RIGA TECHNICAL UNIVERSITY

Atis VILKĀJS

ANALYSIS OF DYNAMICS OF POSITIONING SYSTEMS, OPTIMAL CONTROL AND SYNTHESIS OF CONSTRUCTIONS

Summary of Doctoral Thesis

Riga 2013

RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Machinery
Institute of Mechanics

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DOTORAL THESIS
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DECLARATION OF ACADEMIC INTEGRITY

I declare that I have worked the thesis that has been submitted for the degree of Doctor of Engineering Sciences (or other) to Riga Technical University. The thesis for the degree of Doctor has not been submitted to any other university.

Atis Vilkājs ……………………………. (Signature)

Date: ………………………

The thesis has been written in Latvian. The thesis contains the introduction, 6 chapters, conclusions, reference list, 2 appendices, 119 figures and 1 table; the total number of pages: 107. The refernce list contains 24 items.

CONTENTS

GENERAL DESCRIPTION OF THE DISSERTATION

The topicality of the theme

The topicality of the theme is related to the development of the theory and constructions of high-speed mechatronic positioning systems, which allow to perform automated biological tests and analyses, which increase the productivity of technological process several times (about 10 times) and replace exhausting manual labour in 3D motion (inspecting from 100 to 200 positions in one test).

The aim and main tasks of the dissertation

The aim of the dissertation is to develop in principle new high-speed 2D (two dimensional) and 3D (three dimensional) robotic executive mechanisms of biochip systems (actuators) and to improve the theory for the optimal synthesis of machines and mechanisms in the field of the positioning theory.

The main tasks are as follows:

1. To conduct research and analysis of the current optimal control synthesis;
2. To improve the current method and develop a new method for the optimisation of impulse and mixed-type excitation positioning systems with control boundary conditions and limitations on the phase coordinates;
3. To develop a method for the control synthesis in the adaptive excitation systems by using feedbacks as the functions of phase coordinates;
4. To supplement the adaptive control theory with the control synthesis in the mixed-type (adaptive and time) excitation systems in the presence of accidental parameters;
5. On the basis of the synthesized positioning systems, to create real positioning systems (equipment) using the software SolidWorks in Biosan Ltd;
6. To perform testing of the positioning systems and equipment in Biosan Ltd and check the experimental validity of the theoretical research.

The research object

The research object is the optimal control of robotic executive mechanisms of positioning systems by optimising the current control systems as well as developing a new method for the systems control.

The research hypothesis

The main research hypothesis are as follows:

1. The theory of classical mechanics (Newton's mechanics) can be applied for solving tasks of the dynamic analysis of robot manipulators including collisions (impacts) of objects as well;
2. In the robotic executive mechanisms, three types of interactions as the control of actuator actions can be used - force excitation, impulse excitation and mixed-type excitation (together force and impulse excitations);
3. For the synthesis of actions of robotic mechanisms (for generation and breaking), the interactions of dry friction, viscosic resistance and nonlinear resistance can be used;
4. For modelling interactions of impacts of objects, 3D mechanical models can be used.

The novelty of the research

The novelty of the research comprises the studies in the field of the synthesis of robotic executive mechanisms (in positioning). As the author's reports on international conferences show, the theory of optimal synthesis for the optimisation of robot mechanisms and the synthesis of real objects is applied in practice in the world for the first time.

The practical application of the research

The practical application of the research comprises the creation of real robotic executive mechanisms and their experimental testing. The number of positioning robots has been sold in USA and other countries as well.

The structure of the dissertation and the main results of the research

The dissertation consists of the overview of literature, 6 chapters and the conclusions; the total number of pages: 107.
The main results of the research are as follows:

1. **The method** for the optimisation of the positioning systems with force excitation **has been improved**;
2. **A new method** for the optimisation of the positioning systems **with impulse excitation** has been proposed;
3. **A new method** for the optimisation of the positioning systems with **mixed-type** (force and impulse) **excitation** has been proposed;
4. On the basis of the programme MathCAD, **6 programmes** for the synthesis of control tasks **have been proposed**. They can be used for engineering calculations of synthetic tasks;
5. New control equipment of robotic executive mechanisms (actuators) **has been** theoretically **synthesized**, on the basis of which new high-speed positioning equipment can be created;
6. By using the software SolidWorks, **real control mechanisms** and robotic equipment **have been designed and set for mass production**. They have been experimentally tested and they are operating in USA and other countries.

Theses to be defended

1. The theory of Classical Mechanics can be applied to solving tasks of synthesis of robot dynamics.
2. It is possible to use three types of interactions (force, impulse and mixed-type excitations) for generation control of positioning actuators.
3. Stereomechanical models can be used for modelling interactions of impacts of objects.

The list of main publications

10 publications related to the theme have been prepared, 5 of which have been cited in other editions. The results of the research have been reported on 12 international conferences in Latvia, Lithuania, Poland, Czech Republic and Russia.

The list of scientific publications prepared while carrying out the doctoral thesis:

1. Janis Viba, Edgars Kovals, Atis Vilkajs. "Vibration damping of cargo like pendulum inside vehicle hull". 7 th International Scientific Conference „Engineering for Rual Development", May 29 - 30, 2008 Latvia , Jelgava. 169 - 172 lpp.

2. „Synthesis of Vibrator With Air or Water Flow Excitation”. J. Viba, L. Shtals, A. Vilkajs, E. Kovals. The 4TH International Conference Mechatronic Systems and Materials MSM 2008, 14 - 17 July, Bialystok, Poland. 147 - 148 lpp.
3. „Nonlinear optimal synthesis of the vibrator with flow excitation“. J. Viba, L. Shtals, A. Vilkajs, E. Kovals. Rare attractors and rare phenomena in nonlinear dynamics. 2008., 8-12 september. Rīga, RTU, 2008. 131 - 137 lpp.
4. „Nonlinear optimal synthesis of the vibrator with flow excitation“. J. Viba, L. Shtals, A. Vilkajs, E. Kovals. JVE Journal of Vibroengineering – December 2008, Vilnius, Lithuanian. 493 - 496 lpp.
   Cited: THOMSON SCIENTIFIC, EBSCO, VINITI etc.
5. J. Viba, E. Kovals, A. Vilkajs. „Vibration damping of cargo like pendulum inside vehicle hull”. Динамика виброударных (сильно нелинейных) систем “DYVIS-2009”, Москва – Звенигород 2009, июнь. 463 - 468 lpp.
6. „Synthesis of vibrator with air or water flow excitation“. J. Viba, L. Shtals, A. Vilkajs, E. Kovals. Solid State Phenomena Volts. 147-149. 2009 Switzerland, 462 - 467 lpp.
7. Atis Vilkājs, Sergejs Djacenko, Janis Viba. „Biočipu robota izstrāde”. RTU zinātnisko rakstu krājums, sērija 6, 33 sējums, Mašīnzinātne un transports, Rīga 2010. 55 - 59 lpp.
8. „Optimization of Vibrator Motion with Air Flow Excitation”. J. Viba, M. Eiduks, L. Shtals, E. Kovals, A. Vilkajs. JVE Journal of Vibroengineering. - Vol.12, Issue 1. (2010) 34 - 42. lpp.
   Cited: THOMSON SCIENTIFIC, EBSCO, VINITI etc.
9. „Cargo Pendulum Vibration Damping inside Vehicle Hull”. J. Viba, A. Vilkajs, E. Kovals, B. Grasmanis. JVE Journal of Vibroengineering. - Vol.12, Issue 4. (2010), 381 - 387 lpp.
   Cited: THOMSON SCIENTIFIC, EBSCO, VINITI etc.
10. A. Vilkajs, S. Djacenko, E. Kovals. „Design and production of biochip robot”**.** Vibrations Problems ICOVP 2001. The 10th International Conference on Vibration Problems. ICoVP-2011. 2011, PRAGUE, Czech Republic. 302 - 307 lpp.

CONTENT OF THE DISSERTATION

Chapter 1

In Chapter 1, the analysis of the current research of the optimal control synthesis has been carried out.

The optimal control tasks of electric drive have two significantly distinct approaches. The first of which relates to the so-called stabilisation task, where the behaviour of the controlled mechanisms is viewed under the stabilizing condition or observing condition. The second one relates to the control processes, where the operating mechanism turns from one position into another on condition that it reaches the maximum (minimum) of a previously determined quality criterion. This second one is assumed to be called an optimal control task.

The data obtained from the previous analysis of the task allow to formulate the following optimal control task: to determine from all permissible types of control u and S_i in the given ranges (1)

$$u \subset u_0, \quad S_j \subset S_0, \tag{1}$$

to move to the subsystem for the subsystem

$$\dot{x} = f(t, x, u) + \frac{S_j}{m}\delta(t - t_j), \tag{2}$$

moving from the initial condition x_0 and such the final condition x_1 that gives to the optimisation criterion

$$K = \int_{t_o}^{t_1} f_0(t, x, u, S_j, t_j)dt, \tag{3}$$

the minimal (or maximal) possible value on condition that there are additional limitations

$$z \le z_0; \quad \tau \ge \tau_0; \quad |\dot{x}| \le v_0; \quad |x| \le A_0, \tag{4}$$

where z, τ – values of impact impulses and their subsequent time, z_0, τ_0, v_0, A_0 – limitations. On the calculations of this system, it is essential to take into consideration the features of vibro impacts.

If only the force control is used ((1) – (4) at $S_j = 0$), the task is calculated by using any appropriate method of the optimal control theory: by using the Maximum Principle of Pontryagin, by using the variation calculations, by using the Momentum method or by using other methods as well (Figure 1a).

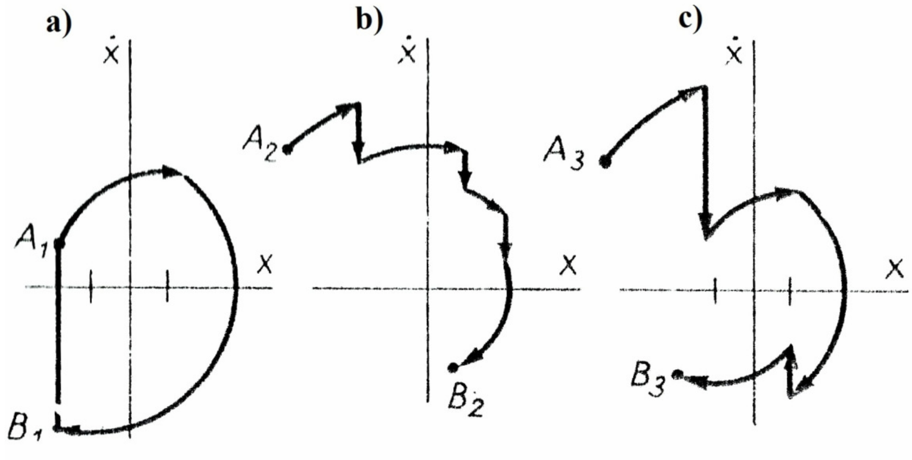

Figure 1. The speed-displacement dependence

In case of impulse control or also mixed-type control, the task of calculating can be so cumbersome that striking impulses S_j are fixed (particularly the passive ones, i.e., formulations for object-to-object collisions as well as with limitations), and additional limitations should be taken into account (4) for the optimality criterion K, which has a complicated structure (3).

According to the given circumstances, a solution method for impulse control $(u=0)$ has been suggested, which is grounded on the usage of the first variation for the optimisation criterion δK. The task is solved as shown (Figure 1 b).

In the beginning, the subsystem's equations of motion are integrated within the time limits $t_{j-1}<t<t_j$ between the impulses S_j. Further, the phase trajectories are linked (from the initial point t_0 to the final point t_1, and in the section points t_j as well), making control equations for the phase trajectory and impulses S with conditions for limit properties by supplementing them with one equation for the determination of the criterion K (3).

Chapter 2

This chapter deals with the optimisation of positioning systems, where the optimisations of limited force, limited phase coordinates and mixed-type control systems have been analysed.

The optimisation of the limited force and limited phase coordinate (speed) control system

The task of optimisation in stages is similar to the discussed above and here is not discussed again. At first, the exit limitation has been viewed, then the arrival in the designated point of phase coordinates from a limitation. An example of optimal action is shown in Figure 2.

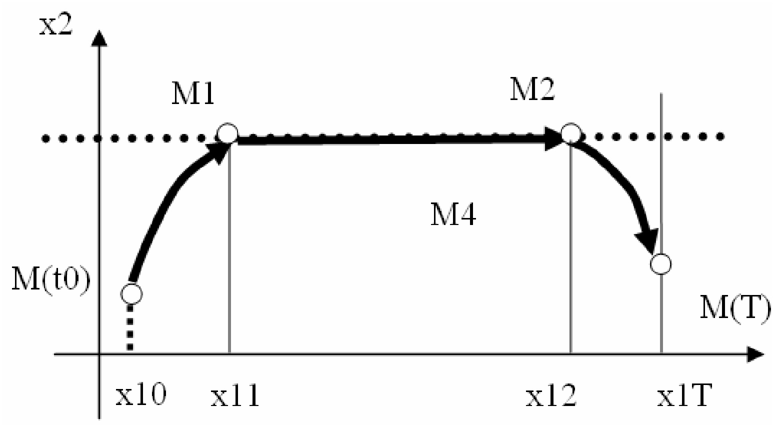

Figure 2. The optimal trajectory in the phase plane if the speed is limited. The exit limitation occurs with the maximum control, correspondingly, the transition from a limitation to a given point of the phase plane occurs with the maximum breaking. Of course, in real situations it is a problem to direct an object along a given trajectory usually because of changing friction forces, which disturb to reach a preferable point along the optimal trajectory.

The optimisation of the limited force and limited phase coordinates cyclic control system

The optimisation of the control of cyclic motion is similar to the optimisation of the control discussed above. For the system with one degree of freedom, the trajectory of cyclic optimal motion in the phase plane is shown in Figure 3. The comments about this control are given below the figure.

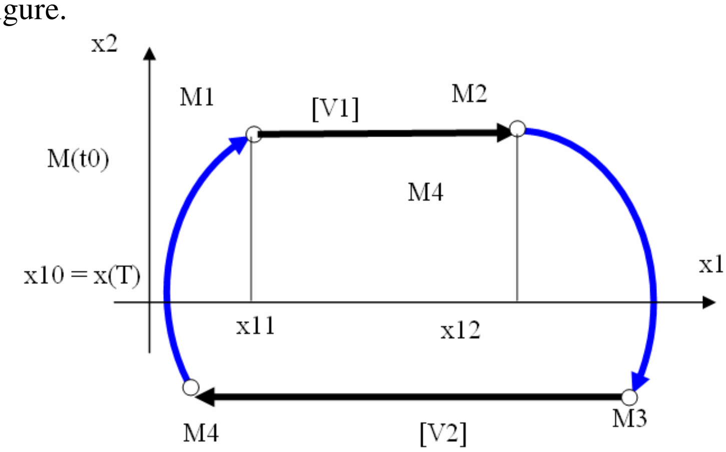

Figure 3. The optimal trajectory of the cyclic (periodic) motion with two speed limits of different values: for motion in one direction [V1] and opposite one [V2]. For this control, a special synthesis in the phase plane is necessary because the control start and break should be

retained, in addition, the control should compensate restriction forces in the motion under limitations.

The optimisation of the mixed-type (force and impulses) control systems with limited phase coordinates

The solution of the optimisation task for the mixed-type control involves the following steps: at first, the action trajectory is divided into several parts depending on where control impulses or speed limits are applied; then, common optimisation tasks are solved in several steps; in the third step, action trajectories are combined using limitation conditions; in the last step, the link variational method is applied and the optimal joint trajectory is found.

An example in the noncyclic action is shown in Figure 4.

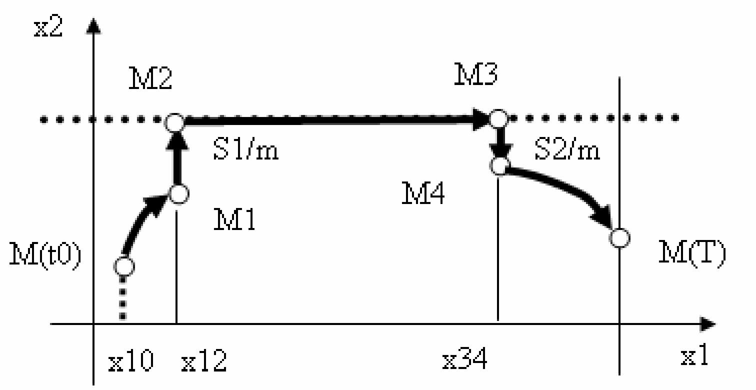

Figure 4. An example with the force limitation, two impulses and one speed limitation. The control in the stages M(t0) – M1 and M4 – M(T) has a force limitation, in the stage M2 – M3 it has a speed limitation, and there are also two impulses S1 and S2, which have limited values.

The link equations for the example of action shown in Figure 4 are as follows:

$$v12 = \frac{U10}{m} \cdot t1 + v10 ; \tag{5}$$

$$x12 = \frac{U10}{m \cdot 2} \cdot t1^2 + v10 \cdot t1 + x10 ; \tag{6}$$

$$V1 = v12 + \frac{S1}{m} ; \tag{7}$$

$$x34 = V1 \cdot t2 ; \tag{8}$$

$$x34 = V1 - \frac{S2}{m} ; \tag{9}$$

$$vT = v34 - \frac{U11}{m} \cdot t3 ; \tag{10}$$

$$xT = v34 \cdot t3 - \frac{U11}{m} \cdot t3^2 + x2 ; \tag{11}$$

$$T = t1 + t2 + t3 . \tag{12}$$

By using variations of link equations, it is possible to find the optimal control action, which is shown in Figure 5.

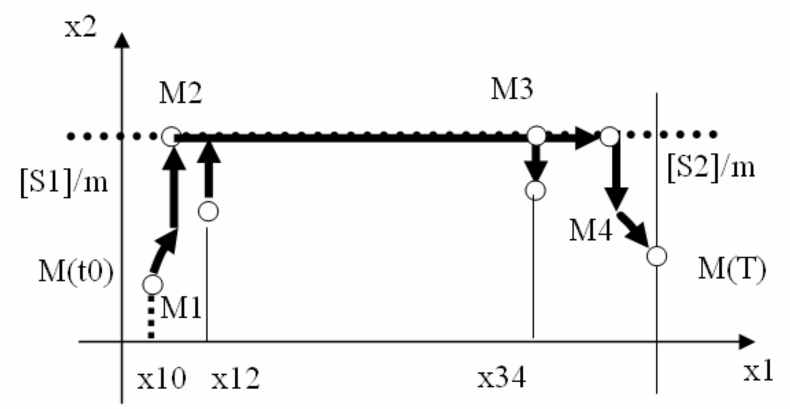

Figure 5. The solution of the optimal control: force control is on the limitations U10, U11. Consequently, impulse control [S1], [S2] is on limitations.

Chapter 3

In the step of optimisation of the optimal sysnthesis, the control of a chosen subsystem $u = u(t)$ is found as the time function because the variation of the optimisation criterion *K* is searched as the time function:

$$\delta K = f(\delta t) \tag{13}$$

where: δK - the variation of the optimisation criterion; δt - the time variation.

The control found in optimisation tasks as the time function is not always stable in real conditions, as a result, disturbances occur during action of a system. Therefore, the obtained control should be realised in the phase plane with feedbacks.

Further, different control syntheses along different main trajectories of synthesis - linear, quadratic and cubic - are discussed.

Generally, when expressing the trajectory of synthesis for the speed *V* as the coordinate *X* function, three equations are obtained:

1. In the linear (the straight line) case:

$$V = C_0 + C_1 \cdot X\ ; \tag{14}$$

2. In the quadratic (the parabola) case:

$$V = C_0 + C_1 \cdot X + C_2 \cdot X^2\ ; \tag{15}$$

3. In the cubic case:

$$V = C_0 + C_1 \cdot X + C_2 \cdot X^2 + C_3 \cdot X^3\ . \tag{16}$$

The coefficients C_0, C_1, C_2 and C_3 should be determined for each separate case by matching them with limitation conditions for the trajectory.

Positioning control along the linear phase trajectory

In the linear case, the straight line at the start of action *X=0* has its initial value *V(0)*. The straight line should end at the positioning place *S2* when the speed becomes negative. The viscosic resistance and dry friction are taken into account in modelling.

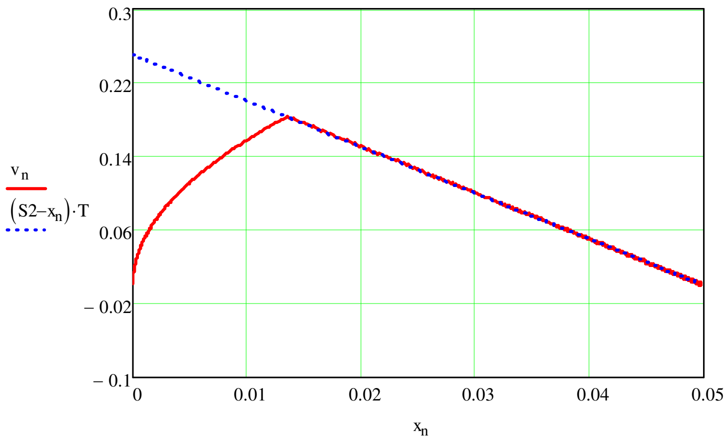

Figure 6. The control in the phase plane

The condition of the model system is accomplished – in the beginning the control *u1* is maximal, then it switches to scanning of the straight line. The system is optimal.

The control function:

$$K_n := u1\left[sign\left[\left[(S2 - x_n)\cdot T - v_n\right]\right]\cdot\left(0.5 + 0.5\cdot sign(v_n)\right)\right].$$

Positioning control along the quadratic phase trajectory

In the quadratic case with symmetrical control, the straight line at the start of action *X=0* has the value *V(0)*. The straight line should move along the parabola and should end at the positioning place *S2* when the speed becomes negative. A system model has been proposed, i.e., modelling parameters, numerical integral equations with initial conditions have been selected. The viscosic resistance and dry friction are taken into account in modelling.

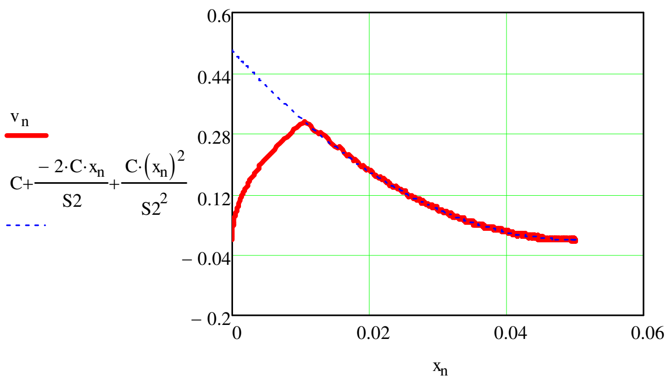

Figure 7. The control in the phase plane. In the beginning the control *u1* is maximal, then it switches to scanning of the parabola that is concave.

The control function:

$$K_n := u1\cdot\left[sign\left[\left[\left[\frac{-C(x_n)^2}{S2^2} + C\right] - v_n\right]\right]\cdot\left(0.5 + 0.5\cdot sign(v_n)\right)\right].$$

Positioning control along the cubic phase trajectory

In the cubic case, the straight line at the start of action *X=0* has the value *V(0)*. The straight line should move along the cubic parabola and should end at the positioning place *S2* when the speed becomes negative. The viscosic resistance and dry friction are taken into account in modelling.

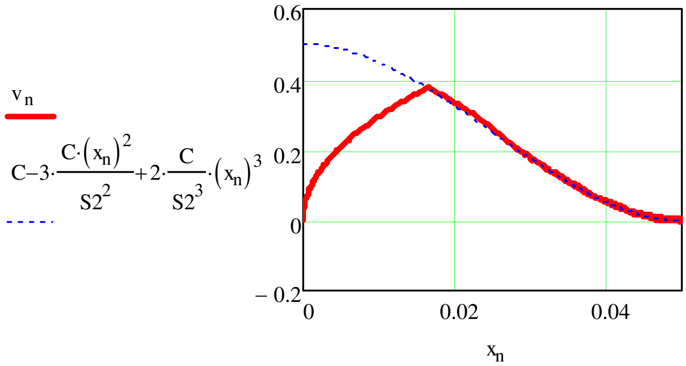

Figure 8. The control in the phase plane. In the beginning the control *u1* is maximal, then it switches to scanning of the symmetric cubic parabola.

The control function:

$$K_n := u1\cdot\left[sign\left[\left[\left[\left[C-3\cdot\frac{C(x_n)^2}{S2^2}+2\cdot\frac{C}{S2^3}(x_n)^3\right]-v_n\right]\right]\right]\cdot(0.5+0.5\cdot sign(v_n))\right].$$

Chapter 4

Chapter 4 deals with the positioning control systems and their analysis described in the chapters above, i.e., the control synthesis in mixed-type (adaptive and time) induced systems in the presence of accidental parameters.

The control synthesis along the linear phase trajectory considering the interaction of dry friction in the nonholonomic system

A system model has been proposed - a model with the quadratic symmetric parabola that is convex in the presence of accidental parameters in the nonholonomic system. The viscosic resistance and dry friction are taken into account in modelling.

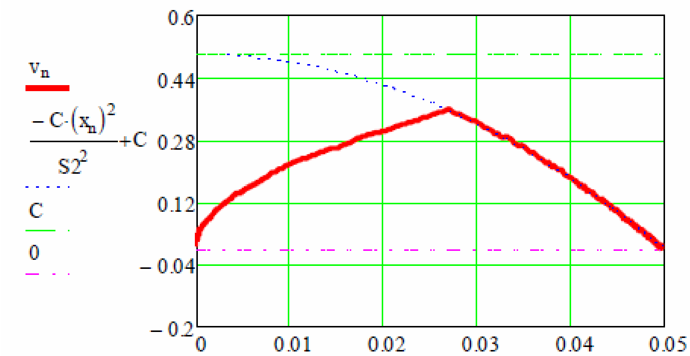

Figure 9. The control in the phase plane. In the beginning the control $u1$ is maximal, then it switches to scanning of the symmetric parabola that is convex.

The control function:

$$K_n := u1\left[sign\left[\left[\left[\frac{-C(x_n)^2}{S2^2}+C\right]-v_n\right]\right]\cdot(0.5+0.5\cdot sign(v_n))\right].$$

The control synthesis along the bilinear phase trajectory considering accidental parameters of the resistance force of viscosic friction

A system model has been proposed - a model with the quadratic symmetric parabola that is convex in the presence of accidental parameters. The viscosic resistance and dry friction are taken into account in modelling.

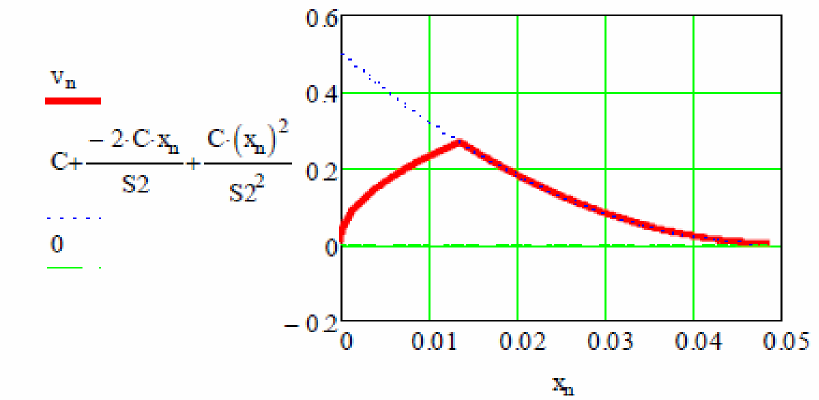

Figure 10. The control in the phase plane. In the beginning the control $u1$ is maximal, then it switches to scanning of the symmetric parabola that is convex. The control stops at a negative speed.

The control function:

$$K_n := u1\left[sign\left[\left[\left[\frac{-C(x_n)^2}{S2^2}+C\right]-v_n\right]\right]\cdot(0.5+0.5\cdot sign(v_n))\right].$$

The control synthesis based on the interaction of polynomial resistance force and nonstationary link inference

A system model has been proposed - a model with the quadratic symmetric parabola that is convex in the presence of accidental parameters of speed limitations. The viscosic resistance and dry friction are taken into account in modelling.

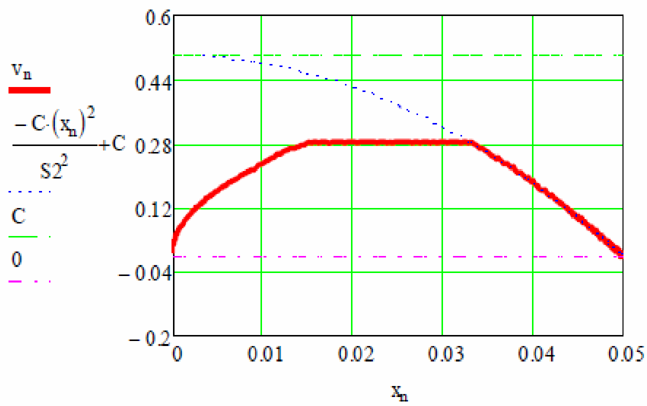

Figure 11. The control in the phase plane. The symmetric control $u1$ is accomplished with a speed limitation; the control maintains a constant speed, then it moves to the parabola that is convex and stops when the speed becomes negative.

The control function:

$$K_n := u1\left[sign\left[\left[\left[\frac{-C(x_n)^2}{S2^2}+C\right]-v_n\right]\right]\cdot(0.5+0.5\cdot sign(v_n))\right].$$

Chapter 5

This is a consolidation of the dissertation for Chapters 5 and 6, which deals with the creating and testing of real positioning equipment. Four devices for different control tasks are described. There is a provision for using these devices in medical laboratories for performing diagnostic tests. The devices have a certain level of complexity and function. All the devices have been newly designed (in the SolidWorks software) and they have no prototypes.

- **The first** device to be discussed is **a plane table fluorometer** (Figure 12).

The kinematic control scheme of the fluorometer is based on action along the axis X and the axis Y (Figure 13).

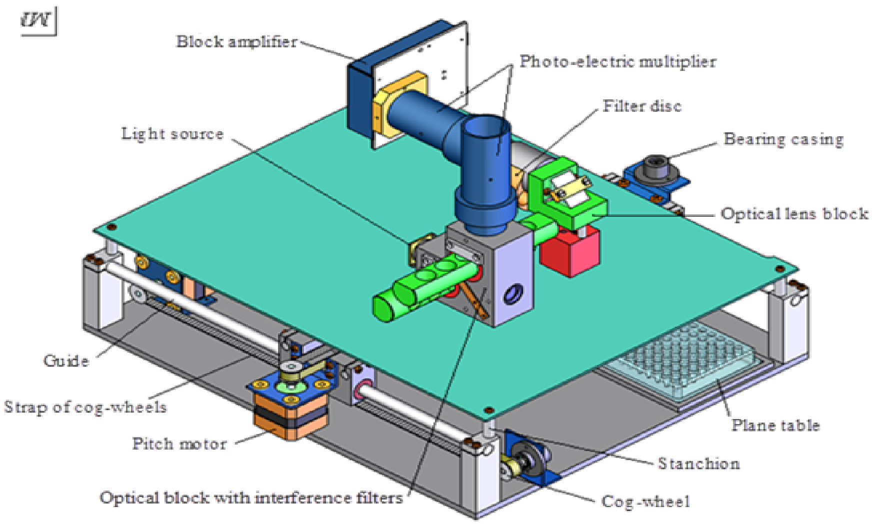

Figure 12. The inner construction of the fluorometer

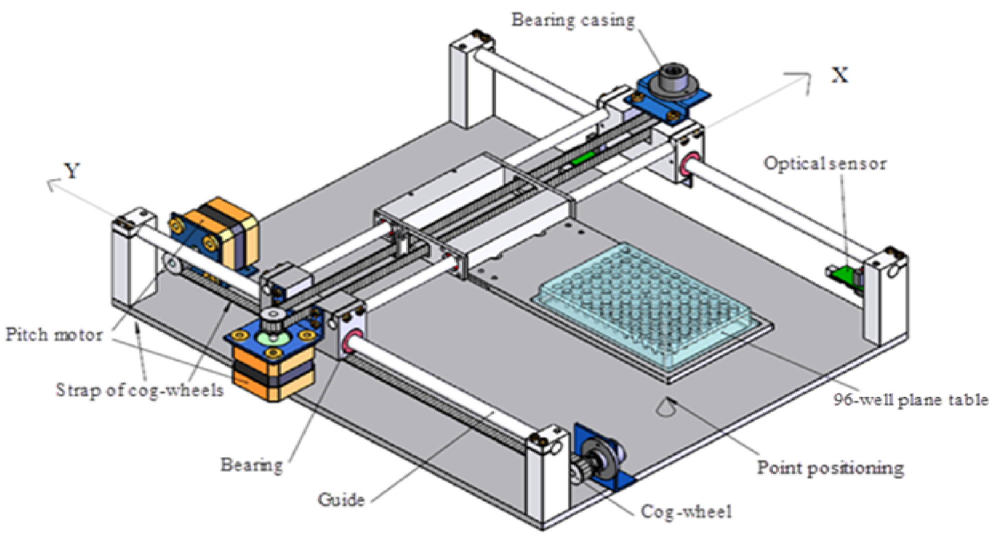

Figure 13. The kinematic control scheme of the fluorometer

The main factor in the system control is its limiting speeds: the system's running start up to the assigned speed V1, then maximally fast breaking up to the second assigned speed V2, and then cyclic switching between these assigned speeds (Figure 14). Moreover, inside this cycle, the precision of system control should be ensured: from the initial point along the given trajectory, one should get to the final point and then return to the zero point.

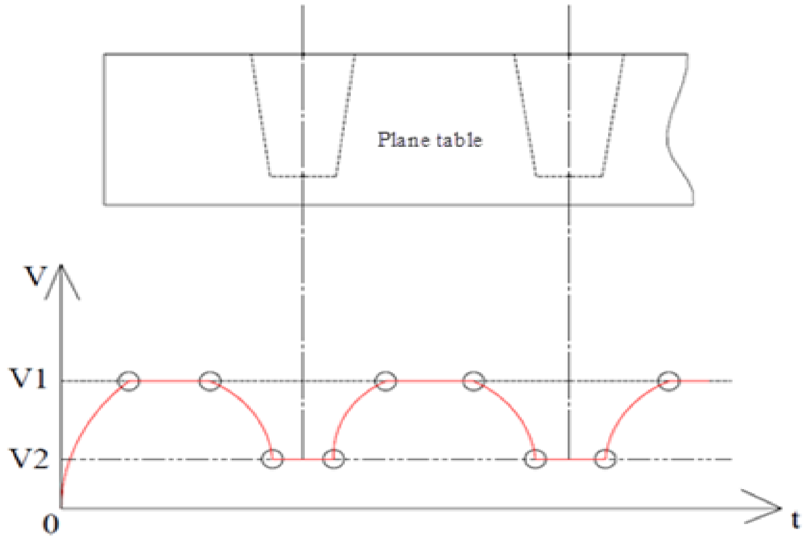

Figure 14. The control of the fluorometer

The prototype of the fluorometer is shown in Figure 15.

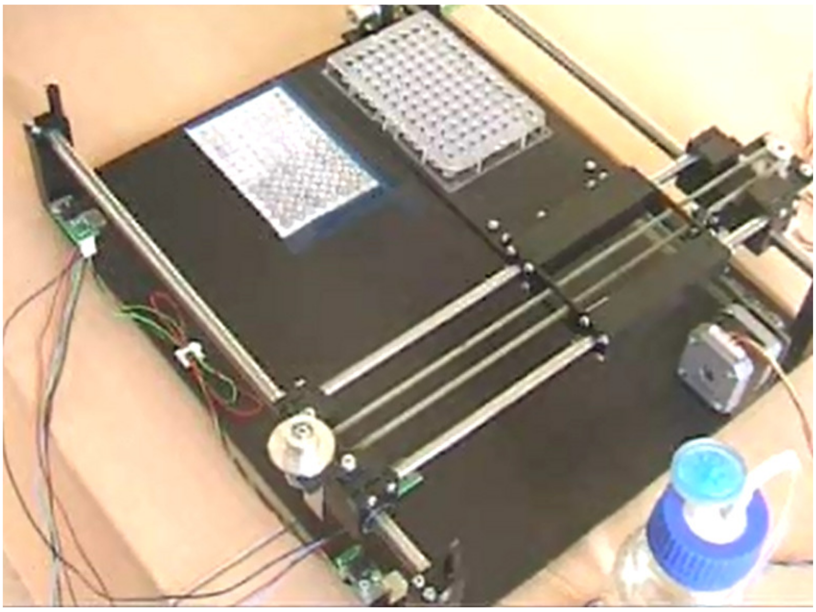

Figure 15. The prototype of the plane table fluorometer

- **The second device** to be discussed is **the biochip robot**.

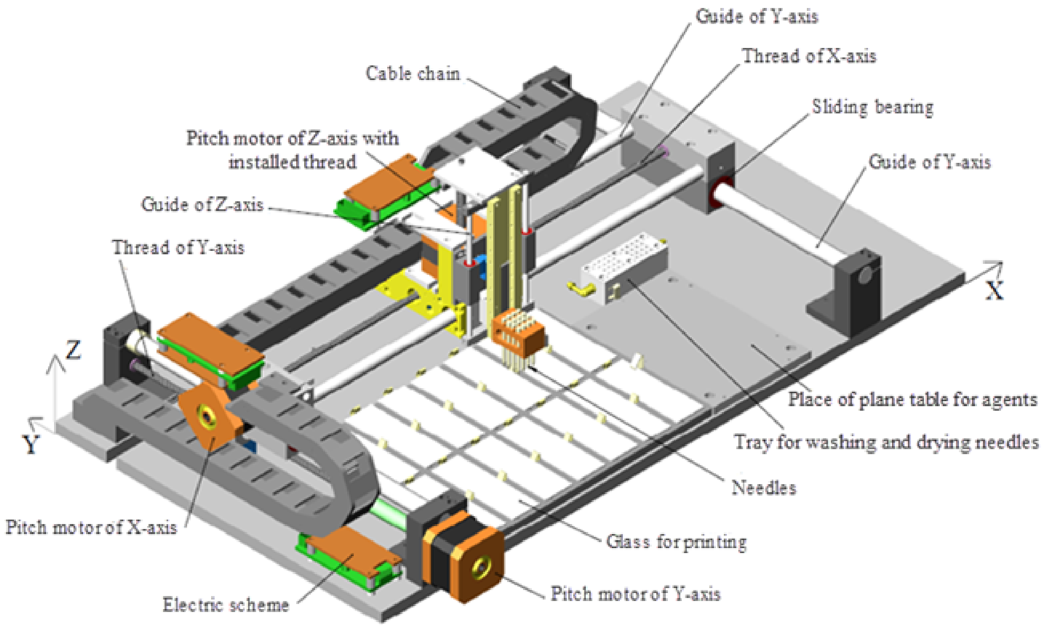

Figure 16. The kinematic scheme of the robot into the SolidWorks environment

The task for the biochip robot is to take an oligonucleotide standard into the dozator needle and squeeze its drop of the diameter of about 0.15 mm onto the glass plate of the size of 25 x 75 mm with the precision of +/-0.01 mm (see Figure 17). Each drop contains information about a concrete DNA. Depending on a task for the chip, hundred thousand drops can be put on the plate.

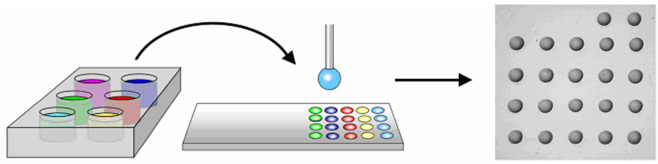

Figure 17. Marking the chips

The created device and its calibration procedure are shown in Figure 18.

Figure 18. The calibration procedure of the robot

- **The third** device to be discussed is the multichannel **fluorometer ALA-1/4** (Figure 19).

From a mechanical point of view, its principle of operation is based on rotary action and point positioning to be used. Control complexity is related to the optical channel, through which laboratory measurements are carried out, therefore, positioning of components at points required is very essential.

Figure 19. The multichannel fluorometer ALA-1/4

The main block of positioning control is shown in Figure 20.

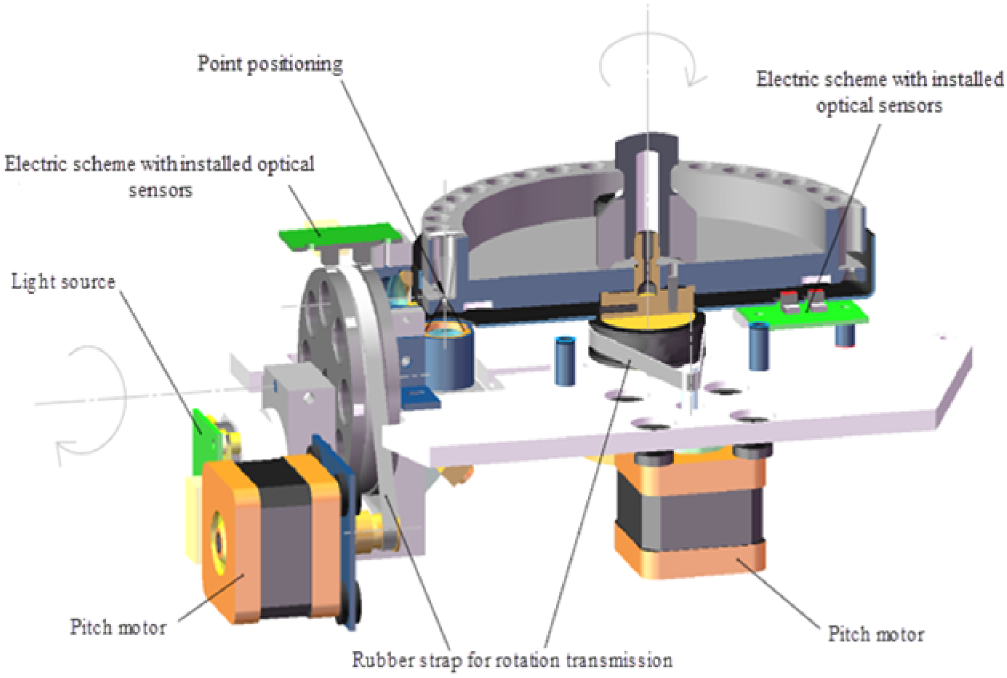

Figure 20. The kinematic scheme of the fluorometer

One relevant fact should be mentioned. In 2010, this device earned a great fame for its innovativity and won a significant prize - Export and Innovation Award 2010.

- Lastly, **The fourth** device to be discussed is the microplate washer **Inteliwasher 3D-IW8** (Figure 21).

The microplate washer is a very peculiar device, which combines in itself mechanical properties, electrical properties and properties of liquid flow together. Moreover, the three properties should interact with each other, which makes the control of the device more complicated.

Figure 21. Inteliwasher **3D-IW8**

The device is meant for washing standardized micro-volume 96-well plates of different types, microstripes and microplane tables on the base of FastFRAME (square-shaped wells) (see Figure 22). This device is suitable for washing wells of different bottom shapes: flat, U-shaped and V-shaped. The apparatus is fully programmable including multi-stage ripening of solutions, sucking (sucking, the combination of sucking/educing of liquid and soaking as well as a soaking cycle for a definite period of time).

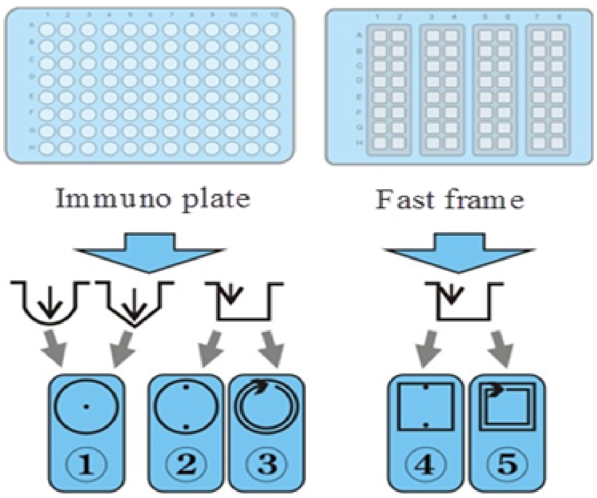

Figure 22. The types of aspiration

The main block of the mechanical system is shown in Figure 23.

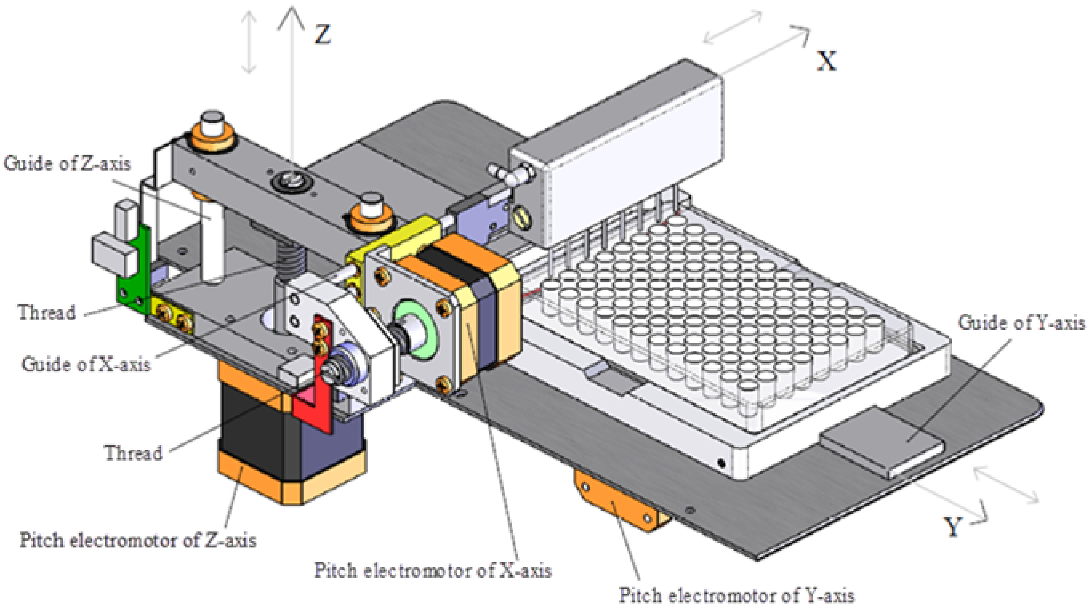

Figure 23. The block of the washing mechanism

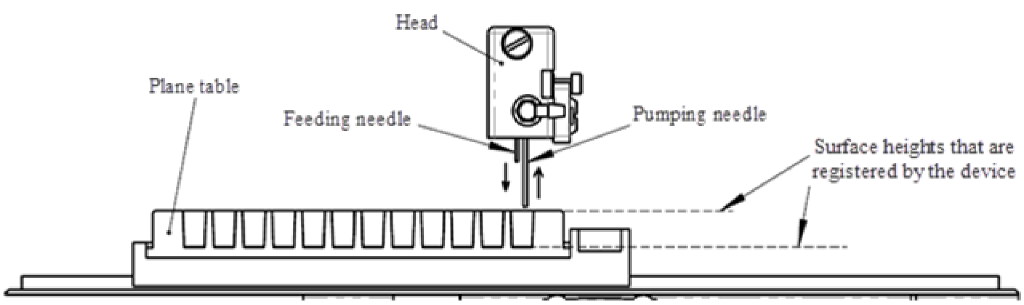

Figure 24. The washer block.

CONCLUSIONS

1. On the basis of the biochip design of Biosan Ltd and the theory of the optimal sysnthesis worked out at the Institute of Mechanics of RTU, a new inverse method for optimal designing of positioning systems has been developed. In this method, the basic elements of the system control are initially studied theoretically, then, on the basis of the study, the action of sensors and actuators is synthesized in real feedback systems.
2. In the field of the positioning optimisation of the simpliest slow speed nonimpact systems, a method for the optimisation of the control of executive mechanisms (actuators) with force excitation has been improved. The method is based on the algorithm for finding the optimal force control, which takes into account limitations of phase coordinates.
3. In high speed mechanical systems with impacts, a new method for the control optimisation of positioning systems with impulse excitation has been carried out. For the control impulses limitations on impulse values and their succeeding time intervals have been taken into account.
4. A new method in the optimisation of positioning systems with mixed-type (forces and impulse) excitation in the presence of accidental parameters has been carried out. The main characteristic feature of the method is two principally different controls: one of them is generated by force excitations, other control is accomplished by object-to-object collisions. The control efficiency has been additionally verified by modelling of systems with accidental excitations.
5. On the basis of the software MathCad, 6 task-level programmes for control synthesis have been carried out, which can be applied for calculations of synthesis tasks in engineering, realising sensor, actuator and computer-based feedbacks.
6. New control equipment of biochip robotic executive mechanisms (actuators) has been theoretically synthesised, on the basis of which new high-speed positioning equipment can be created.
7. By using the software SolidWorks, real control mechanisms and robotic equipment have been designed and set for mass production. They have been experimentally tested and they are operating in USA and other countries.

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