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THE CALCULATION AND DESIGN OF THE SERIAL MODULAR ROBOT TRTR1

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Abstract: *In this paper the authors present calculation and construction elements for the serial modular robot TRTR1. This robot is an alternative to the KUKA articulated robot, used to the palletizing of car batteries manufactured at S.C. ROMBAT S.A., from Bistriţa, Romania. The paper presents specific calculation, leading to the determination of the dynamic equations of the robot, used to choose the driving engines. The robot has a modular construction. Starting from the base of the robot, the constructions details of the modules are presented.*
Key words: *serial modular robot, dynamic equations, design, horizontal module, vertical module.*

1. INTRODUCTION

In the manufacturing of car batteries at S.C. ROMBAT S.A. from Bistriţa, Romania, for the palletizing of batteries is used an articulated robot with five degrees of freedom (fig. 1). Following the palletizing operation, done with this robot, it can be seen that the robot is used inefficient because all the engines are working at each handling. Thus, came the idea of replacing this robot with one that has four degrees of freedom (TRTR1), that will be implemented in the palletizing of the car batteries.

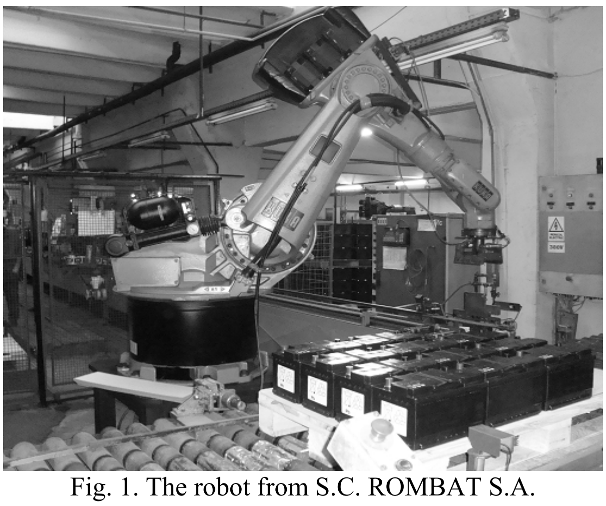


Fig. 1. The robot from S.C. ROMBAT S.A.

2. THE DYNAMIC EQUATIONS OF THE TRTR1 ROBOT

Industrial robots design involves choosing the architectural structure of the robot and the driving engines. In the design stage is required an evaluation of the following indicators: number of degrees of freedom, shape and sizes of the working space, mobility, loading capacity, service factor etc.

This type of evaluation is possible only by doing a dynamic study of the robot. The TRTR1 robot is an alternative to the five degrees of freedom robot made from articulated elements, implemented in the manufacturing process of car batteries at S.C. ROMBAT S.A. The two robots, the proposed TRTR1 and the existing one, are destined to palletize car batteries at the end of manufacturing line.

The kinematic scheme of the TRTR1 robot is presented in figure 2. The robot has the following modules: module 1 of translation on vertical, module 2 of rotation of the robot's arm, module 3 of translation of the arm and module 4 of orientation of the clamping device (with the car battery that is caught in this device).

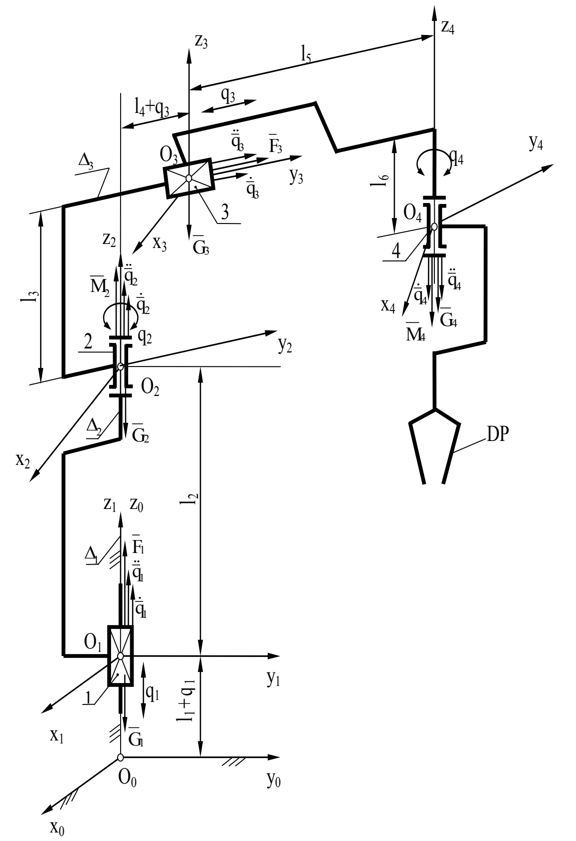


Fig. 2. The kinematic scheme of the TRTR1 robot

In figure 2 the following notations were made:

$l_i, i = 1 \div 5$ - the design parameters of the robot;

$q_k, k = 1 \div 4$ - the kinematic and geometric parameters (the generalized coordinates);

$\overline{G}_i, i = 1 \div 4$ - the gravity forces of the robot's modules 1, 2, 3 and the gravity force G_4 of the system composed of the module 4, the clamping device and the battery that is caught in this device;

$\overline{F}_1, \overline{F}_3$ - the motivities;

$\overline{M}_2, \overline{M}_4$ - the engine moments;

$\dot{q}_k, \ddot{q}_k, k = 1 \div 4$ - the velocities and accelerations (linear and angular);

$m_i, i = 1 \div 4$ - the masses for the robot's modules;

$J_{\Delta_2}^{(2)}$ - the mechanical moment of inertia for the mobile crew of the rotation module 2, determined in relation with the axis Δ_2;

$J_{Z_3}^{(3)}$ - the mechanical moment of inertia determined in relation with the axis O_3z_3;

$J_{Z_4}^{(4)}$ - the mechanical moment of inertia determined in relation with the axis O_3z_4.

The reference frames introduced in figure 2 are:

- the fixed frame $O_0x_0y_0z_0$, with the origin O_0 in a point from the Δ_1 axis;

- the mobile frames $O_ix_iy_iz_i$, $i=1 \div 4$, with the origins O_i in the centers of gravity of the modules 1, 2, 3 and the assembly 4 (the clamping device and the battery that is caught in this device).

The differential equations of movement, were determined from the Lagrange′s equations of second type [3]:

$$\frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}_k}\right) - \frac{\partial E_c}{\partial q_k} = Q_k, k = 1 \div 4, \qquad (1)$$

where E_c is the kinetic energy of the robot and $Q_k, k = 1 \div 4$ are the generalized forces.

By summarizing the kinetic energies of each module the kinetic energy of the robot is obtained and has the following expresion:

$$E_c = \frac{1}{2}\left(\sum_{i=1}^{4} m_i\right)\dot{q}_1^2 + \frac{1}{2}\Big[J_{\Delta_2}^{(2)} + J_{z_3}^{(3)} + J_{z_4}^{(4)} + m_3(l_4 + q_3)^2 + m_4(l_4 + l_5 + q_3)^2\Big]\dot{q}_2^2 + \frac{1}{2}\left(\sum_{i=3}^{4} m_i\right)\dot{q}_3^2 + \frac{1}{2}\cdot J_{z_4}^{(4)}\dot{q}_4^2 \pm J_{z_4}^{(4)}\dot{q}_2\dot{q}_4. \qquad (2)$$

For a compact writing of (2), the following notations were made:

$$c_{11} = \frac{1}{2}\left(\sum_{i=1}^{4} m_i\right);\ c_{22} = \frac{1}{2}\Big[J_{\Delta_2}^{(2)} + J_{z_3}^{(3)} + J_{z_4}^{(4)} + m_3 \cdot (l_4 + q_3)^2 + m_4(l_4 + l_5 + q_5)^2\Big];\ c_{33} = \frac{1}{2}\left(\sum_{i=3}^{4} m_i\right);$$

$$c_{44} = \frac{1}{2}J_{z_4}^{(4)};\ c_{24} = \pm J_{z_4}^{(4)}. \qquad (3)$$

So, the kinetic energy of the TRTR1 robot becoms:

$$E_c = c_{11}\dot{q}_1^2 + c_{22}\dot{q}_2^2 + c_{33}\dot{q}_3^2 + c_{44}\dot{q}_4^2 + c_{24}\dot{q}_2\dot{q}_4. \quad (4)$$

The second member from relation (1) contains the generalized forces $Q_k, k = 1 \div 4$. These forces are determined by giving basic virtual displacements so that the parameters q_k will vary with $\delta q_1, \delta q_2, \delta q_3, \delta q_4$.

According to [3], the generalized driving forces Q_k are:

$$Q_k = \frac{\delta L}{\delta q_k}, k = 1 \div 4. \quad (5)$$

The virtual mechanical work δL, corresponding to the external forces and to some basic virtual displacements has the expression:

$$\delta L = \sum_{i=1}^{n} \overline{F}_i \cdot \delta \overline{r}_i + \sum_{i=1}^{n} M_i \cdot \delta \overline{\theta}_i, \quad (6)$$

that in case of the TRTR1 robot, presented in fig. 2, becomes:

$$\begin{aligned} \delta L &= (F_1 - G_1)\delta q_1 + \overline{G}_2 \cdot \delta \overline{r}_2 + (\overline{G}_3 + \overline{F}_3) \cdot \delta \overline{r}_3 + \\ &+ \overline{G}_4 \cdot \delta \overline{r}_4 + M_2 \delta q_2 + M_4 \delta q_4. \end{aligned} \quad (7)$$

From fig. 2, the following specifications can be made: $\delta \overline{r}_2 = \delta q_1 \overline{k}_2$, $\delta \overline{r}_3 = \delta q_1 \overline{k}_2 + \delta q_3 \overline{j}_3$,

$$\delta \overline{r}_4 = \delta q_1 \overline{k}_2 + \delta q_3 \overline{j}_3,$$

so (7) becomes:

$$\delta L = \left(F_1 - \sum_{i=1}^{4} G_i \right) \delta q_1 + M_2 \cdot \delta q_2 + \overline{F}_3 \cdot \delta q_3 + M_4 \cdot \delta q_4. \quad (8)$$

Taking into consideration (5) and (8), the generalized driving forces have the expressions:

$$Q_1 = F_1 - \sum_{i=1}^{4} G_i, \; Q_2 = M_2, \; Q_3 = F_3, \; Q_4 = M_4. \quad (9)$$

The differential equations of TRTR1 robot are obtained by introducing in (1) the expressions (3) and (9). Thus:

$$\begin{aligned} &\left(\sum_{i=1}^{4} m_i \right) \ddot{q}_1 = F_1 - \sum_{i=1}^{4} G_1 \\ &\left[J_{\Delta_2}^{(2)} + J_{z_3}^{(3)} + J_{z_4}^{(4)} + m_3 (l_4 + q_3)^2 + m_4 (l_4 + l_5 + q_3)^2 \right] \ddot{q}_2 \pm \\ &\pm J_{z_4}^{(4)} \ddot{q}_4 + 2 \left[m_3 (l_4 + q_3) + m_4 (l_4 + l_5 + q_3) \right] \dot{q}_2 \dot{q}_3 = M_2 \\ &\left(\sum_{i=3}^{4} m_i \right) \ddot{q}_3 - \left[m_3 (l_4 + q_3) + m_4 (l_4 + l_5 + q_3) \right] \dot{q}_2^2 = F_3 \\ &J_{z_4}^{(4)} (\pm \ddot{q}_2 + \ddot{q}_4) = M_4. \end{aligned} \quad (10)$$

With the system (10) of differential equations the two basic problems of dynamics can be solved.

In the direct problem, if the mechanical design parameters of the robot, the laws of variation for forces and moments and the initial conditions of movement are known, the laws of motion on the robot's axis, the time functions $q_k = q_k(t)$, $k = 1 \div 4$, can be determined.

In the case of the inverse problem, the mechanical design parameters of the robot and the laws of movement on each axis are known and is required to determine the laws of variation for the engine agent (driving forces and moments).

Approaching the inverse problem, the dynamic study of the serial modular robot TRTR1 solves the following problems:

- choosing the optimal version for arranging the modules in the mechanical structure of the robot so that the energy consumption is minimal;
- choosing the laws of movement on robot's axis so that the energy consumption is minimal.
- choosing the driving engines by taking into consideration the organology of each module and the dynamics of the robot.

3. THE CONCEPTION AND DESIGN OF THE TRTR1 ROBOT

Because the palletizing line from Rombat is a permanent line for the palletization of car batteries of 66 [Ah] and 77 [Ah], the robot is especially designed for palletization, to replace the existent robot. By replacing the articulated robot KUKA (with five degrees of freedom), with TRTR1, some advantages are obtained: a reduced consumption of energy and space, lower construction costs.

The proposed robot is a serial robot, type TRTR (Fig. 3).

The robot is driven by four gearmotors. The transmission movement for the rotation modules is done with belt drive. At the first translation module, the translation movement is done with a ball screw that is driven by the gearmotor, also using belt drive. For the horizontal translation module the transmission of the translation movement is done with pinion rack gear.

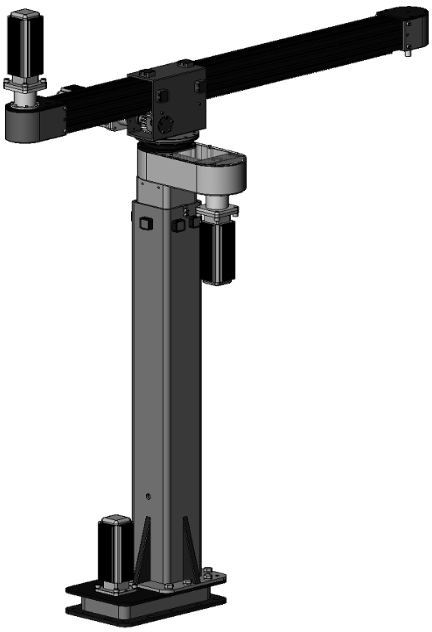


Fig. 3. The proposed robot TRTR1

3.1. The vertical translation module

For the vertical translation module MTV (fig. 4 and fig. 5), an transformation mechanism is chosen so that the rotation movement becomes a translation movement. This mechanism is an screw nut mechanism used to reduce friction, ensuring accuracy and increased reliability.

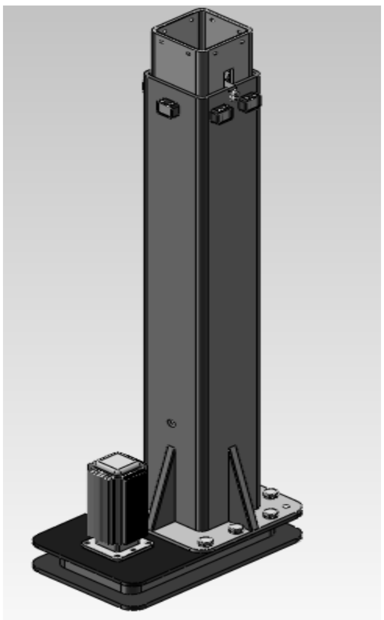


Fig. 4. The translation module

The construction of this module is built in telescopic version, aiming that the sleeve flanges are coaxial and placed at the ends of te module.

Ball screw drive is made by an actuator with integrated planetary gearbox, equipped with resolver and electromagnetical brake, through a synchronous cogged belt gear. The actuator with a resolver ensures a good positioning accuracy, because collects the information from the ball screw through the cogged belt gear.

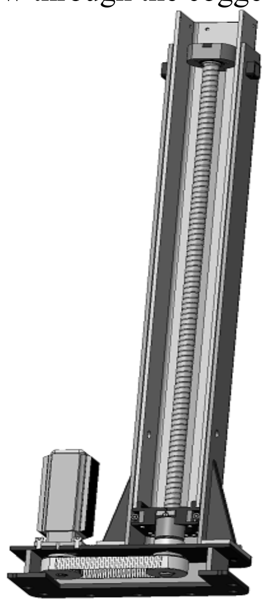


Fig. 5. The vertical translation module

The screw takes the rotation movement and pass it on the ball nut. The ball nut is solidary fixed with the mobile arm. The mobile arm is toggled inside the fixed arm, having only the possibility to move across it because of the cross roller guideways roller between the two arms.

The fixed and mobile arm are made of square pipe of different geometric dimensions to allow fitting inside one another. The guidance of the mobile part is provided by the cross roller guideways.

3.2. The rotation module

The rotation of the robot's arm is ensured by the rotation module MR (Fig.6, Fig. 7 and Fig.8). This module has a simple construction with a kinematic chain consist of actuator (with resolver and electromagnetical brake), planetary gearbox build in the actuator's encasing, synchronous cogged belt gear and the rotation element.The actuator can rotate in both ways ensuring reversibility.

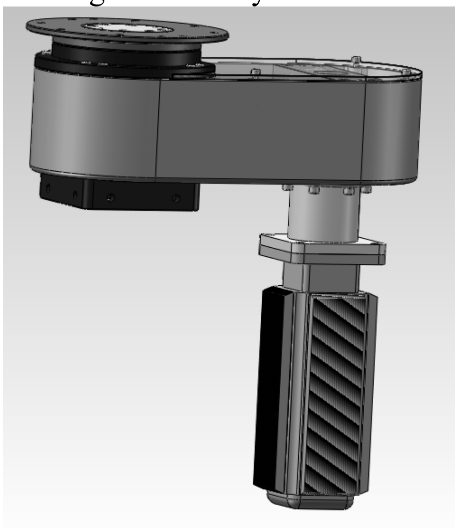


Fig. 6. The rotation module (isometric view)

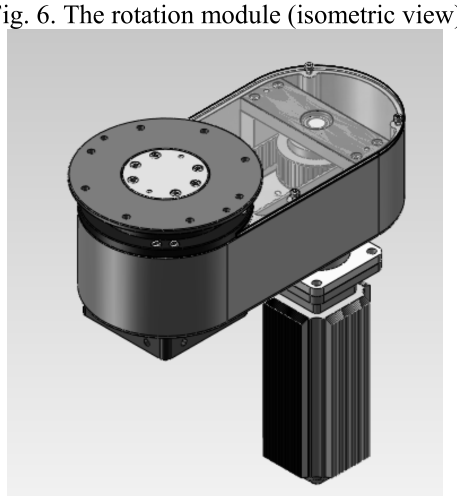


Fig. 7. The rotation module (isometric view)

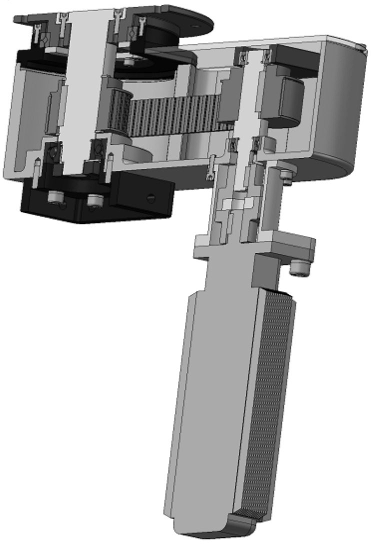


Fig. 8. The rotation module (cross section)

The vertical axis of the robot is presented in figure 9.

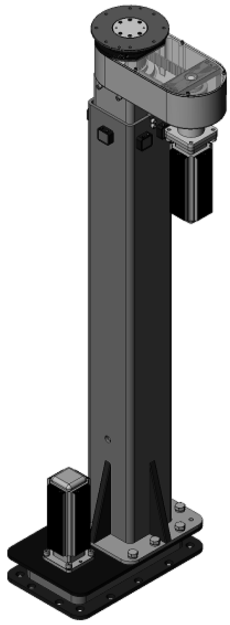
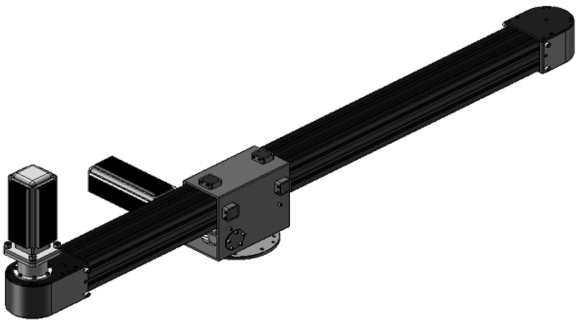


Fig. 9. The vertical axis TR of the TRTR1 robot

3.3. The horizontal translation module (robot's arm)

For the construction of the robot's arm (fig. 10), a special aluminium frame from Bosch



Rexroth company was used.

Fig. 10. The arm of te robot

At the bottom a rack was installed. The assembly required to achive the translation movement consists of a rack (mentioned above), a pinion, a gearmotor, a shell, guide rollers and support rollers (fig. 11). The guide and support rollers are mounted in the shell. The rollers come in direct contact with the frame and achive its support and guidance. The axle is also found inside the shell. The axle is supported by two radial bearings on which the pinion is mounted by means of a shim and two safety rings. Because of the special frame, a special construction of this module was chosen.

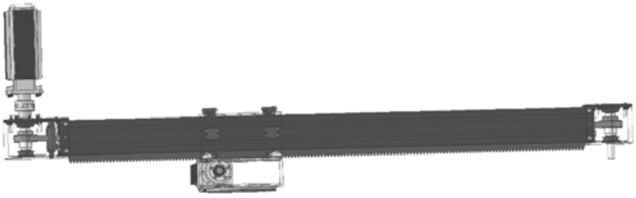


Fig. 11. The horizontal module (cross section)

Therefore, on one side of the frame the shell, that supports the axle on which the griper is caught, was placed. On the other side of the frame a shell was designed. In this shell an axle driven by a gearmotor (mounted on the same shell) and the rollers that stretch the belt from one end of the frame to the other can be found (the belt passes through the frame's interior). To reduce the manufacturing costs and the problems that may occur by introducing bevel gear train (necessary for the vertical positioning of the belt), the belt was positioned horizontally. Because the belt is very long and it's positioned on horizontal, a contact section between the belt and the frame occurs. For this reason, a low roughness polyurethane element was used. This element reduces friction and it was recommended by the belt's manufacturer. The axles of the rotation module are assembled by means of angular-contact roller bearing.

4. CONCLUSIONS

This paper proposes an alternative to the robot used in S.C. ROMAT S.A. Bistriţa for the palletizing process of car batteries.

The proposed robot TRTR1 is a slender robot, with reduced energy consumption and lower manufacturing costs.

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Calculul şi proiectarea robotului serial modular TRTR1

Autorii prezintă în lucrare elemente de calcul şi construcţie a robotului serial modular TRTR1. Acest robot este o alternativă la robotul articulat KUKA, utilizat la paletizarea acumulatorilor auto fabricaţi la S.C. ROMBAT S.A. din Bistriţa, România. În lucrare sunt prezentate calcule specifice care conduc la determinarea ecuaţiilor dinamice ale robotului, necesare determinării motoarelor de acţionare. Construcţia robotului este modulară. Pornind de la baza robotului, sunt prezentate detalii de construcţie a modulelor: de translaţie pe verticală, de rotaţie a braţului, de translaţie şi de rotaţie din componenţa braţului robotului.

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