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ANALYSIS OF THE INTERACTION OF ROBOTS IN DECENTRALIZED MULTI-ROBOT SYSTEM FOR TRANSPORT TASKS DURING START OF THE MOVEMENT

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Abstract

The article presents the analysis of the influence of control signal time delays on the start of movement of a distributed group of robots and on the implementation of their programmed trajectory. Static analysis was carried out in a distributed group of robots, which were imposed by constraint resulting from connecting the robots with a transport pallet. Then, dynamic analysis of loads occurring as a result of control signal delays in MSC Adams View software was performed.

Introduction

Entrepreneurs who are constantly striving to achieve success and strengthen their position on the market are increasingly asking themselves: how to increase production efficiency and reduce costs? One of the answers to this question is the automation of in-house logistics. This solution is becoming increasingly important because according to Industry 4.0 standards internal transport is becoming one of the most important areas undergoing change. Due to the increasingly limited labour force resources and the growing costs of transporting products in the production process, transport is considered in the category of losses. Therefore, there is a need to minimize the costs associated with the internal transport of products consisting in shortening the routes and time of product movement. One solution to this problem is the introduction of autonomous transport robots that accurately, quickly and safely perform the tasks entrusted to them (Control Engineering, 2019) according to a report from the United Nations Conference on Trade and Development, robot-based transport facilitates and optimizes the work of those employed in factories and
is able to reduce production time by up to a quarter (trans.info.pl, 2019). An example of the introduction of mobile robots as a transport system is the Seat factory in Spain, where robots transport about 24,000 car parts daily (Fig. 1).

Cooperating mobile robots in in-house transport are navigated based on of independently created maps or previously uploaded building plans. To measure the location, data with a camera, built-in sensors and laser scanners are used, which are equipped with robots. Thanks to this, robots can avoid obstacles and react to people and other robots encountered on the road. A safety and navigation system that stops or releases the robot at the right moment is a very important element of the control algorithm.

Another example required in cooperation with robots carrying out transport tasks is the synchronous start and stopping of a whole group of robots. An extensive factory environment usually consists of many rooms, production lines and other devices that cause interference and delay in wireless transmission (SIWEK et al. 2018a). Even low control signal delays can cause large positioning errors for individual robots in a group (SIWEK et al. 2018b). A particularly sensitive case of positioning errors is the cooperation of mobile robots with industrial robots. Picking or putting down a part transported by a mobile robot requires a particularly precise position of the mobile robot (KACZMAREK et al. 2018). Methods of controlling groups of robots appear in the literature, which to some extent eliminate robot positioning errors. One example is the Virtual Structure algorithm described in detail in (TAN and LEWIS, 1996). Another example is the optimal trajectory planning algorithm described in detail in (CHENG et al., 2016). However, considering
distributed groups of robots that are most often used for transport tasks, the key problem is time drift in individual robots. In the literature, this problem has been described for a long time and methods of solving it are proposed (AUTEFAGE et al., 2015).

The article presents an analysis of the interaction between robots in a dispersed group transporting cargo. The situations in which robots have delays in control signals were considered. This causes that the robot that starts the movement earlier exerts a force on other stationary robots, through the supporting platform (pallet, frame). The effect of this phenomenon is possible, unwanted change in the position and orientation of the initial group, which will result in the incorrect position of the group after completing the set trajectory. In addition, with frequent occurrences of such situations, there is a risk of faster wear or damage to drive system components.

**Analysis of the interaction of robots in a distributed multi-robot system**

In a distributed multi-robot system, robots form a single network, however, they interpret signals from the management center independently of each other and change their position or activity in an appropriate way. The location coordinates of individual robots included in the distributed group are calculated independently of each other, but relative to a common, stationary reference system. The important thing in this case is that each of the robots is part of a group of robots that perform a specific task in a consistent manner. To be able to do this, it is first necessary to specify the initial conditions (configuration - arrangement of the group of robots) and time synchronization in all robots (SIWEK et al. 2018b). In the case of distributed group control, attention should be paid to control data transmission errors, which cause control algorithm delays. Occurring in the work environment electromagnetic interference (e.g. high density of wireless networks), power network interference, and hardware differences in used robots (e.g. network cards, processors) will result in a lack of synchronization in the execution of the control algorithm. This will cause delays in the implementation of the assumed task by individual robots. Incorrect or inefficient time synchronization will result in erroneous operation of the distributed group control algorithm. In practice, this means that actions such as starting a move, performing a manoeuvre, stopping will be implemented asynchronously by individual robots. The result of this will be incorrect execution of the task (movement along the wrong trajectory, failure to maintain formation, collision with an obstacle). For the purposes of analysing the interaction of robots in a distributed group, the motion of a group of three mobile robots with differential drive has considered (Fig. 2). The robots have carried a load placed
on a rigid transport pallet. The robots have connected to the pallet by means of rotary joints with one degree of freedom. The view of the transport system has shown in Figure 2 (1 - transported element, 2 - pallet, 3 - mobile robot, 4 - swivel joint).

Fig. 2. View of the transport system

Static analysis of loads in a distributed multi-robot system, on which constraints resulting from the connection of robots are imposed

In order to conduct the analysis, the phenomenon of starting the movement of a group of transport robots has been considered. It has assumed that two robots (Robot 1 – R1 and Robot 3 – R3) would be delayed (due to data transmission errors) compared to the third (Robot 2 – R2). It has causes (through the pallet) robot No. 2 as a driving force to delayed robots No. 1 and 3. The force increases to the maximum value resulting from the maximum driving moment of the robot. In practice, this phenomenon may result in wheel boxing, engine burning or joint breakage. A simplified diagram of the transport system is shown in Figure 3, where: 1, 2, 3 mobile robots, d1, d2, d3 – dimensions of the transport pallet, α1, α2 – inclination angles of the outer beams of the pallet, Oxy - global coordinate system, F - force with which robot 2 pushes the pallet, R_{1x}, R_{1y}, R_{4x}, 

Accept
$R_{3y}$ - reactions in joints 1 and 2 according to the x and y axes of the global coordinate system $Oxy$, $N_{ij}$ where $i, j = 1,...,4$ - internal forces in the structural elements of the pallet.

Fig. 3. Simplified scheme of the transport system

The effect of this phenomenon will be reactions in the joints of the robot 1 and 3, and internal forces in the structural elements of the transport pallet. The transport pallet diagram shown in Figure 3 can be considered 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 are treated as fixed supports. The joints by means of which the pallet is connected to the robots can only be rotated in axes perpendicular to the ground plane $xy$. The balance of forces and moments in the truss nodes was used to determine the reaction in supports and internal forces in the frame structural elements. To this end, the system of equations (1) has been formulated as shown below, where $M_1$, $M_2$, $M_3$ are the total torques in the truss joints and $Px$ i $Py$ are summary forces along the axis of the global coordinate system $Oxy$. 
\[\sum M_1 = -Fd_3 - R_{3y}d_1 + R_{3x}(d_2 - d_3) = 0\]
\[\sum M_2 = R_{3x}d_2 - R_{1x}d_3 + R_{1y}d_1 = 0\]
\[\sum M_3 = -Fd_2 + R_{1x}(d_2 - d_3) + R_{1y}d_1 = 0\]
\[\sum P_x = -F + R_{1x} - R_{3x} = 0\] \hspace{1cm} (1)

In addition, an auxiliary equation (2) was formulated, using which the absence of errors in the system of equations (1) was checked.

\[\sum P_y = R_{1y} + R_{3y} = 0\] \hspace{1cm} (2)

The above system of equations has been transformed into matrix form (3), and then it has been solved in MATLAB software. When determining the reaction of supports, the dimensions of the truss included in Table 1 have been taken into account. The force value \( F = 250 \) N has been adopted, which corresponds to the value of the force generated by the robot drive with a fully charged battery. The values of the determined reactions have been presented in Table 2.

\[
\begin{bmatrix}
Fd_3 \\
0 \\
Fd_2 \\
F
\end{bmatrix}
= 
\begin{bmatrix}
0 & 0 & d_2 - d_3 & -d_1 \\
-d_1 & d_3 & d_2 & 0 \\
d_2 - d_3 & d_1 & 0 & 0 \\
1 & 0 & -1 & 0
\end{bmatrix}
\begin{bmatrix}
R_{1x} \\
R_{1y} \\
R_{3x} \\
R_{3y}
\end{bmatrix}
\] \hspace{1cm} (3)

Table 1. Values of transport system parameters

| Parameter | d1 [m] | d2 [m] | d3 [m] | \(\alpha_2\) [deg] | \(\alpha_3\) [deg] |
|-----------|--------|--------|--------|-------------------|-------------------|
| Value     | 1.0    | 1.2    | 0.7    | 60                | 75                |

Table 2. Values of determined reactions

| Parameter | R1x [N] | R1y [N] | R3x [N] | R3y [N] |
|-----------|---------|---------|---------|---------|
| Value     | -197.5  | 127.5   | 75      | -75     |

Determining the value of the reaction of supports allowed the determination of internal forces in the frame structural elements. To this end, systems of equation equations (4), (5), (6) have been formulated in joints 1, 2
and 3, which were solved in MATLAB software. The determined values of internal forces have been shown in Table 3.

Joint 1

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

Joint 2

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

Joint 3

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

Table 3. Values of determined 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        |

**Dynamic analysis of loads occurring as a result of control signal delays**

The analysis has been carried out using MSC Adams software. To this end, a simplified transport system model has been implemented in the software (Fig. 4), enabling measurement of position deviations caused by the force \(F = 250\) N acting on delayed robots for a time equal to the delay of control signals. Initially, the initial conditions of the simulation have been formulated. The initial position and initial orientation of the robots in the global coordinate system have been determined. A simplified robot model made of a body and two drive wheels has been adopted. Rotary joints controlled by drive torque have been declared on the wheels. At the connection points of the transport pallet, rotary joints with free rotation have been declared. The transported load has been rigidly connected to the transport pallet. All components of the simulation model have given a mass consistent with their real mass and moments of inertia determined in the CAD program relative to the center of gravity. Only motion on a plane related to the ground has been analysed,
therefore constraints have been imposed on the model allowing only motion on the plane.

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

During the simulation of the transport system movement, displacements along the Ox and Oy axes of the frame attachment points to the robots have been determined. The robot speed was set at 0.5 m/s. The time delays of the control signals ranged from 0 ms to 200 ms. Figures 5, 6 and 7 show the change in position error during group movement for individual robots due to three values of delays Robot 1 and Robot 3: 0, 50 and 200 ms.
Analyzing the trajectories presented in Figures 5-7, one can notice errors in the robot's final position caused by the time delay. A way to eliminate the errors noted is to formulate a control law that takes into account delays caused by time-varying force acting on the robots. Therefore, the goal function should take into account the difference in forces between robots that should be minimized.

**Results and discussion**

The article presents the applications of mobile robots working in a dispersed group in the large-size transport of irregularly shaped objects. During the literature analysis, it was noticed that an important problem in this type of applications is the accuracy of achieving the given position by the transport system resulting from the time delays of the signals controlling the system. Therefore, a number of simulation tests were conducted, the results of which allow stating that:
- The appearance of time delays of the control signals causes a non-synchronous start of the robots forming a dispersed group;
- During the non-synchronous start of the movement, there are reactions to the force with which the mobile robot, through the transported load, affects the remaining, still motionless robots, which in turn translates into the life and accuracy of their propulsion systems;
- Emerging forces result in displacement and change of orientation of the transport system, which causes position and orientation errors in relation to the initial configuration.

The solution to the problems described above can be the application of the control law, taking into account the dynamic synchronization of robots in a dispersed group, and minimizing the purpose function, in which there is a difference of forces between the robots.

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