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System of 3D printers cooperating via the Internet - studying the impact of network delays on the operation of the system

***Abstract**. The paper presents the system cooperating with each other via the Internet 3D printers. It is described a mathematical model of the printer robot and kinematic chain. The mathematical model of dynamics manipulator 3D printer and its control system was implemented in Matlab/Simulink environment, for both the master printer (the system of setpoint), as well as a slave printer, working as a copier. In the system of setpoint is contained a printed shape of the element, which during operation is converted at a given trajectory of movement of the manipulator master printer. Subsequent points of trajectories are transmitted via the Internet to the slave printer, where reproduced is the shape of the printed element.*

Streszczenie.** W artykule przedstawiono układ współpracujących ze sobą poprzez sieć Internet drukarek druku przestrzennego. Opisano model matematyczny robota drukarki oraz łańcuch kinematyczny. Opracowany model matematyczny dynamiki manipulatora drukarki 3D oraz jej układ sterowania został zaimplementowany w środowisku Matlab/Simulink, zarówno dla drukarki nadrzędnej (układ zadający), jak też dla drukarki podrzędnej pracującej, jako kopiarka. W układzie zadającym zawarty jest kształt drukowanego elementu, który podczas pracy przekształcany jest na zadaną trajektorię ruchu manipulatora drukarki nadrzędnej. Kolejne punkty trajektorii są przesyłane poprzez sieć Internet do drukarki podrzędnej, gdzie jest realizowane odtwarzanie kształtu drukowanego elementu. W artykule przedstawiono wyniki odtwarzania zadanego kształtu dla różnych zadanych wartości opóźnień transmisji danych przez sieć Internet. (System drukarek 3D współpracujących przez Internetem - badanie wpływu opóźnień sieci na działanie systemu***).*

Keywords: kinematic chain, 3D printer, Internet, system of cooperating 3D printers.
Słowa kluczowe: łańcuch kinematyczny, drukarka 3D, Internet, system współpracujących drukarek 3D.

Introduction

Technology 3D printing is a process for producing three-dimensional, physical objects based on a computer model. At first it was only one method of rapid prototyping used both to build prototype molds. According to the progress, has also increased the accuracy of create of objects through a 3D printer, it has become the method of execution ready-made objects e.g. toys. This technology is also used in the preparation of dentures.

The authors conducted a preliminary study on the possibility of printing 3D objects at the same time in different places of the Internet, using the master printer (robot that prints) and slave printers (robot that copies).

A block diagram representing a basic structure cooperating printers - robots illustrated in Fig 1.

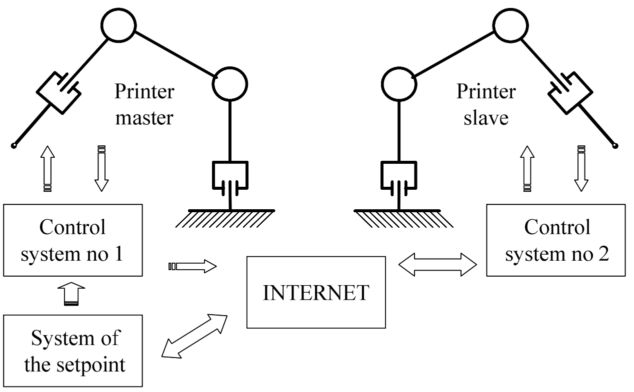

Fig. 1 Block diagram of the system of cooperating via the Internet, 3D printers

The ability to simultaneously printing 3D objects in many places in the factory or in the world at the same time is part of the development of modern manufacturing [7] in the world (Factory 4.0).

Analyzed in this paper the system cooperating 3D printers, consists of: of the two kinematic chains robot manipulators (printers), the control system of robots, systems of data transmission via the Internet, system of setpoint.

Mathematical model of robot 3D printer

In the system setpoint is contained a printed shape of the element, which during operation is converted at a given trajectory of movement of the manipulator master printer. The control system 1 through contained in the model of the dynamics of the manipulator, generates the required drive torque in the joints and transmits the measured joints variables via the Internet. The control system 2 controls the operation of the slave printer, takes over the sent (via the Internet) joints variables (with master printer) and prints by recreating. Both the master printer and the slave printer have the same kinematic chains of their manipulators. As opposed to applied in much of the existing 3D printers kinematic chains composed of prismatic joints, in the model of the 3D printer adopted kinematic chains composed of rotary joints.

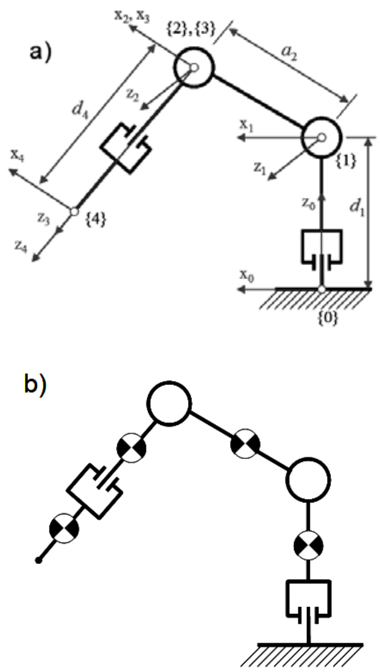

Fig.2. The described kinematic chain of robotic 3D printer - a), the position of the center of gravity members - b)

Limited number of degrees of freedom manipulator to four for a single printer, and described kinematic chain manipulator 3D printer was presented in Fig 2 a). Fig 2 b) shows the positions of the centers of gravity of individual members manipulator 3D printer.
In the Figure 2 parameters mean: d_1 - offset joint 1, a_2 - the length of the member 2, d_4 - offset working tip (print head), joints variable (rotation angles of individual joints ϑ_i) is the rotation around the axis z_0 - z_3 subsequent coordinate systems selected by the {0} - {3}.

A table of kinematic parameters, presenting all the kinematic parameter of 3D printer manipulator is presented in Table 1.

Table 1. Kinematic parameters of manipulator 3D printer

człon	a_i	α_i	d_i	ϑ_i
1	0	$-\pi/2$	d_1	ϑ_1
2	a_2	0	0	ϑ_2
3	0	$-\pi/2$	0	ϑ_3
4	0	0	d_4	ϑ_4

On the basis of the table kinematic parameters were formulated homogeneous transformation matrices, describing the position and orientation of each of coordinate systems (in the function of joints variables) in the basic coordinate system {0}. Single homogeneous transformation resulting from the use of notation Denavit - Hartenberg to describe the kinematic chain of 3D printer, is composed of four elementary transformations (rotation around the axis z_i, rotation around the axis x_i, translation along the axis z_i and translation along the axis x_i) and has the form:

$$\boldsymbol{A}_i = \boldsymbol{R}_{z_i,\vartheta_i}\boldsymbol{Tr}_{z_i,d_1}\boldsymbol{Tr}_{x_i,a_i}\boldsymbol{R}_{x_i,\alpha_i} \tag{1}$$

where: $\boldsymbol{R}_{zi}$, $\boldsymbol{R}_{xi}$ - rotation around the axis of z_i and x_i, $\boldsymbol{Tr}_{zi}$, $\boldsymbol{Tr}_{xi}$ - translation along the axis x_i and z_i.

Transforming homogeneous describing the position and orientation of the end effector (print head) in the base coordinate system is in the form of the product of four homogeneous transformations (1), means:

$$\boldsymbol{T}_0^4 = \prod_{i=1}^{4}\boldsymbol{A}_i \tag{2}$$

For the formulate equations of the dynamics of the manipulator 3D printer, is necessary to find a transformation homogeneous for all members of gravity (Fig. 2 b), they have the form:

$$\boldsymbol{T}_0^{c1} = \boldsymbol{A}_{c1} \tag{3}$$

$$\boldsymbol{T}_0^{c2} = \boldsymbol{A}_1\boldsymbol{A}_{c2} \tag{4}$$

$$\boldsymbol{T}_0^{c3} = \boldsymbol{A}_1\boldsymbol{A}_2\boldsymbol{A}_{c3} \tag{5}$$

$$\boldsymbol{T}_0^{c4} = \boldsymbol{A}_1\boldsymbol{A}_2\boldsymbol{A}_3\boldsymbol{A}_{c4} \tag{6}$$

where: matrices $\boldsymbol{A}_i$ been formulated by (1), whereas matrices $\boldsymbol{A}_{ci}$ - represented the position and orientation of gravity on individual members.

The equations of the dynamics of manipulator 3D printer have the form [1, 2]:

$$\boldsymbol{D}\ddot{\vartheta} + \boldsymbol{C}\dot{\vartheta} + \boldsymbol{G} = \boldsymbol{\tau} \tag{7}$$

where: $\boldsymbol{D}$ - matrix of inertia, $\boldsymbol{C}$ - matrix of Coriolis and centrifugal forces, $\boldsymbol{G}$ - vector forces/moments of gravity, ϑ - vector of the angular displacements.

Canonical form of equation (7), convenient to implement the mathematical model in MATLAB/Simulink is following:

$$\ddot{\vartheta} = \boldsymbol{D}^{-1}(\boldsymbol{\tau} - \boldsymbol{C}\dot{\vartheta} - \boldsymbol{G}) \tag{8}$$

Equation (7) and (8) will be used to formulate a dynamic manipulator model of 3D printer and its control system. Equations (8) represent a model of the dynamics of the manipulator of the printer, and the equations (7) will be used to the formulation of the control system, so-called inverse dynamics model [3]. The mathematical model implemented in MATLAB/Simulink has been presented in Fig.3.

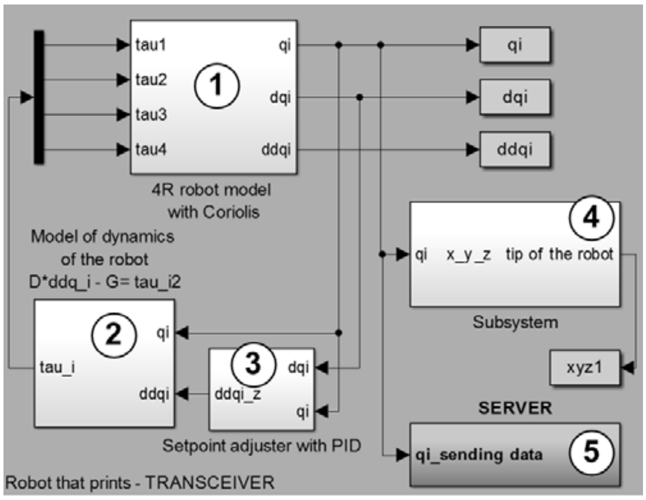

Fig.3. The implemented mathematical model of the dynamics of the manipulator 3D printer as well as its control system

In block, indicated in Figure 3, the number "1" contains a mathematical model manipulator 3D printer. Input values of the block are joints driving torque ("tau1" - "tau4"). The output signals of this block are joints variables "qi", joints of speed indicated by "dqi" and joints of accelerate - "ddqi". The signals of the angular displacements and angular velocities, provide feedback signals that are introduced into the input block "3" represents the system of setpoint trajectory as well as regulators the setpoint position and speed setting. The output of the block "3", it given angular acceleration, which, together with the signal of the angular displacement values are inputs to the block "2". In this block, according to the formula (7) (the given angular displacements, angular velocities and accelerations angle) are calculated required driving torque. Calculated driving moments are the input of the block "1" (Fig. 3). The block "4" is used for the presentation the trajectory of the tip of the working robot, based on the joints variables.

Block "5" (S-Function tool) contains a program written in C++, which is used to provide data exchange via the Internet. For model 3D printer of robot (master), program operates in Server mode, while for model 3D printer of robot (slave), program operates in Client mode.

The mathematical model of slave printer (working as a copier) does not differ substantially from the model presented in Figure 3, except for a modification of the block adjuster "3" and the program mode for the transmission of data via the Internet. Block of setpoint is equipped with additional input to which the input signals are joints variables sent via the Internet.

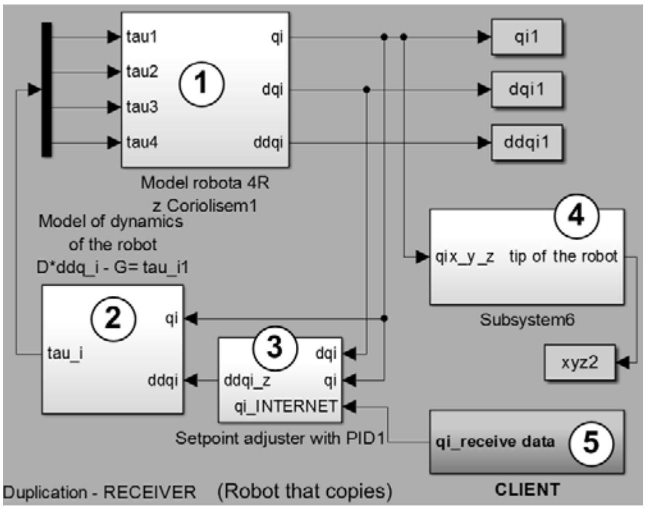

Fig.4. The implemented mathematical model of the dynamics of the manipulator 3D printer as well as its control system, working as a copier

Block setpoint "3" slave printer (working as a copier) does not include systems that generate trajectory.

Test stand and results

Block diagram of test stand for system of cooperating 3D printers via the Intranet is presented in Fig.5.

The stand consists of two computers connected through the network cards to the local network (Intranet). The transmission of data between two computers was realized in the system Server-Client.

Mathematical model of the dynamics of the manipulator 3D printer as well as its control system (robot that prints) has been implemented on the server side, whereas the mathematical model of the dynamics of the manipulator 3D printer as well as its control system (robot that copies) which works as a copier, has been implemented on the client side. The exchange of data between computers is carried out by an actual connection, therefore, to ensure that correctness of data transmissions between the data generated during the simulation on two different computers, was applied the tool **RTBlock**, which is available for Simulink environment. The RTBlock tool forces the environment execution the simulation process similar to the real-time with an accuracy of 1 ms. In addition it allows the setting for the process of simulation highest priority in the operating system.

Data exchange through network cards (using TCP/IP) is realized by the author programs written in C++ [4]. The program codes were implemented in the user-definable block ***(S-Function)*** in simulink environment, both on the server side (Robot that prints), as also on the client side (Robot that copies).

Figure 6 presents exemplary trajectory of robotic 3D printer movement registered via Intranet.

In the local area network, without delay of data transmission, was achieved the same shape of the printed element for both the master printer (robot that prints) as well as the slave printer (robot that copies).

With the use of tools **Transport delay** in environment simulink, was increased the delay of data transmission in a local area network (between models of robots). For delay values to 10 ms was not observed change in the waveform of individual joints variables. By increasing the delay of data transmission over 10 ms, waveforms of individual joints variables do not overlap. The deviation is the greater the greater the delay value [5]. Delays data transmission from the value of which can be observed deviation in waveforms joints variables is obviously dependent on the model of dynamics of the robot.

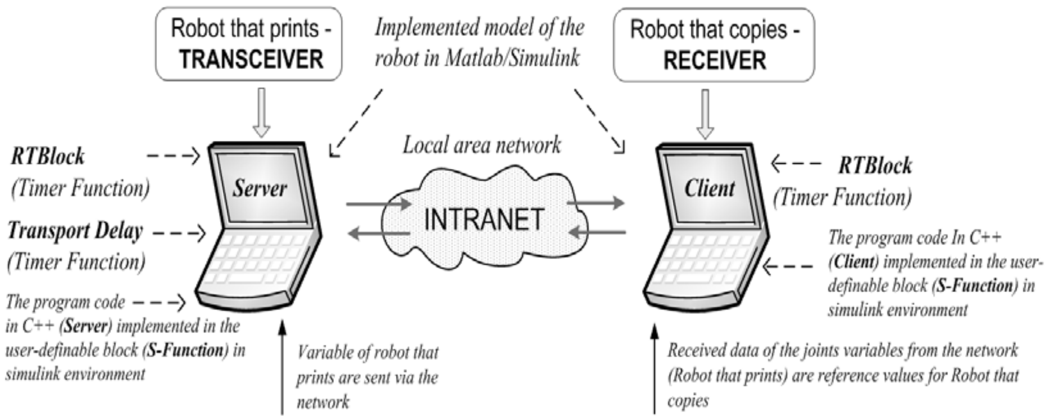

Fig. 5. Block diagram of test stand for system of cooperating 3D printers via the Intranet

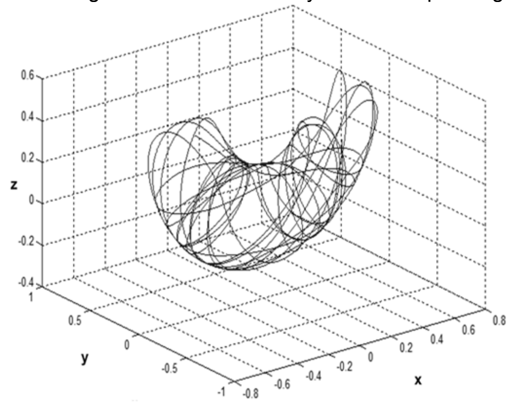

Fig.6. Trajectory of robotic 3D printer movement registered via Intranet - exemplary the shape of the printed element

The next stage of research will be the use the network emulator [6], in order to conduct research on the impact of stochastic changes of the delay and packet loss (actual conditions in the Internet) on the cooperating 3D printers.

Conclusions

The results obtained on the basis of conducted research on the test stand, made it possible to formulate the following conclusions:

- Thanks to the tool RTBlock (Real-Time Blockset) implemented in the dynamics model manipulator 3D printer in Simulink, forced on the Microsoft Windows operating system and Matlab/Simulink, conditions for the implementation of the simulation similar to real time (with an accuracy of 1 ms). These conditions have proved suitable in to conducting the planned research program, related to control via the Internet.

- The use of Matlab/Simulink to study the possibility of duplicate a predetermined shape of the printed element via the Internet makes it easier to research on solutions to control robots via the Internet.
- Due to the limited dynamic work 3D printer, data transmission delay of less than 10 ms do not affect the quality of duplicated shape.
- In the next stage of the research will be extended to take into account loss of data packets, on the print quality.

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