case of velocity value change (Figs.3 and 4); the actuator speed and position during smooth stopping at different values of the feed-back coefficients (Figs.5, 6, 7, 8); the actuator speed and position during smooth starting and stopping (Figs. 9, 10).

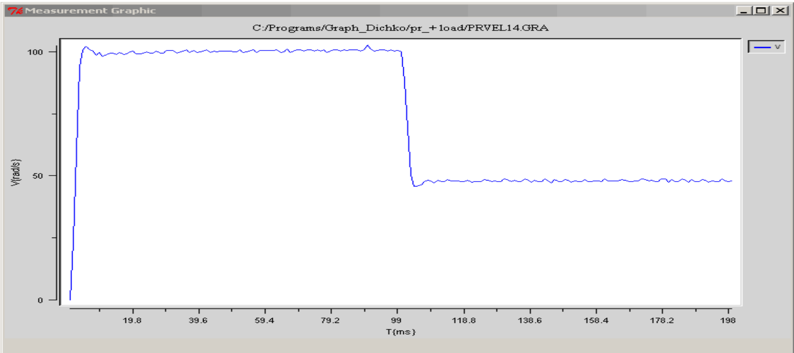

Fig. 3. Linear motion (*V*, rad/s) with velocity change (*T*, ms)

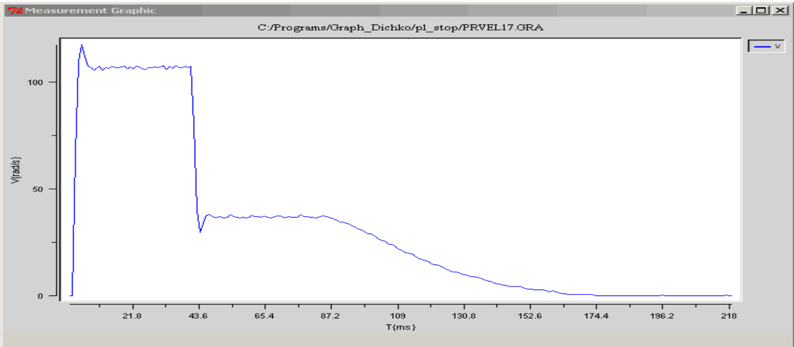

Fig. 4. Position during linear motion (*V*, rad/s) and velocity change (*T*, ms)

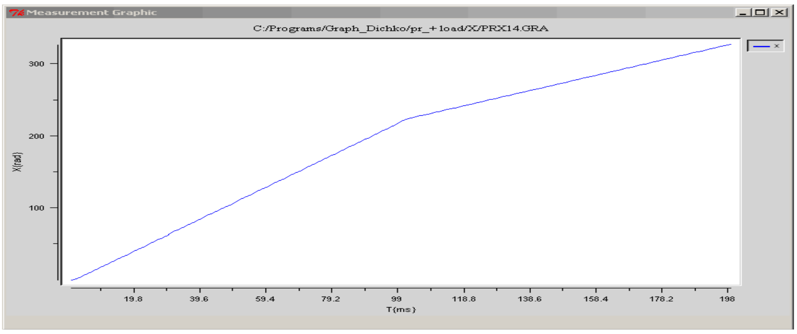

Fig. 5. Velocity during a motion (*X*, rad) realizing smooth stopping (*T*, ms)

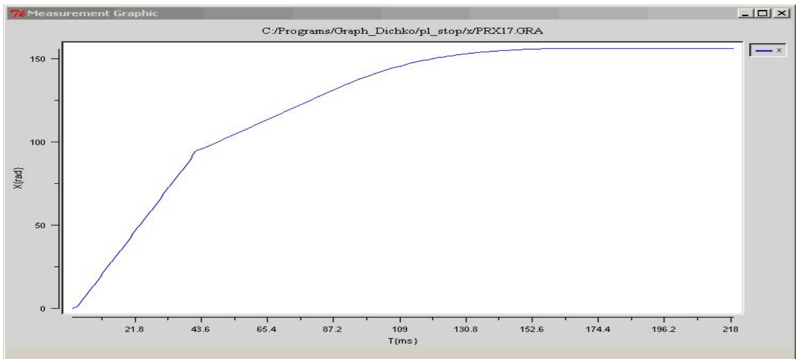

Fig. 6. The actuator position (*X*, rad) during smooth stopping (*T*, ms)

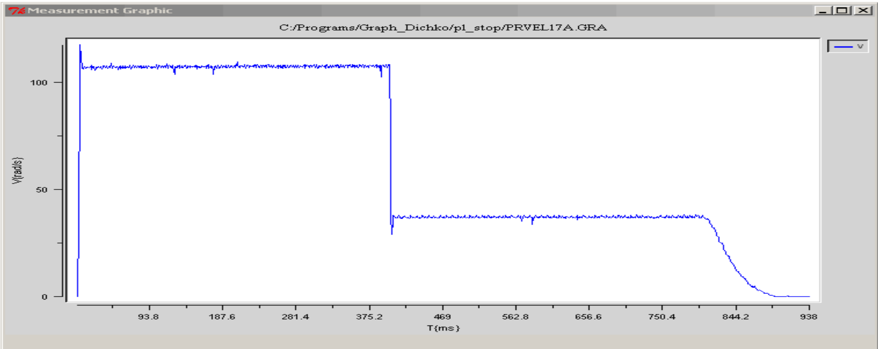

Fig. 7. Velocity (V, rad/s) during smooth stopping (T, ms)

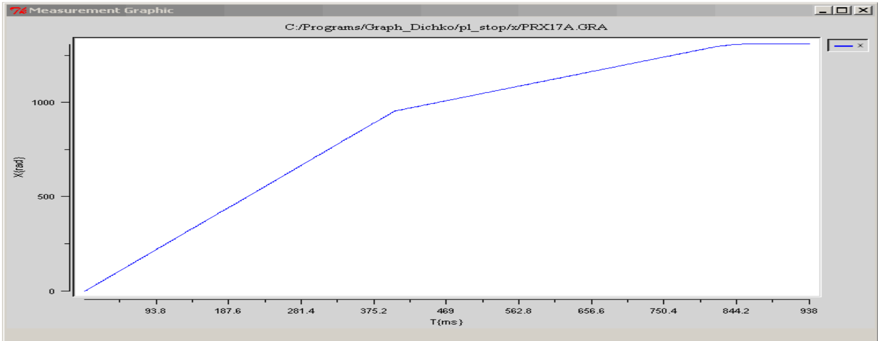

Fig. 8. The actuator position (X, rad) during smooth stopping (T, ms)

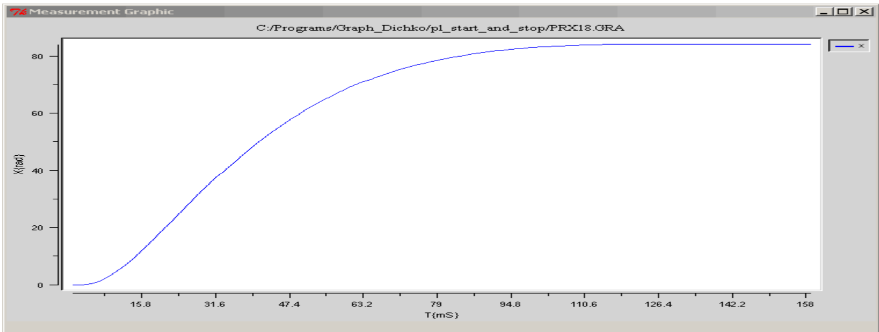

Fig. 9. The actuator position (X, rad) during smooth starting and stopping (T, ms)

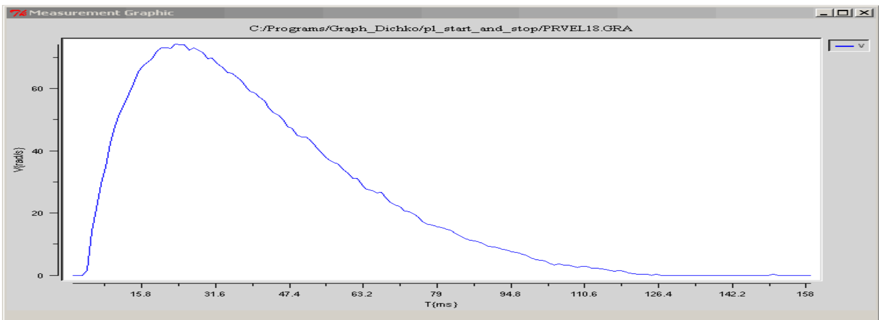

Fig. 10. The actuator velocity (V, rad/s) during smooth starting and stopping (T, ms)

4. Summary

The work presents experimental results showing the bone drilling execution according to the synthesized control law in different regimes taking into account the resistant force. A mathematical model is obtained by the graph theory and the Orthogonality principle. An experimental setup is completed for arranging the data concerning real bones drilling. The control law synthesis is done on the base of the mathematical model and the Servocontrol method by standard corrections. The forces of interaction appearing during the drilling process due to variable bone density are taken into account. This work presents results, which are a part of the mechatronic device future design for surgery drilling automation. Its successful completing and practical application will reduce and solve the problems appearing during the orthopedic drilling operation.

In the last years it is seen that more and more scientific works are devoted to robots application in surgery and especially in the orthopedic one in part. As a proof of that the foundation of "The International Society for Computer Assisted Orthopedic Surgery" can be mentioned. The main themes of this symposium include also the computer investigations and automatic manipulations in orthopedic surgery. The activities connected with the foundation of new organizations as well as the appearance of new scientific meetings devoted to specific tasks and problems – all that proves the arising interest to this really actual field and guarantees its development in the future.

References

1. Saha, S., S. Pal, A. Albight. Surgical Drilling: Design and Performance of an Improved Drill. – Journal of Biomech. Eng., Vol. **104**, 1982, 245-252.
2. Petrov, N., G. Popov, S. Mechkarski. Freeze-Drying Effect and Gamma-Sterilization on the Longitudinal Elastic Modulus of Bone Transplants. – Journal of Biomechanics, Vol. **12**, 1982, 30-33.
3. Davies, B. L., R. D. Hibberd, A. G. Timoney, J. E. Wickhan. Mechanical Constraints – the Answer to Safe Robotic Surgery. – Innovation and Technology in Biology and Medicine, Vol. **13**, 1992, No 4, 426-436.
4. Zamanov, V. B., D. N. Karastoyanov, S. M. Sotirov. Mechanics and Control of Robots. Sofia, Litera print, 1993.
5. Ho, S. C., R. D. Hibberd, B. L. Davies. Robot Assisted Knee Surgery. – IEEE Mag. Engineering in Medicine and Biology, Vol. **14**, 1995, No 3, 292-300.
6. Bouazza-Marouf, K., J. Browbank, J. R. Hewitt. Robot-Assisted Invasive Orthopedic Surgery. – Mechatronics Int. J., Vol. **6**, 1996, No 3, 381-397.
7. Allotta, B., F. Belmonte, P. Dario, L. Rinaldi. The Control of Penetration in a Mechatronic Drill for Orthopedic Surgery. – In: Proc. Multiconf. Computational Engineering in Systems Applications, Symp. "Robotics and Cybernetics", Lille, France, 1996, 222-227.
8. Allotta, B., G. Giacalone, L. Rinaldi. A Hand-Held Drilling Tool for Orthopedic Surgery. – In: IEEE Trans. on Mechatronics, Vol. **2**, December 1997, No 4, 218-229.
9. Boiadjiev, G., D. Vassileva. Redundancy Influence on Mechatronic System Sensibility. – In: Proc. of the First Int. Symposium on Mechatronics, Chemnitz 2002, ISBN 3-00-007504-6, 425-434.
10. Boiadjiev, G., R. Kastelov, T. Boiadjiev, D. Vassileva. Robot Application in Medicine for Orthopaedic Drilling Manipulation. – In: The 8th Mechatronics Forum International Conference on Mechatronics 2002, Twente, Netherlands. (CD), ISBN 9036517664. Book of Abstracts, ISBN 9036517672. 87 p.

11. B o i a d j i e v, G., T. B o i a d j i e v. Dynamic Control of Manipulation Robots by Standard Corrections. Theoretical and Experimental Analysis and Results. – Int. Journal "Information – Theories&Applications", Vol. **8**, 2001, No 3, ISSN 1310-0513, 158-168.
12. B o i a d j i e v, T., G. B o i a d j i e v. Drilling Orthopedic Manipulation. Control Law Synthesis. Edition of Scientific Machine Union, Drianovo,Vol. **5**, 2001, ISSN 1310-3946, 2.65-1.73 (in Bulgarian).
13. B o i a d j i e v, T., G. B o i a d j i e v. Force Control Synthesis During Interaction with Variable Density Environment. – In: 9th National Congress on Theoretical and Applied Mechanics, Varna 2001, Vol. **2**, ISBN 954-9526-10-0, 88-94.
14. B o i a d j i e v, T., G. B o i a d j i e v. Automation of Drilling as Orthopedic Manipulation. – Problems of Engineering Cybernetics and Robotics, Vol. **53**, 2002, 118-122.
15. B o i a d j i e v, G., R. K a s t e l o v, T. B o i a d j i e v, D. V a s s i l e v a. Robot Application in Medicine for Orthopaedic Drilling Manipulation. – In: The 8th Mechatronics Forum International Conference on Mechatronics 2002, Twente, Netherlands. (CD), ISBN 9036517664, Book of Abstracts, ISBN 9036517672. 87 p.
16. B o i a d j i e v, T., V. V i t k o v, G. B o i a d j i e v, K. Z a g u r s k i. Experimental Set-up for Resistant Force Determination during Bone Drilling. – Edition of Scientific Machine Union, Drianovo, 2002, Vol. **5**, ISSN 1310-3946, 3.35-3.40 (in Bulgarian).
17. B o i a d j i e v, T., G. B o i a d j i e v. Control Voltage Synthesis during Orthopedic Drilling Manipulation at the Presence of Resistant Force. Edition of Scientific Machine Union, Drianovo, 2003, Vol. **5**, ISSN 1310-3946, 2.11-2.16 (in Bulgarian).
18. B o i a d j i e v, T., G. B o i a d j i e v, V. V i t k o v. Surgery Assisting Robot Module for Orthopedic Manipulation Bone Drilling. – In: 11th Int. Power Electronics and Motion Control Conference EPE-PEMC 2004, 2-4 Sept., Riga, Latvia, CD, ISBN 9984-32-033-2.
19. B o i a d j i e v, G., T. B o i a d j i e v, D. V a s s i l e v a, D. K a r a s t o y a n o v. Thermal Effects Evaluation during Robot Bone Drilling. – Edition of Scientific Machine Union, Drianovo, 2004, Vol. **5**, ISSN 1310-3946, 1.1-1.6 (in Bulgarian).
20. B o i a d j i e v, T., R. B o z k o v a, G. B o i a d j i e v, D. U z u n o v a. Control of Robot Systems for Bone Drilling Orthopedic Manipulation. – Edition of Scientific Machine Union, Drianovo, 2005, Vol. **5**, ISSN 1310-3946, 1.17-1.22 (in Bulgarian).

Экспериментальная проверка законов управления для автоматического сверлящего модуля в хирургии

Тони Бояджиев[1], *Казимир Загурски*[1], *Владимир Витков*[2], *Георги Бояджиев*[2]

[1] *Центральная лаборатория мехатроники и приборостроения, 1113 София*
E-mail: Tonyboev@clmi.bas.bg
[2] *Институт механики, 1113 София*
E-mail: George@imbm.bas.bg

(Р е з ю м е)

В статье представлены экспериментальные результаты для проверки законов управления, которые синтезированны для автоматического пробывающего модуля в хирургии. Сделана обосновка необходимости автоматизации сверления и анализированны проблемы, возникающие при субективном манипулировании. Приведены некоторые предыдущие исследования коллектива, касающие математического моделирования и уравнений движения, синтезирования управляющего сигнала и экспериментального определения силы сопротивления в процессе пробывания человечесих костей. Показаны графики, визуализирующие разные режимы движения при соответствующем управлении.