Таблица 3. **Суммарная глубина захода зубьев колес H_w**

Δz	z_g					
	50	60	70	80	90	100
1	1,69	1,66	1,65	1,64	1,63	1,62
2	1,79	1,77	1,76	1,75	1,74	1,74
3	1,84	1,83	1,82	1,81	1,80	1,80

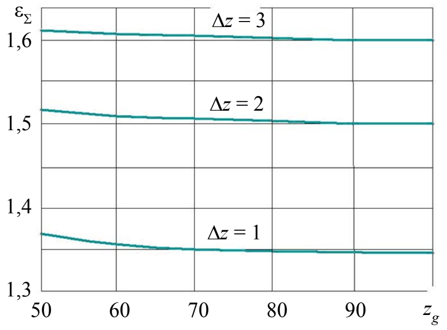

Рис. 4. Зависимость результирующего коэффициента перекрытия от Δz и числа зубьев сателлита

Таким образом, выполнение зубьев колес планетарной передачи типа K-H-V разными по высоте в разных их поперечных сечениях позволяет существенно повысить коэффициент перекрытия зацепления и плавность работы механизма, не нарушая условия отсутствия интерференции продольной кромки внешнего зуба с главной поверхностью внутреннего.

Библиографические ссылки

1. *Кудрявцев В. Н.* Планетарные передачи: справочник / В. Н. Кудрявцев, Ю. Н. Кирдяшев. – М. : Машиностроение, 1977. – 535 с.

2. Пат. 2445529 РФ МПК F16H 1/32.

3. *Плеханов Ф. И.* Влияние геометрии зацепления колес планетарной передачи типа K-H-V на показатели ее прочности // Вестник машиностроения. – 2013. – №3. – С. 16–20.

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Geometry of Non-Traditional Internal Engagement of *K-H-V* Planetary Gears

Variable-height gearing is proposed for K-H-V epicyclic gears as a better alternative to classical constant-height gearing. Equations for contact ratio and working depth are derived, and graphical dependences of these parameters on the number of teeth in the planetary gear and the difference of the number of teeth in the planetary gear and the annulus are shown.

Key words: epicyclic gearing, K-H-V, gear geometry, non-traditional engagement.

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ROBOT ARM CONTROL BASED ON INS WITH THE SUPPORT OF SIMULATION IN MATLAB / SIMULINK

This paper describes the activity system and the importance of INS with the possibility of implementation to the robot control. The contribution also introduces the execution of DC motor regulation utilized for the positioning of a rotary positioned arm. The motor control comprises the current regulation, angular velocity and the rotation of the motor shaft fixed to the arm regarding the required angular change course of the arm rotation. The regulation structure of the DC motor is carried out in MATLAB/Simulink program. The arm movement is investigated via the mathematical model and virtual dynamic model formed in MSC.ADAMS program.

Key words: INS, gyroscope, accelerometer, dynamic model, PID controller, MATLAB/Simulink.

The integration of navigational information represents the actual issue of reaching higher accuracy of required navigational parameters by using more, less accurate navigation systems. The inertial navigation is the navigation based on uninterrupted evaluating of the position of a navigated object with utilizing the sensors which are sensitive to motion, i.e. gyroscopes and accelerometers, which are regarded as primary inertial sensors or other sensors located on the navigated object. The position, orientation, direction and velocity of motion without external sources of information about the motion are constantly determined by means of the navigation computer and data from sensors. The actual position of the object is evaluated on the basis of knowledge of the initial position and subsequent continual measuring the acceleration and direction of motion

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in a reference system.. The principle of inertial navigation obeys the laws of classical mechanics defined by Newton. The INS includes at least one navigation computer and a platform or a module containing accelerometers and gyroscopes. From the constructional point of view inertial navigation systems are divided into platform so-called gimballed systems and non-platform so-called strapdown systems. In the platform system inertial sensors are attached to the platform which is installed in a gimbals suspension with three degrees of freedom with the aim of remaining the constant space orientation in defined directions (north – south, east – west and vertically on performing the gravitational attraction), while the gimbals suspension is firmly connected to the construction of the navigated object. The moving mechanical parts of the systems cause relatively low reliability towards the non-platform systems. The inertial sensors of non-platform systems are firmly connected to the construction of the object (usually in the centre), for whose navigation they are determined. Both types of the inertial navigation systems consist of an inertial measurement unit and a navigation computer.

The aim of the research is to investigate and develop a new combined inertial navigation system based on electronic gyroscopes, magnetic and barometric sensors. The mentioned system will ensure the accuracy which is necessary for example for the calibration of robotic workplaces and thereby the necessities of utilizing the calibration agents will be limited. A big advantage of the INS is also its autonomy in comparison with methods used nowadays. This leads to the essential simplification of calibration and it even carries big possibilities with it in the field of control and measuring, for example, avoiding the accidental collisions of robots etc. To solve a problem of ensuring the required accuracy is a basic problem. The integration of more measuring devices (INS) is one of the possibilities [11]. The integration of navigation information represents the topical issue of achieving greater accuracy of required navigation parameters. The crucial activity is focused on three basic fields:

– The first goal is to analyze accelerometer and gyroscopic sensors and their possibilities of utilization for inertial navigation. The simulation of the effect of sensors with different metrological parameters and their effect on the properties of the proposed combined navigation system.

– The second goal is to optimize a specialized processor system for processing the data from the defined sensors in connection with controlling items of an industrial robot [10]. The proposal of an algorithm of combined navigation with respect to the used processor system.

– The third goal is to verify experimentally the proposed inertial navigation system in real conditions of the industrial robot operation.

Characteristic of issue

The demand of navigation autonomy, i.e. the independence of the external sources of navigation information became the reason for implementing the inertial navigation systems. The principle of inertial navigation is based on Newton's laws which express a change of motion under the action of external forces and acceleration which is directionally and by size proportional to the acting external force. The inertial navigation system consists of a measurement unit containing accelerometers and gyroscopes and from a navigation computer which evaluates the data from measuring devices. In contrast to all the other navigation systems inertial navigation is completely autonomous, self-sustaining and independent of the surrounding environment, i.e. the system is resistant to outside influences such as magnetic disturbances, electronic interference and signal distortion. Computing operations in the inertial navigation system are based on Newton's law of motion.

For the purpose of navigation in a coordinate system it is necessary to keep the direction of motion in the direction of acceleration. This is not practically possible, and therefore sensors – gyroscopes are used for detecting the rotary motion. Seeing that each free object in space has six degrees of freedom (internally mutually independent variables) the inertial navigation system usually consists of three gyroscopes and three accelerometers where each pair (gyroscope, accelerometer) is able to record the rotation or acceleration in the direction of one axis which is perpendicular to the others. Of the six degrees it is three linear degrees of freedom "Fig. 1", the translation in the X-axis, Y-axis and Z-axis which indicate the position of the object and three degrees of freedom of rotation which indicate rotating around the X-axis, Y-axis, and Z-axis. The position of the object is also known if we know the six variables. If this data is observed for a certain period of time, it is possible to determine the trajectory and speed of an object's motion from it. The electronic gyroscope is one of the most modern gyroscopic sensors. The mentioned sensors use the Coriolis force which acts on the particle moving with certain speed in a rotating non-inertial reference system and which is directly proportional to the absolute value of the angular velocity vector of this system. The Coriolis force acts on the resonating mass, which is flexibly embedded in the frame and when the frame turns, in the direction perpendicular to the axis of rotation (perpendicularly to the plane of the frame) and perpendicular to the direction of motion of resonating mass. The Coriolis force also alternates its orientation in the direction perpendicular to the direction of motion because the resonating mass oscillates in one direction. The amplitude of this force is measured by means of a change of electric capacity of a condenser whose electrodes are connected to the stable and movable frame.

The inertial measurement unit (IMU) is an essential item of each INS. Sensors, whose output is influenced by the motion of the object on which the IMU is placed, are regarded as primary sensors of the IMU. Primary sensors in inertial navigation are sensors of angular velocity, whose output signals after integration are used for determining the orientation in space, and accelerometers whose output signals after precise compensation of gravitational acceleration and the Coriolis force can be integrated onto the speed and position. Such an inertial measurement unit has six degrees of freedom. This means it enables to measure translational and rotary motion in three orthogonal axes. The accuracy of inertial sensors plays a key role in autonomous navigation. Errors of current inertial sensors have the approximate value of 0.01°/hour for gyroscopes and 100 μg for accelerometers. The mentioned errors are integrated in time and cause the error of determining the position which is expressed by the non-accuracy of measuring per hour, which is, however, minimal. Such high-power IMU are implemented only into the inertial navigation systems for special use. The mutual integration of accelerometers, gyroscopes, magnetometers, barometric sensors and microprocessor items into a compact unit, whose output values is the data about position, rotation, height and the like, is a current trend in the development and production of inertial units. Basic inertial sensors are supplemented with a GPS module or magnetic sensor to compensate the errors of inertial sensors.

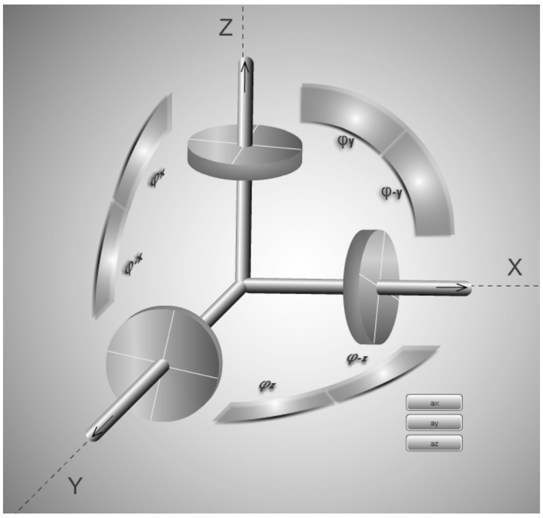

Fig. 1. Basic principle of INS activity

In the following part there is an example of solving robot arm movement in one axis. Also the possibilities for extending the arm movement simulation result solved by a mathematical model in a virtual environment, and the program MATLAB / Simulink.

Rotation arm dynamics

By the arm rotation "Fig. 2" round the horizontal axis *0*, neglecting the friction of the positioning, the arm is subject to M_m torque, M_D moment of inertia and the moment of the related gravitational force component M_G. The equation of the motion describing the arm movement is as follows:

$$M_m = M_D + M_G \Rightarrow M_m = J_0\ddot{\varphi} + mgL\sin\varphi, \qquad (1)$$

where J_0 is the arm moment of inertia to the rotation axis *0*, *m* is the arm mass, *L* is the distance between the rotation axis and the arm centre, *g* is the gravimetric acceleration, φ φ is the angle of the rotation and $\ddot{\varphi}$ is the angular acceleration of the solid.

Equation (1) is the mathematical arm model and its solution MATLAB/Simulink program is shown in "Fig 2", left. The driving motor moment illustrated by the block of the constant value will be substituted by the block scheme of an electromotor control [1,2]. This solution is qualified by knowing the mass, moment of inertia and arm centre regarding the rotation axis as well. These parameters can be calculated via geometry, dimensions and the density of the arm material.

Virtual dynamic arm model developed in MSC. ADAMS program is advantageous as it is not necessary to constitute the mathematical system description, which can be quite complicated for the complex sets of fixed solids [3, 5]. The system, in our case the arm, represents a 3D geometric built in a random CAD program and imported to MSC.ADAMS program "Fig. 2". The geometric model is appropriately positioned, the numeric value of the arm material density is assigned (subsequently the program automatically calculates the position of the centre, the weight and moments of inertia to the centre axes), then by the rotation geometric bond it is fixed to the stable space and the place of driving moment is prescribed. In addition, for the needs of the control, it is essential to develop the sensors of the angle rotation and the angular arm velocity. The prepared virtual model can be imported to MATLAB/Simulink program, to which the block scheme of the electromotor control is applied "Fig. 2", right).

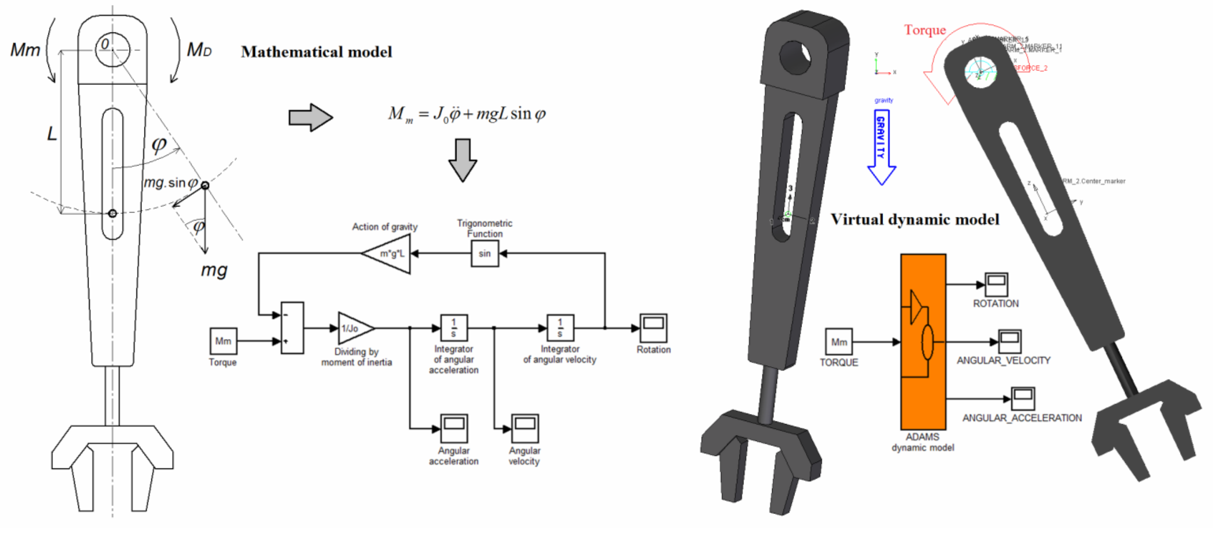

Fig. 2. Mathematical (left) and virtual dynamic (right) arm models

The manipulation arm parameters: mass $m = 0.798$ kg, moment of inertia to the rotation axis $J_0 = 0.013655$ kg.m^2, distance between the rotation axis and the centre $L = 0.096$ m. The prescribed arm rotation is shown in "Fig. 2", left. Via the inverse dynamic analysis in MSC.ADAMS program we can obtain the corresponding rotation moment for the motion required, "Fig. 3", right. The maximum value of the rotation moment is 0.7514 Nm.

Model of DC motor with regulation

As the main control drive the Parvex RS110M DC motor [7] with the gear (gear ratio 1:50) was used ensuring the decrease of the required rotation moment and increase of working motor revolutions. Motor parameters are shown in Tab. 1.

DC linear motor model with permanent magnet in MATLAB/Simulink program was developed on the basis of the mathematical models of mechanical (2) and electrical (3) motor parts [1, 2]:

$$M_m - M_L = J_m \frac{d\omega}{dt}, \tag{2}$$

$$u = R_m i + L_m \frac{di}{dt} + u_i, \tag{3}$$

where M_m is the motor torque, M_L is the moment load of the motor power, J_m is the moment of inertia of the rotor, ω is the motor speed, u is the power voltage, R_m is the motor anchor resistance, L_m is the motor anchor's winding inductance, i is the current flowing through the motor windings, t is the time and u_i is the induced voltage on the motor anchor's winding. The relation of the mechanical and electrical parts is expressed as follows:

$$u_i = C_{u\omega}\omega; \; M_m = C_{um} i, \tag{4}$$

where C_{um} is the torque constant of the motor and $C_{u\omega}$ is the voltage constant of the motor.

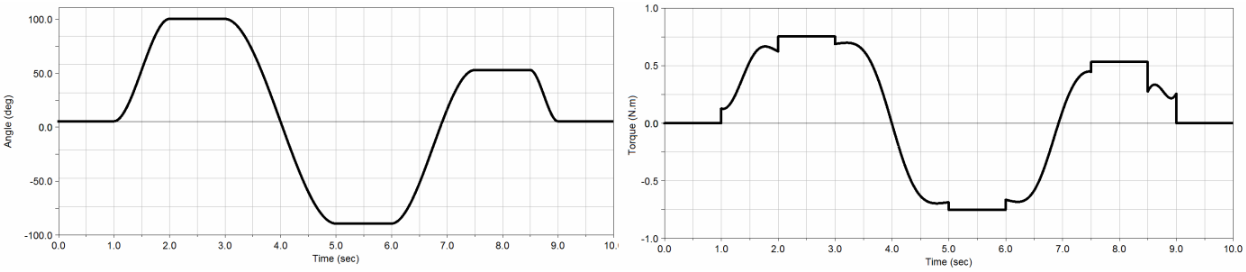

Fig. 3. Prescribed arm rotation (left), course of torque (right)

Table 1. **Parameters of DC servomotor Parvex RS110M [7]**

Rotor inertia	Winding inductance	Winding resistance	Torque constant	Voltage constant	Torque	Maximum supply voltage	Peak current	Nominal current	Maximum speed
J_m [kg.m^2]	L_m [H]	R_m [Ω]	C_{um} [N.m/A]	$C_{u\omega}$ [N.m/A]	M_m *[Nm]*	U_{max} [V]	I_{max} [A]	I_{nom} [A]	ω_{max} [rpm]
2.4.10^{-6}	0.0016	4.5	0.037	0.037	0.05	33	4	1.5	8300

For the motor modeling we used the model, in which the losses in iron are not considered. We used the cascade regulation to control the manipulation arm positioning "Fig. 3". The innermost loop represents the current control, or DC motor torque control. The control of the angular velocity is the loop which is given precedence, and the arm rotation control is the highest loop. For the current loop, P regulator is utilized, for the angular velocity regulation of the motor PI regulator is used, and the positioning loop is controlled by P regulator.

Individual constants of regulators were obtained via the auto-tuning in MATLAB/Simulink program and are shown in Tab. 3. In the overall model the limitations arising from the motor used, as shown are in Tab. 1, were utilized. In the model the dynamics of sensors and dry friction is not considered.

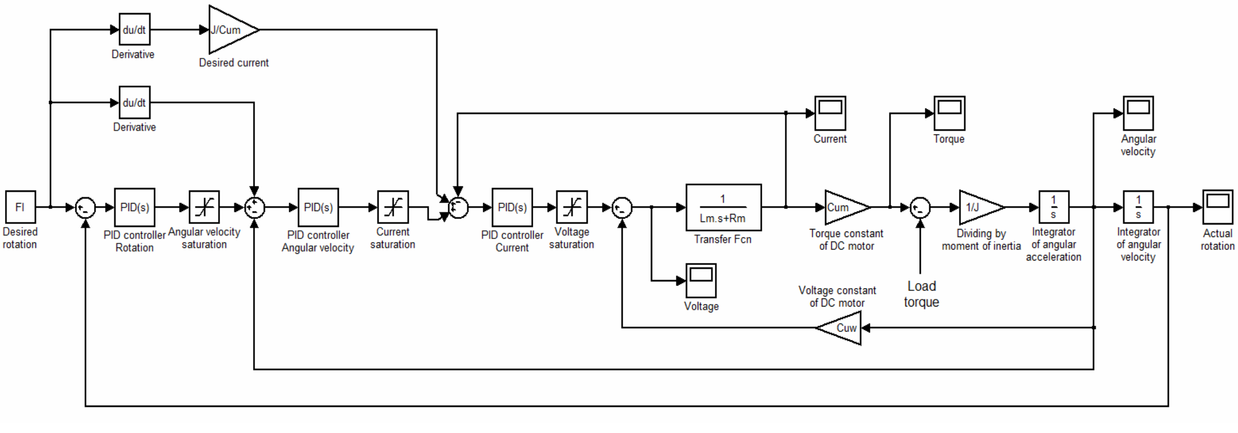

Fig. 4. Regulation scheme of JM motor

Table 2. **Terms of the individual controllers**

Controller	Current	Angular velocity	Rotation
P	9.184	1.342	2.398
I	–	2.629	–

Arm regulation

The schemes of arm position control for the mathematical model and virtual dynamic models are illustrated in "Figs. 5 and 6". In both cases the same motor regulators set ups were used. In case of the virtual model, the input of the load velocity effect to the arm movement to the control motor block is missing. The data together with the arm inertia effects are automatically generated in the block of the dynamic model developed in ADAMS program.

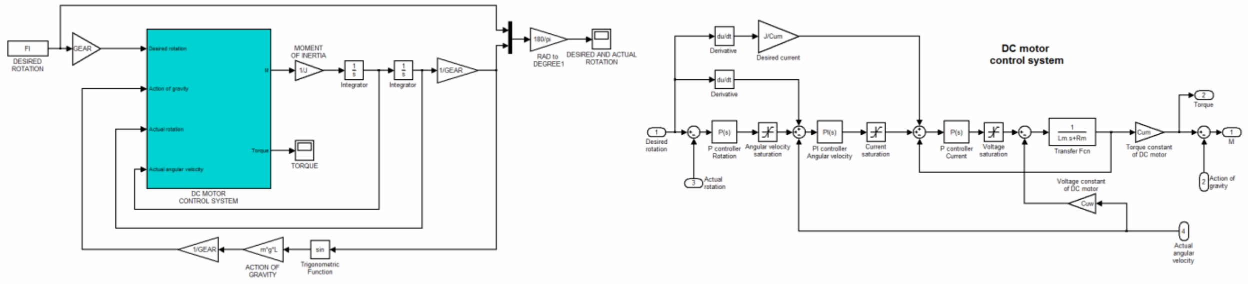

Fig. 5. Mathematical arm model control

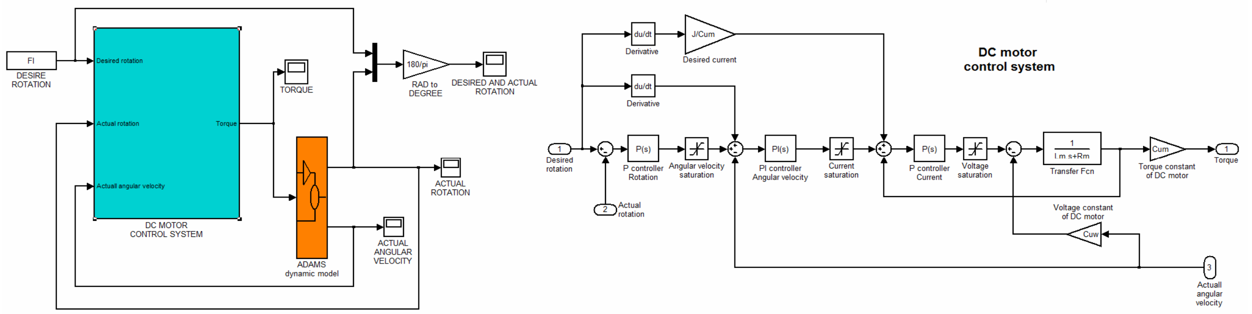

Fig. 6. Virtual dynamic arm model control

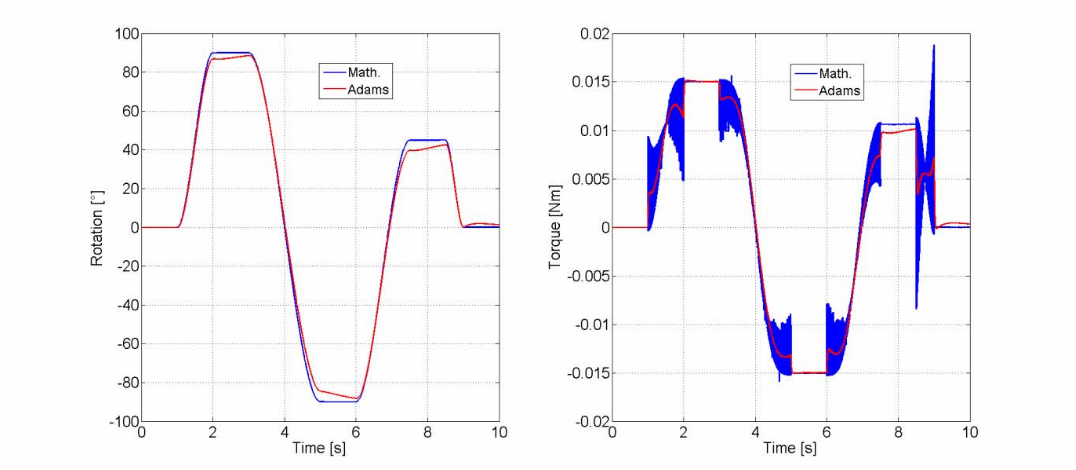

Fig. 7. Course of arm rotation and motor torque for mathematical model (Math.) and virtual dynamic model (Adams)

Conclusion

The results of the controlled position are illustrated in "Fig. 7". Regarding the rotation required; the course of the arm rotation from the mathematical model is very precise. For the virtual dynamic model the deviations are more significant "Fig. 8", therefore, it would be necessary to modify the values of regulators for this model.

All in all, we present the solution of the dynamic system regulation on a dynamic model incorporating the influences of the forces of inertia emerging in the movement of the system as well as all the external forces influencing the system. The significance of these models utilization is much higher for the complex systems of fixed solids, where the mathematical description is more demanding.

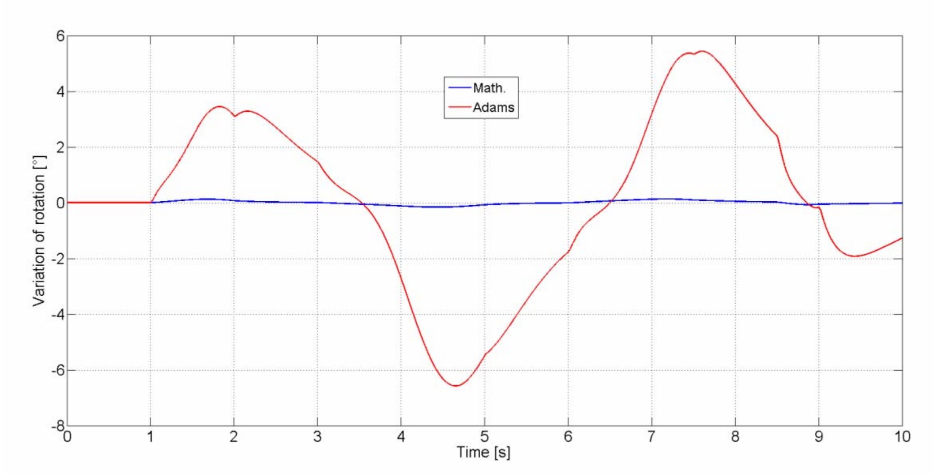

Fig. 8. Deviation of arm rotation regarding the value required

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References

1. *Žalman M.* Actuators. – STU Bratislava, 2003. – ISBN 80-227-1835-1.

2. *Schmid D.* Management and control for engineering and mechatronics. – Verlag EUROPA, 2005. – ISBN 80-86706-10-9.

3. *Bishop H. R.* The Mechatronics Handbook. – CRC Press, 2006. – ISBN 0-8493-0066-5.

4. *Heimann B.*, *Gerth W.*, *Popp K.* Mechatronik – Komponenten – Methoden – Beispiele. – HANSER, 2007. – ISBN 978-3-446-40599-8.

5. *Weber W.* Industrieroboter. – HANSER, 2009. – ISBN 978-3-446-41031-2.

6. *Barbour N.*, *Elwell J.*, *Setterlund R.* Inertial instruments: Where to now. – URL: www.media.mit.edu/resenv/classes/.../Inertialnotes/DraperOverview.pdf [cit. 2011-07-15].

7. *Nikitin Y. R.*, *Abramov I. V.* Models of information processes of mechatronic systems diagnosis // University Review. – 2011. – Vol. 5. – No. 1. – P. 12–16. – ISSN 1337-6047.

8. *Titterton D. H.*, *Weston J. L.* Strapdown inertial navigation technology (2nd Edition). – URL: http://www.knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=1241> [cit. 2011-07-12].

9. *Šípoš Ľ.* Inertial navigation. – Zvolen, 2011.

10. *Nikitin Y.R.* Diagnostic models of mechatronic modules and analysis techniques // Procceding of 2nd International Conference “Advances in Mechatronics”, December 2007, Brno, Czech Republic. – ISBN 978-80-7231-314-3.

11. *Soták M.* Integration navigation systems. – Košice, 2006.

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Контроллер руки робота на основе ИНС с применением моделирования MATLAB / SIMULINK

В статье описаны принципы работы и возможности применения инерционной навигационной системы (INS) для управления роботами. Также дано описание настройки двигателя постоянного тока, применяемого для позиционирования вращающегося манипулятора. Система управления двигателем включает в себя настройку силы тока, угловой скорости и согласование вращения вала двигателя, соединенного с рукой робота, с учетом требуемого углового изменения поворота руки. Настройка двигателя постоянного тока выполняется в программной среде MATLAB/Simulink. Движения руки описаны с помощью математической модели и виртуальной динамической модели, полученной с помощью программы MSC.ADAMS.

Ключевые слова: INS, гироскоп, акселерометр, динамическая модель, PID-контроллер, MATLAB/Simulink.