Original Research Paper

The Dynamics of the Planar Cinematic Balanced Chain at the Plan Module 3R

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Abstract: In some previous papers, the mechatronic module 3R, plan, is a basic module on which the complete, geometric, cinematic, dynamic calculation of the anthropomorphic robots, the most used today's industrial robots, is built. The importance of the study of anthropomorphic robots has also been signaled, being today the most widespread robots worldwide, due to its simple design, construction, implementation, operation and maintenance. In addition, anthropomorphic systems are simpler from a technological and cheaper point of view, performing a continuous, demanding, repetitive work without any major maintenance problems. The basic module of these robots was also presented geometrically, cinematically, of the forces, of its total static balancing and of the forces that arise within or after balancing. In the present paper, we want to highlight the dynamics of the already statically balanced total module. It has been presented in other works and studied matrix spatially, or more simply in a plan, but in this case, it is necessary to move from the working plane to the real space, or vice versa, passage that we will present in this study. In the basic plan module already presented in other geometric and cinematic works, we want to highlight some dynamic features such as static balancing, total balancing and determination of the strength of the module after balancing. Through a total static balancing, balancing the gravitational forces and moments generated by the forces of gravity is achieved, balancing the forces of inertia and the moments (couples) generated by the presence of inertial forces (not to be confused with the inertial moments of the mechanism, which appear separately from the other forces, being part of the inertial torsion of a mechanism and depending on both the inertial masses of the mechanism and its angular accelerations. Balancing the mechanism can be done through various methods. Partial balancing is achieved almost in all cases where the actuators (electric drive motors) are fitted with a mechanical reduction, a mechanical transmission, a sprocket, spiral gear, spool screw type. This results in a "forced" drive balancing from the transmission, which makes the operation of the assembly to be correct but rigid and with mechanical shocks. Such balancing is not possible when the actuators directly actuate the elements of the kinematic chain without using mechanical reducers.

Keywords: Anthropomorphic Mechatronic Systems, Robots, Total Static Balancing, Kinetostatics, Dynamics

Science Publications

Introduction

A In some previous papers, the mechatronic module 3R, plan, is a basic module on which the complete, geometric, cinematic, dynamic calculation of the anthropomorphic robots, the most used today's industrial robots, is built. The importance of the study of anthropomorphic robots has also been signaled, being today the most widespread robots worldwide, due to its simple design, construction, implementation, operation and maintenance. In addition, anthromomorphic systems are simpler from a technological and cheaper point of view, performing a continuous, demanding, repetitive work without any major maintenance problems. The basic module of these robots was also presented geometrically, cinematically, of the forces, of its total static balancing and of the forces that arise within or after balancing. In the present paper we want to highlight the dynamics of the already statically balanced total module. It has been presented in other works and studied matrix spatially, or more simply in a plan, but in this case, it is necessary to move from the working plane to the real space, or vice versa, passage that we will present in this study. In the basic plan module already presented in other geometric and cinematic works, we want to highlight some dynamic features such as static balancing, total balancing and determination of the strength of the module after balancing. Through a total static balancing, balancing the gravitational forces and moments generated by the forces of gravity is achieved, balancing the forces of inertia and the moments (couples) generated by the presence of inertial forces (not to be confused with the inertial moments of the mechanism, which appear separately from the other forces, being part of the inertial torsion of a mechanism and depending on both the inertial masses of the mechanism and its angular accelerations. Balancing the mechanism can be done through various methods. Partial balancing is achieved almost in all cases where the actuators (electric drive motors) are fitted with a mechanical reduction, a mechanical transmission, a sprocket, spiral gear, spool screw type. This results in a "forced" drive balancing from the transmission, which makes the operation of the assembly to be correct but rigid and with mechanical shocks. Such balancing is not possible when the actuators directly actuate the elements of the kinematic chain without using mechanical reducers (Antonescu and Petrescu, 1985; 1989; Antonescu *et al.*, 1985a; 1985b; 1986; 1987; 1988; 1994; 1997; 2000a; 2000b; 2001; Aversa *et al.*, 2017a; 2017b; 2017c; 2017d; 2017e; 2016a; 2016b; 2016c; 2016d; 2016e; 2016f; 2016g; 2016h; 2016i; 2016j; 2016k; 2016l; 2016m; 2016n; 2016o; Berto *et al.*, 2016a; 2016b; 2016c; 2016d; Cao *et al.*, 2013; Dong *et al.*, 2013; Comanescu, 2010; Franklin, 1930; He *et al.*, 2013; Lee,

2013; Lin *et al.*, 2013; Liu *et al.*, 2013; Mirsayar *et al.*, 2017; Padula and Perdereau, 2013; Perumaal and Jawahar, 2013; Petrescu, 2011; 2015a; 2015b; Petrescu and Petrescu, 1995a; 1995b; 1997a; 1997b; 1997c; 2000a; 2000b; 2002a; 2002b; 2003; 2005a; 2005b; 2005c; 2005d; 2005e; 2011; 2012a; 2012b; 2013a; 2013b; 2016a; 2016; 2016c; Petrescu *et al.*, 2009; 2016; 2017a; 2017b; 2017c; 2017d; 2017e; 2017f; 2017g; 2017h; 2017i; 2017j; 2017k; 2017l; 2017m; 2017n; 2017o; 2017p; 2017q; 2017r; 2017s; 2017t; 2017u; 2017v; 2017w; 2017x; 2017y; 2017z; 2017aa; 2017ab; 2017ac; 2017ad; 2017ae).

Shows the kinematic diagram of the planar chain and Fig. 2 shows the kinematic scheme of the space chain.

The mechanism in Fig. 1 (planar cinematic chain) must be balanced to have a normal operation.

Through a total static balancing, balancing the gravitational forces and moments generated by the forces of gravity is achieved, balancing the forces of inertia and the moments (couples) generated by the presence of inertial forces (not to be confused with the inertial moments of the mechanism, which appear separately from the other forces, being part of the inertial torsion of a mechanism and depending on both the inertial masses of the mechanism and its angular accelerations.

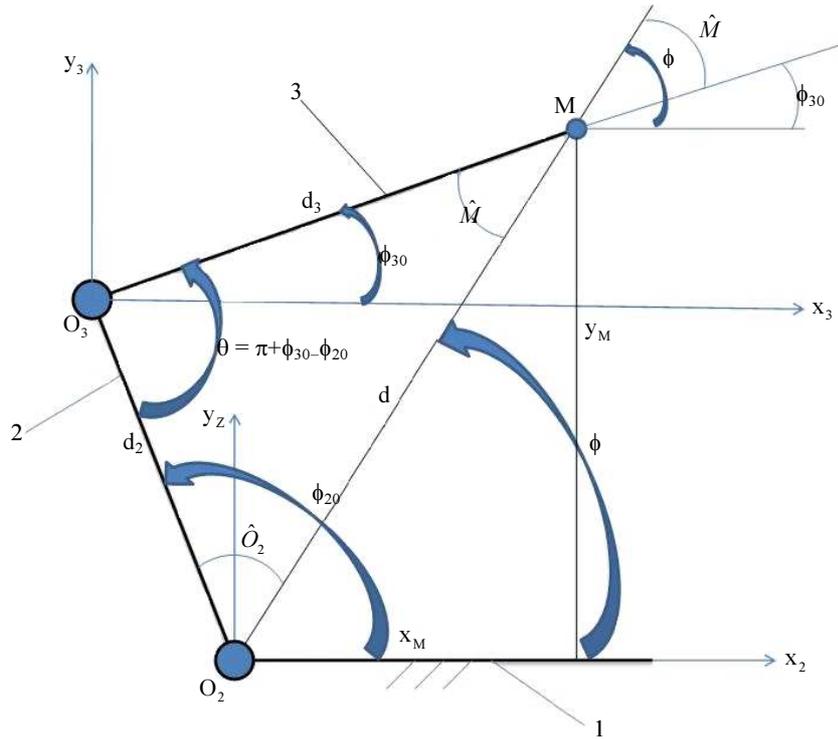Balancing the mechanism can be done through various methods.

Partial balancing is achieved almost in all cases where the actuators (electric drive motors) are fitted with a mechanical reduction, a mechanical transmission, a sprocket, spiral gear, spool screw type.

Such a reducer called the unisens (the movement allowed by it is a two-way rotation, but the transmission of the force and the motor moment can only be done in one direction, from the spindle to the worm gear, vice versa from the worm gear to the screw the force can not be transmitted and the movement is not possible by blocking the mechanism, which makes it apt to transmit the movement from the wheel of a vehicle to its wheels in the steering mechanism, not allowing the wheel forces due to the unevenness of the ground, to be transmitted to the steering wheel and implicitly to the driver, or this mechanism is suitable for mechanical meters so that they do not twist and vice versa etc.) can balance the transmission by letting the forces and motor moments unfold, but not allowing the kinematic elements to influence the movement through their forces of weight and inertia.

This results in a "forced" drive balancing from the transmission, which makes the operation of the assembly to be correct but rigid and with mechanical shocks.

Such balancing is not possible when the actuators directly actuate the elements of the kinematic chain without using mechanical reducers.

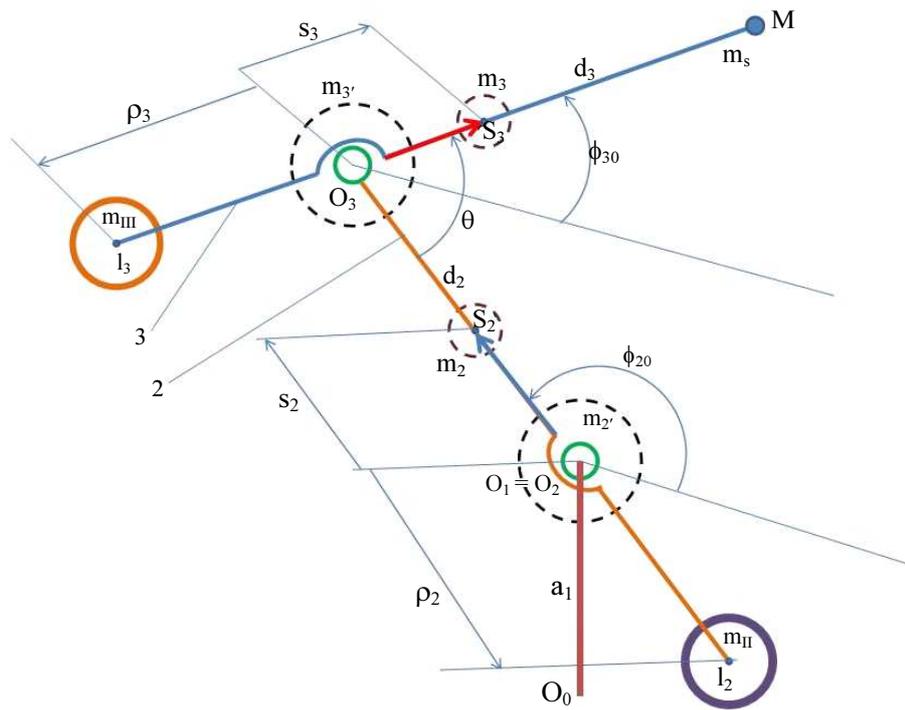It is necessary in this situation for a real, permanent balancing.

Fig. 1: The kinematic scheme of the plan chain
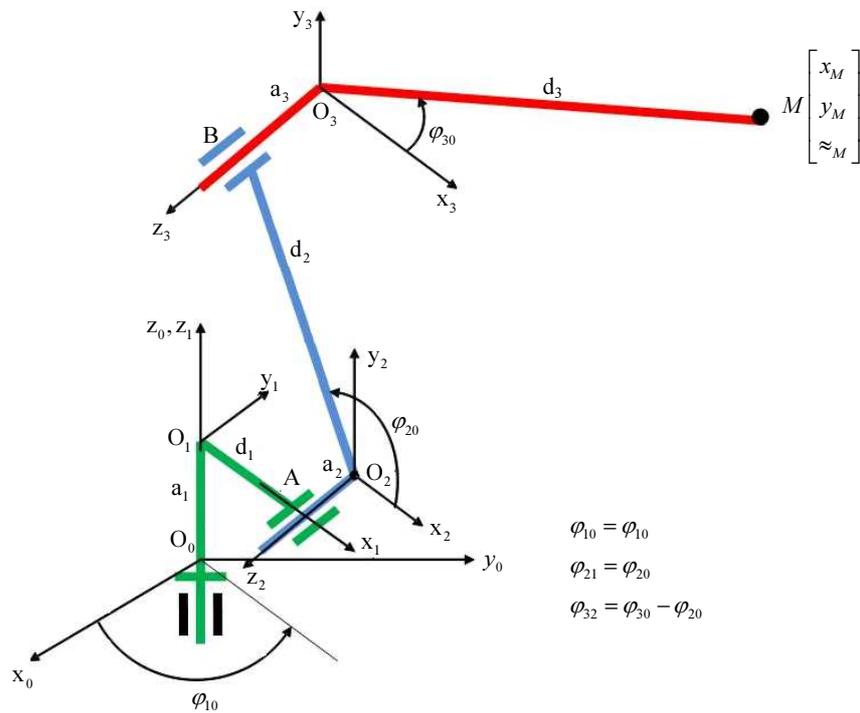
Fig. 2: The kinematic scheme of the spatial chain

In addition, in situations where hypoid reducers are used, it is also good to have a permanent, permanent static balancing that achieves a normal, quiet operation of the mechanism and the whole assembly.

25

Fig. 3: Balancing the plan cinematic chain

As has already been shown, by balancing the static totality of a mobile cinematic chain, it is possible to balance the weight forces and couples produced by them, as well as balancing the inertial forces and the couples produced by them, but not balancing the moment of inertia.

Arcing balancing methods generally did not work very well, the springs having to be very well calibrated, so that the elastic forces realized (stored) by them are neither too small (insufficient balancing) nor too large (because prematurely kinematic elements and couplers and also greatly forces actuators).

The most used method is the classic one, with additional counterweight masses, similar to traditional folk fountains.

Total balancing of the open robotic kinematic chain is shown in Fig. 3.

Materials and Methods

From the previous works, we observe the two dynamical relationships that generate the necessary motor moments (actuators) from the kinetostatic system, which are connected together in the dynamic system (1):

These relationships necessary in studying the dynamics of the planar cinematic chain can be obtained directly by another method, using Lagrange differential equations of the second type and preserving the kinetic energy of the mechanism.

This method is more direct compared to the cinetostatic study, but has the disadvantage that it no longer determines the loads (reactions, inner forces) from the kinematic couples of the studied chain, necessary for the organological calculation of the resistance of the materials to the stresses, by choosing some dimensions (thicknesses or diameters) of the kinematic elements 2 and 3 and of the coupling links:

$$
\begin{cases}
M_{m_2} = J^*_{O_2} \cdot \varepsilon_2 \\
M_{m_3} = J_{O_3} \cdot \varepsilon_3 \\
M_{m_2} = \left(m_2 \cdot s_2^2 + m_{II} \cdot \rho_2^2 + m_{3'} \cdot d_2^2 \right) \cdot \ddot{\varphi}_{20} \\
M_{m_3} = \left(m_s \cdot d_3^2 + m_3 \cdot s_3^2 + m_{III} \cdot \rho_3^2 \right) \cdot \ddot{\varphi}_{30}
\end{cases}
\tag{1}
$$

After balancing, the center of gravity of element 3 moves from point S_3 to mobile O_3 (Fig. 4) and the mass of element 3 increases from m_3 to $m_{3'}$; the center of gravity of element 2 moves from point S_2 to fixed O_2

joint, while the final mass of element 2 concentrated in O_2 increases to $m_{2'}$.

First, we determine the speeds of the final weight centers, i.e., the linear and angular velocities in the two O_2 and O_3 joints (relations 2).

So the linear velocities (the components or the scaling projections on the x and y-axes) of the two joints are determined, but also the angular velocities of the two elements considered concentrated each around the respective joint according to Fig. 4:

$$\begin{cases} \dot{x}_{O_2} = 0; \dot{y}_{O_2} = 0; \dot{\varphi}_{20} \equiv \omega_{20} \equiv \omega_2 \\ \dot{x}_{O_3} = -d_2 \cdot \sin\varphi_{20} \cdot \omega_2; \dot{y}_{O_3} = d_2 \cdot \cos\dot{\varphi}_{20} \cdot \omega_2; \dot{\varphi}_{30} \equiv \omega_{30} \equiv \omega_3 \end{cases} \quad (2)$$

For speeds, it is necessary to determine the mass or mechanical moments of inertia, which in order not to be confused with the moments of inertia, should be called inertial masses or masses of inertia, representing the inertial mass of each element and as the mass of each element generates linear amplification of the element's inertial force (linear) of the element (useful in the dynamic study) and the inertial mass of each element generates by the angular acceleration the moment of inertia of the respective element considered concentrated around the center of gravity of the element.

Inertial masses are determined on elements around an axis of the respective element at a certain point, being generally variable on the respective element depending on the point around which it is determined. Generally, we are interested in the inertial mass (mass moment of inertia) in the center of gravity of the element, determined around the axis of rotation (Oz).

The classical notation of inertial masses (of mass or mechanical inertia moments) is J, in order to differentiate such resistance moments of resistance, denoted by I, used in the material resistance calculations.

There is a relationship between them.

Unfortunately, many specialists today mark moments of mass inertia with I as well as resistance.

For mass concentrates, the mass (mechanical) inertia determined in relation to an axis in the center of gravity is calculated by summing the products between each concentrated mass and the square of the distance from it to the point where we want to determine the mass inertia moment in our case the center of gravity of the element.
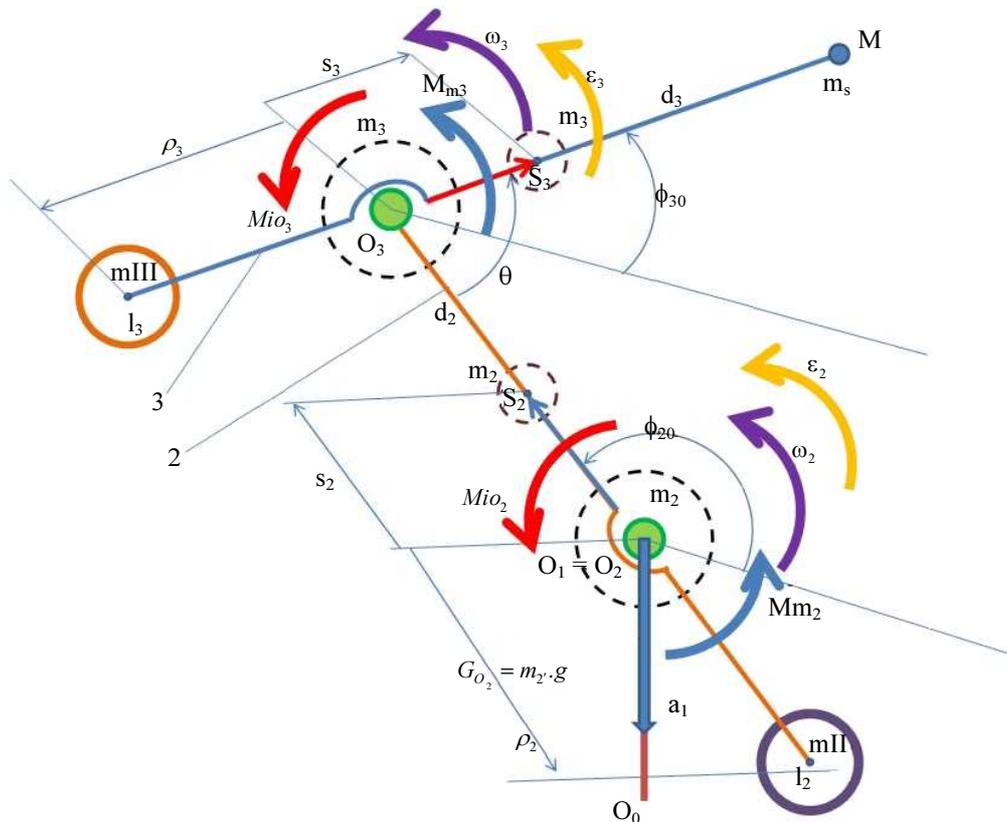

Fig. 4: Dynamics of balanced plan cinematic chain

For element 3, the momentum of mass or mechanical inertia (inertial mass) is determined by the relationship (3):

$$J_{O_3} = m_s \cdot d_3^2 + m_3 \cdot s_3^2 + m_{III} \cdot \rho_3^2 \qquad (3)$$

Thus, the mass of load m_s endured by endefactor M with the distance d_3 from the endeffector to the center of gravity of the O_3 element is multiplied by square and is summed up with the product of the mass of the element 3 and the square of the distance from the center of mass to the O_3 joint, also adds the additional mass m_{III} of the element 3 multiplied by the square of the distance from the point I_3 to the movable joint O_3.

For element 2, the mass (mechanical) inertia moment around the end center of gravity of element 2 (fixed joint O_3) is determined using the relationship (4):

$$J_{O_2} = m_2 \cdot s_2^2 + m_{II} \cdot \rho_2^2 \qquad (4)$$

Then determine the kinetic energy of the mechanism (the planar kinematic chain) with the help of relations (5):

$$\begin{cases} E = \dfrac{1}{2} \cdot J_{O_2} \cdot \omega_2^2 + \dfrac{1}{2} \cdot J_{O_3} \cdot \omega_3^2 + \dfrac{1}{2} \cdot m_{3'} \cdot \dot{x}_{O_3}^2 + \dfrac{1}{2} \cdot m_{3'} \cdot \dot{y}_{O_3}^2 \\[2mm] = \dfrac{1}{2} \cdot J_{O_2} \cdot \omega_2^2 + \dfrac{1}{2} \cdot J_{O_3} \cdot \omega_3^2 + \dfrac{1}{2} \cdot m_{3'} \cdot d_2^2 \cdot \omega_2^2 \\[2mm] = \dfrac{1}{2} \cdot J_{O_3} \cdot \omega_3^2 + \dfrac{1}{2} \cdot \omega_2^2 \cdot \left(J_{O_2} + m_{3'} \cdot d_2^2 \right) \\[2mm] = \dfrac{1}{2} \cdot J_{O_3} \cdot \omega_3^2 + \dfrac{1}{2} \cdot J_{O_2}^* \cdot \omega_2^2 \\[2mm] J_{O_2}^* = J_{O_2} + m_{3'} \cdot d_2^2 \end{cases} \qquad (5)$$

The equation of the kinetic energy of the balanced planar chain cinematic chain is simplified by the final relation (6):

$$E = \dfrac{1}{2} \cdot J_{O_3} \cdot \omega_3^2 + \dfrac{1}{2} \cdot J_{O_2}^* \cdot \omega_2^2 \qquad (6)$$

The second Lagrange differential equations are used (relations 7):

$$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \dot{q}_k} \right) - \dfrac{\partial E}{\partial q_k} = Q_k \quad cu \quad k = 2,\ 3 \\[3mm] \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \dot{q}_2} \right) - \dfrac{\partial E}{\partial q_2} = Q_2 \\[3mm] \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \dot{q}_3} \right) - \dfrac{\partial E}{\partial q_3} = Q_3 \end{cases} \qquad (7)$$

Results

As the kinetic energy in this case does not directly depend on the kinematic parameters of positions q_2 and q_3 represented by the position angles φ_{20} and φ_{30}, Lagrange simplified formulas (8) can be used:

$$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \dot{q}_k} \right) = Q_k \quad cu \quad k = 2,\ 3 \\[3mm] \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \dot{q}_2} \right) = Q_2 \Rightarrow \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \omega_2} \right) = M_{m_2} \\[3mm] \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \dot{q}_3} \right) = Q_3 \Rightarrow \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \omega_3} \right) = M_{m_3} \end{cases} \qquad (8)$$

By replacing the partial derivatives and deriving from time, the system (8) takes the form (9):

$$\begin{cases} \dfrac{\partial E}{\partial \omega_2} = J_{O_2}^* \cdot \omega_2 \Rightarrow \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \omega_2} \right) = J_{O_2}^* \cdot \varepsilon_2 \\[2mm] \Rightarrow J_{O_2}^* \cdot \varepsilon_2 = M_{m_2} \\[2mm] \dfrac{\partial E}{\partial \omega_3} = J_{O_3} \cdot \omega_3 \Rightarrow \dfrac{d}{dt}\left(\dfrac{\partial E}{\partial \omega_3} \right) = J_{O_3} \cdot \varepsilon_3 \\[2mm] \Rightarrow J_{O_3} \cdot \varepsilon_3 = M_{m_3} \\[2mm] J_{O_2}^* \cdot \varepsilon_2 = M_{m_2} \\[2mm] J_{O_3} \cdot \varepsilon_3 = M_{m_3} \\[2mm] J_{O_2}^* = m_2 \cdot s_2^2 + m_{II} \cdot \rho_2^2 + m_{3'} \cdot d_2^2 \\[2mm] J_{O_3} = m_s \cdot d_3^2 + m_3 \cdot s_3^2 + m_{III} \cdot \rho_3^2 \\[2mm] M_{m_2} = \left(m_2 \cdot s_2^2 + m_{II} \cdot \rho_2^2 + m_{3'} \cdot d_2^2 \right) \cdot \varepsilon_2 \\[2mm] M_{m_3} = \left(m_s \cdot d_3^2 + m_3 \cdot s_3^2 + m_{III} \cdot \rho_3^2 \right) \cdot \varepsilon_3 \end{cases} \qquad (9)$$

Discussion

The mechanism in Fig. 1 (planar cinematic chain) must be balanced to have a normal operation.

Through a total static balancing, balancing the gravitational forces and moments generated by the forces of gravity is achieved, balancing the forces of inertia and the moments (couples) generated by the presence of inertial forces (not to be confused with the inertial moments of the mechanism, which appear separately from the other forces, being part of the inertial torsion of a mechanism and depending on both the inertial masses of the mechanism and its angular accelerations.

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This results in a "forced" drive balancing from the transmission, which makes the operation of the assembly to be correct but rigid and with mechanical shocks.

Such balancing is not possible when the actuators directly actuate the elements of the kinematic chain without using mechanical reducers.

It is necessary in this situation for a real, permanent balancing.

In addition, in situations where hypoid reducers are used, it is also good to have a permanent, permanent static balancing that achieves a normal, quiet operation of the mechanism and the whole assembly.

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Author's Contributions

This section should state the contributions made by each author in the preparation, development and publication of this manuscript.

Ethics

Authors should address any ethical issues that may arise after the publication of this manuscript.

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