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AN ANALYSIS OF THE INTERACTIONS BETWEEN INDIVIDUAL ROBOTS IN A DECENTRALIZED MULTI-ROBOT TRANSPORT SYSTEM DURING MOVEMENT INITIATION

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Abstract

The article analyzes the influence of control signal delays on the initiation of movement in a distributed group of robots and the implementation of the robots' programmed trajectory. A static analysis was carried out in a distributed group of robots, where the applied constraint was the connection of the robots to a transport pallet. The loads resulting from delayed transmission of the control signal were subjected to a dynamic analysis in MSC Adams View software.

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Introduction

Entrepreneurs are constantly faced with the challenge of increasing their production efficiency and reducing their operating costs in order to achieve success and strengthen their position on the market. This goal can be attained through the automation of in-house logistics. This solution is gaining widespread popularity because according to Industry 4.0 standards, internal transport is one of the most dynamically developing sectors of the economy. Transport operations generate losses due to increasing labor shortages and the growing costs of transport in the production process. Therefore, the costs associated with the internal transport of products have to be minimized by shortening product transport routes and times. Transport costs can be decreased by introducing autonomous robots which perform transport operations accurately, quickly and safely (*Autonomiczne mobilne roboty…* 2018). According to a report of the United Nations Conference on Trade and Development, robot-based transport facilitates and optimizes the work of factory employees and decreases production time by as much as 25% (JURCZAK 2018). Such a solution has been implemented in the Seat factory in Spain where mobile robots transport around 24,000 car parts daily (Fig. 1).

Fig. 1. Mobile transport robots at the Seat factory in Spain

Cooperating mobile robots for in-house transport are navigated based on independently created maps or previously uploaded building plans. The robots are equipped with cameras, built-in sensors and laser scanners to determine the location of the transported objects, avoid obstacles, respond to humans and other robots encountered on the route. A safety and navigation system that stops or activates the robot at the right moment is a very important element of the control algorithm.

An effective solution enabling the synchronous activation and deactivation of a group of transport robots is also required for managing robotized tasks. The factory environment usually consists of numerous rooms, production lines and devices that cause interference and delays in wireless transmission (SIWEK et al. 2018b). Even minor delays in the transmission of the control signal can cause considerable errors in the positioning of individual robots in a group (SIWEK et al. 2018a). The cooperation between mobile robots and industrial robots is particularly sensitive to positioning errors. A mobile robot has to assume a precisely controlled position to lift or put down an object (KACZMAREK et al. 2018). Various methods for controlling robot groups and eliminating positioning errors have been proposed in the literature. Such solutions include the Virtual Structure algorithm described by TAN and LEWIS (1996) and the optimal trajectory planning algorithm developed by CHENG et al. (2016). However, the time drift between individual robots is one of the key problems in transport operations involving distributed groups of robots. This problem has been discussed extensively and various solutions have been proposed in the literature (AUTEFAGE et al. 2015).

The article analyzes the interactions between individual robots that transport cargo in a dispersed group. The circumstances under which the control signal is delayed were examined. When the control signal is delayed, the robot that is activated earlier exerts a load on stationary robots through the support platform (pallet, frame). The above can lead to undesirable changes in the position and orientation of the robot group before and after the set trajectory is completed. If such changes occur frequently, they can accelerate wear or cause damage to drive system components.

An analysis of the interactions between individual robots in a distributed multi-robot system

In a distributed multi-robot system, robots form a single network, but they interpret signals from the management center independently of each other and change their position or activity accordingly. The location coordinates of each robot in a distributed group are calculated independently, but relative to a common, stationary reference system. Each robot belongs to a group of robots that perform a specific task in a consistent manner. For the task to be carried out in a coordinated manner, the initial conditions (configuration of the robot group) have to be set, and the clocks of individual robots have to be synchronized (SIWEK et al. 2018a). In the process of controlling a distributed group, attention should be paid to errors in the transmission of control data which cause delays in the control algorithm. Electromagnetic interference (caused by, for example, numerous wireless networks), power network interference, and hardware differences between the operating robots (network cards, processors) can impair the synchronized execution of the control algorithm and, consequently, lead to delays in task performance by individual robots. Incorrect or inefficient time synchronization will lead to operating errors in the control algorithm of the distributed group. In practice, the activation, maneuvering and deactivation of individual robots will proceed asynchronously. As a result, the task will not be correctly performed because robots will move along the wrong trajectory, they will fail to maintain formation, or they will collide with obstacles. In this article, the movement of a group of three mobile robots with differential drives was examined to determine the interactions between individual robots in the group (Fig. 2). The robots were tasked with transporting a load on a rigid transport pallet. They were connected to the pallet by rotary joints with one degree of freedom. The analyzed transport system is presented in Figure 2.

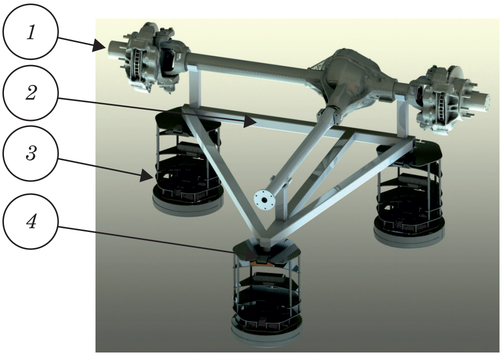

Fig. 2. View of the transport system: *1* – transported element, *2* – pallet, *3* – mobile robot, *4* – swivel joint

A static analysis of loads in a distributed multi-robot system where the applied constraint is the connection of the robots to the pallets.

The initiation of movement in a group of transport robots was analyzed. It was assumed that two robots (Robot 1 and Robot 3) would be delayed (due to data transmission errors) relative to the third robot (Robot 2). The force with which Robot 2 pushes the pallet acts as a driving force on delayed Robots 1 and 3. The force would increase to the maximum value due to the robot's maximum driving moment. In practice, the above could lead to wheel boxing, engine burning or joint breakage. A simplified diagram of the transport system is shown in Figure 3, where: *1,…,4* – transport pallet joint number; d_1, d_2, d_3 – dimensions of the transport pallet; a_2, a_3– inclination angles of the outer beams of the pallet;

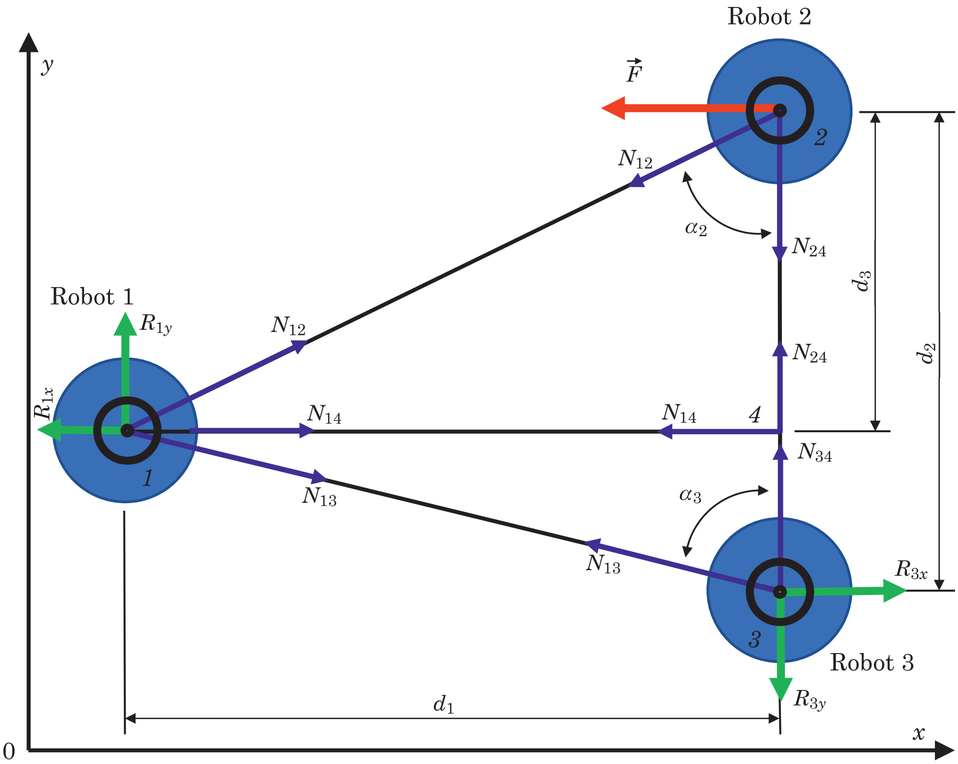

Fig. 3. Simplified diagram of the transport system, description in the text

$0xy$ – global coordinate system; F – force with which Robot 2 pushes the pallet; R_1x, R_1y, R_3x, R_3y – joint reaction forces in Robots 1 and 3 according to the x and y axes of the global coordinate system $0xy$; N_{ij} where $i, j = 1,\ldots,4$ – internal forces in the structural elements of the pallet.

The applied force will elicit a reaction in the joints of Robots 1 and 3, and it will cause internal forces in the structural elements of the transport pallet. The transport pallet shown in Figure 3 can be regarded as a truss. If the loads are applied only to the joints, and the joints do not move relative to each other, the system can be considered static. Robots 1 and 3 act as fixed supports. The joints connecting the pallet to the robots can only be rotated in axes perpendicular to the ground plane xy. The balance of forces and moments in truss nodes was used to determine the reaction in supports and the internal forces acting on the structural elements of the frame. This task was accomplished by developing a system of equations (1), where M_1, M_2, M_3 are the total torques in truss joints, and Px and Py represent the sum of forces acting in the axis of the global coordinate system $0xy$.

$$\begin{aligned} \sum M_1 &= -Fd_3 - R_{3y}d_1 + R_{3x}(d_2 - d_3) = 0 \\ \sum M_2 &= R_{3x}d_2 - R_{1x}d_3 + R_{1y}d_1 = 0 \\ \sum M_3 &= -Fd_2 + R_{1x}(d_2 - d_3) + R_{1y}d_1 = 0 \\ \sum P_x &= -F + R_{1x} - R_{3x} = 0 \end{aligned} \tag{1}$$

An auxiliary equation (2) was also formulated to check equation (1) for errors:

$$\sum P_y = R_{1y} + R_{3y} = 0 \tag{2}$$

The above system of equations was transformed into a matrix (3) which was solved in MATLAB software. The dimensions of the truss (Tab. 1) were taken into account when determining the reaction of the supports. The value of the force was set at $F = 250$ N, and it corresponds to the value of the force generated by a robot with a fully charged battery. The values of support reactions are presented in Table 2.

$$\begin{bmatrix} Fd_3 \\ 0 \\ Fd_2 \\ F \end{bmatrix} = \begin{bmatrix} 0 & 0 & d_2 - d_3 & -d_1 \\ -d_1 & d_3 & d_2 & 0 \\ d_2 - d_3 & d_1 & 0 & 0 \\ 1 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} R_{1x} \\ R_{1y} \\ R_{3x} \\ R_{3y} \end{bmatrix} \tag{3}$$

Table 1

Parameters of the transport system

Parameter	d_1 [m]	d_2 [m]	d_3 [m]	α_2 [deg]	α_3 [deg]
Value	1.0	1.2	0.7	60	75

Table 2

Support reactions

Parameter	R_1x [N]	R_1y [N]	R_3x [N]	R_3y [N]
Value	-197.5	127.5	75	-75

The calculated values of support reactions were used to determine the internal forces acting on the structural elements of the frame. The reactions of joints 1, 2 and 3 were calculated with equations (4), (5), (6) in MATLAB software. The values of internal forces are presented in Table 3.

Joint 1

$$\sum P_{1x} = -R_{1x} + N_{13}\sin(90^\circ - \alpha_3) + N_{12}\cos(90^\circ - \alpha_2) + N_{14} = 0$$
$$\sum P_{1y} = R_{1y} + N_{12}\sin\alpha_2 - N_{13}\sin\alpha_3 = 0 \tag{4}$$

Joint 2

$$\sum P_{2x} = -F - N_{12}\cos(90^\circ - \alpha_2) = 0$$
$$\sum P_{2y} = -N_{24} - N_{12}\sin\alpha_2 = 0 \tag{5}$$

Joint 3

$$\sum P_{3x} = R_{3x} - N_{13}\sin(90^\circ - \alpha_3) = 0$$
$$\sum P_{3y} = -R_{3y} + N_{34} + N_{13}\sin\alpha_3 = 0 \tag{6}$$

Table 3

Values of internal forces

Parameter	N_{12}[N]	N_{13} [N]	N_{14} [N]	N_{24} [N]	N_{34} [N]
Value	-287.35	288.46	-22.5	250	-351.92

A dynamic analysis of loads resulting from control signal delays

The analysis was carried out using MSC Adams software. A simplified transport system was modeled (Fig. 4) to determine deviations in the positioning of delayed robots, caused by force F = 250 N. The deviations were measured over a time period equivalent to the delay in the transmission of the control signal. The initial conditions for the simulation were formulated in the first step. The initial position and the initial orientation of the robots in the global coordinate system were determined. A simplified model of a robot composed of a body and two drive wheels was adopted. Rotary joints controlled by drive torque were positioned on wheels. Rotary joints with free rotation were applied at the point of connection to the transport pallet. The transported load was rigidly connected to the pallet. The mass of all modeled components was equivalent to their real mass. The moment of inertia was determined in the CAD program relative to the center of gravity. The analysis accounted only for the movements along the ground plane, and the appropriate constrains were implemented in the model.

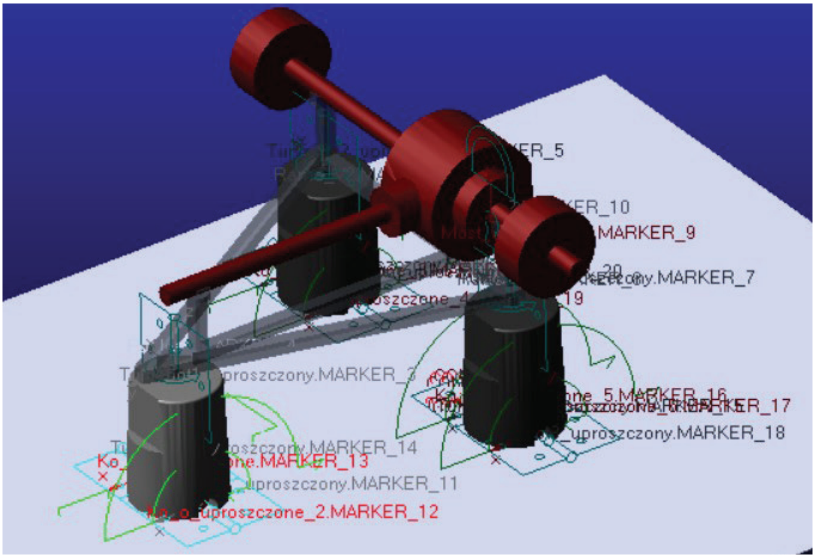

Fig. 4. Simplified simulation model of the transport system in MSC Adams software

Displacements along x and y axes of the frame at the points of connection to the robots were determined during the simulation of movement in the transport system. The delays in the transmission of control signals ranged from 0 ms to 200 ms. The changes in the positional errors of individual robots during group movement, caused by three delays in the transmission of control signals of Robot 1 and Robot 3 relative to Robot 2 (0, 50 and 200 ms), are presented in Figures 5, 6 and 7.

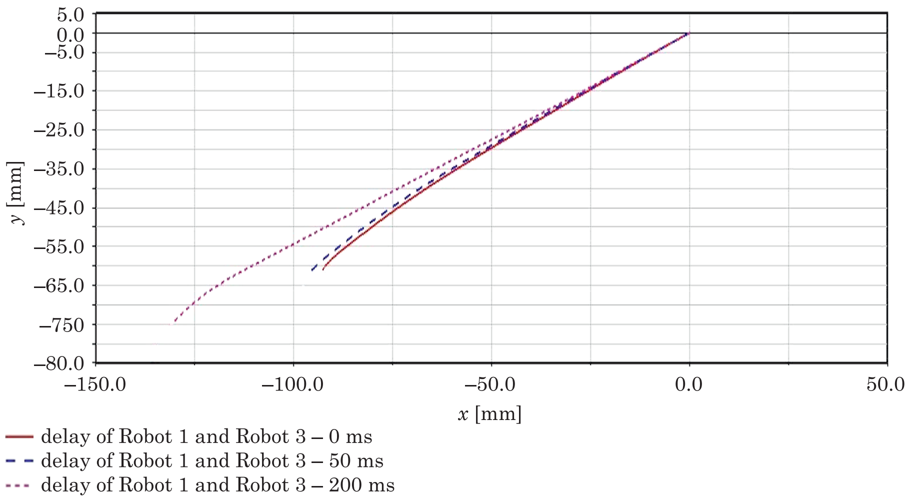

Fig. 5. Trajectory of Robot 1 resulting from the delay of control signals

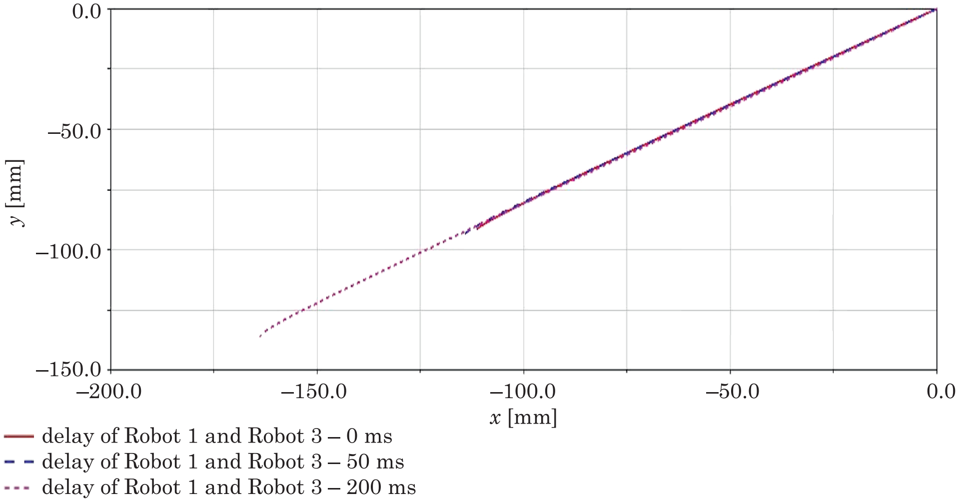

Fig. 6. Trajectory of Robot 2 resulting from the delay of control signals

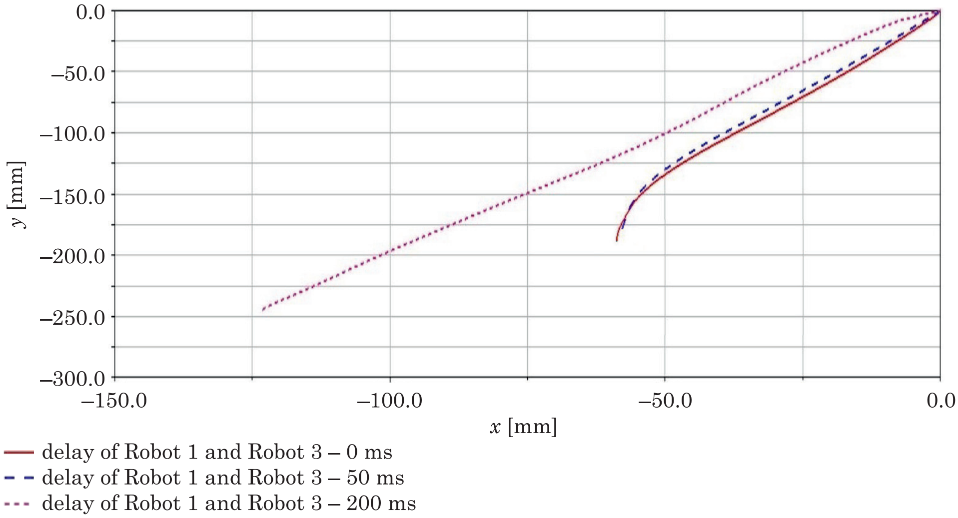

Fig. 7. Trajectory of Robot 3 resulting from the delay of control signals

An analysis of the trajectories presented in Figures 5-7 reveals errors in the robot's final position caused by the time delay. These errors can be eliminated by formulating a control law that accounts for the delays caused by the time-varying force acting on the robots. Therefore, the differences in the forces between robots should be minimized in the process of formulating the goal function.

Results and Discussion

The article discusses the practical applications of mobile robots working in a dispersed group to transport large-sized and irregularly shaped objects. A review of the literature revealed that delays in the transmission of control signals to the robot system compromise the system's positioning accuracy and constitute an important problem in robotized transport operations. The results of the simulation tests conducted in this study indicate that:

– The delays in the transmission of control signals lead to non-synchronous activation of robots in a dispersed group;

– During non-synchronous initiation of movement, the force with which a mobile robot pushes the transported load elicits a reaction in the motionless robots. These reactions affect the service life and the accuracy of the robots' propulsion systems;

– The resulting forces lead to displacement and changes in the orientation of the transport system, which, consequently, causes positional and orientation errors relative to the initial configuration.

The above problems can be resolved by formulating a control law that accounts for the dynamic synchronization of robots in a dispersed group and by minimizing differences in the forces between robots in the process of formulating the goal function.

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