

Original Research Paper

Total Static Balancing and Kinetostatics of the 3R Base Cinematic Chain

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Abstract: 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. The forces that appear in the unbalanced base module were also presented in other papers, so we want to fill in only the aspects of the already balanced module forces in this study. 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 cannot 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.

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

Introduction

Anthropomorphic mechatronic systems are the most widely used robotics systems worldwide today in industry and in all automated environments. These systems are best suited to the modern automation and mechatronisation needs of the modern world, being mobile, dynamic, light, robust, complex, technologically simple, easy to design and manufactured, implemented, maintained and used in almost any industrial site, both in machine building and in special environments, such as chemical, toxic, dyeing, underwater, nuclear, in space.... Anthropomorphic robots are flexible, dynamic, stable, lightweight, fast, fast, inexpensive, easy-to-install, mechanical, mechanical, mechanical and mechanical systems with a pleasant appearance, modern industrial design and easy to design and implement in any workplace, imposed. The anthropomorphic robots are part of the classical series of mechatronic systems, being in the form of arms and having at least three space rotation, to which other components may eventually be added, thus lengthening the entire kinematic chain. You can also add all the planetary or spatial rotating arms or others that are translating. At the end we always have the end effector element that can be a manipulator, that is, a hand to grasp the objects, in which case one can speak of a prehensive device, that is a gripping device that today imitates very well a human hand even if it is one mechanical, may also be a painting, cutting or welding device, or one for machining. The base support and schematics of all anthropomorphic robots remain the 3R space system. 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. 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. The forces that appear in the unbalanced base module were also presented in other papers, so we want to fill in only the aspects of the already balanced module forces in this study (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).

Materials and Methods (Total Static Balancing of the Planar Kinematic Chain by the Classical Method (with Counterweight))

Figure 1 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 unisons (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.

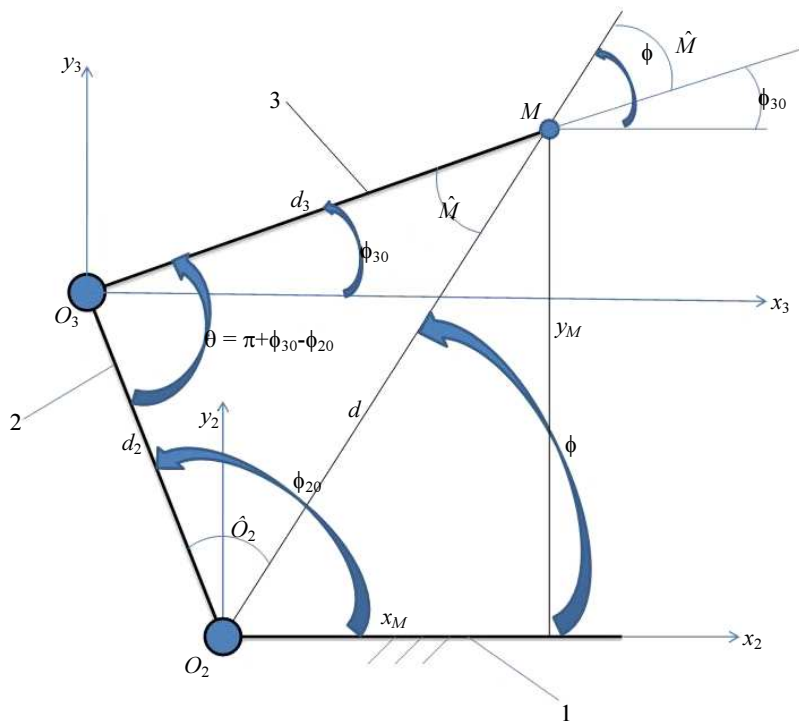


Fig. 1: The kinematic scheme of the plan chain

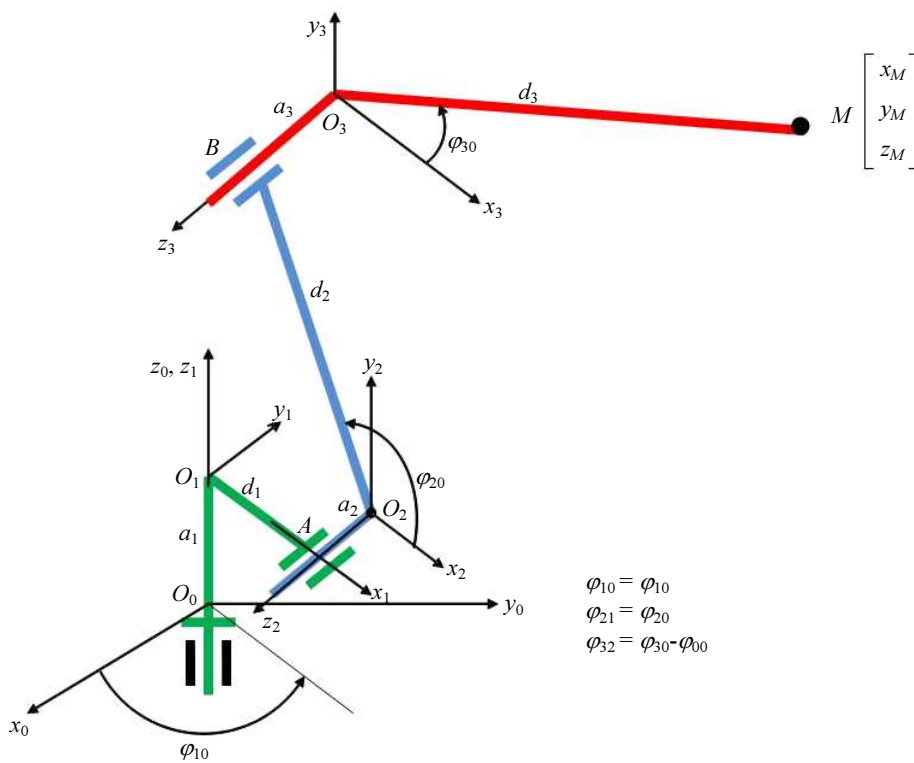


Fig. 2: The kinematic scheme of the spatial chain

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.

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.

Write the sum of the moments of the weight forces on element 3 relative to point O_3 (relation 1):

$$\sum M_{O_3}^{(3)} = 0 \Rightarrow m_s \cdot d_3 + m_3 \cdot s_3 = m_{III} \cdot \rho_3 \quad (1)$$

Thus, the weight of the endeffector load (with the mass carried by it) at the distance d_3 to O_3 , plus the mass

of the bulkhead 3 centered in the center or weight s_3 at the distance s_3 from the O_3 point, are balanced by the weight of the supplementary mass m_{III} is mounted at a distance ρ_3 from the O_3 joint on the other side (i.e., on the extension of element 3). The balancing is like a scraper, or a lever of degree 1.

In general, the m_{III} balancing mass is chosen and the mounting distance ρ_3 (relationship 2) is calculated by computing:

$$\rho_3 = \frac{m_s \cdot d_3 + m_3 \cdot s_3}{m_{III}} \quad (2)$$

After balancing, the mass of the element 3 concentrated in the O_3 joint acquires the value of m_3' given by the relationship (3):

$$m_3' = m_3 + m_s + m_{III} \quad (3)$$

The sum of the moments of the weight forces on elements 2 and 3 (considered as a common platform) with respect to O_2 (relationship 4) is written. The mass of element 3 is the final one obtained after balancing, m_3' and positioned (concentrated) at point O_3 :

$$\sum M_{O_2}^{(2+3)} = 0 \Rightarrow m_3' \cdot d_2 + m_2 \cdot s_2 = m_{II} \cdot \rho_2 \quad (4)$$

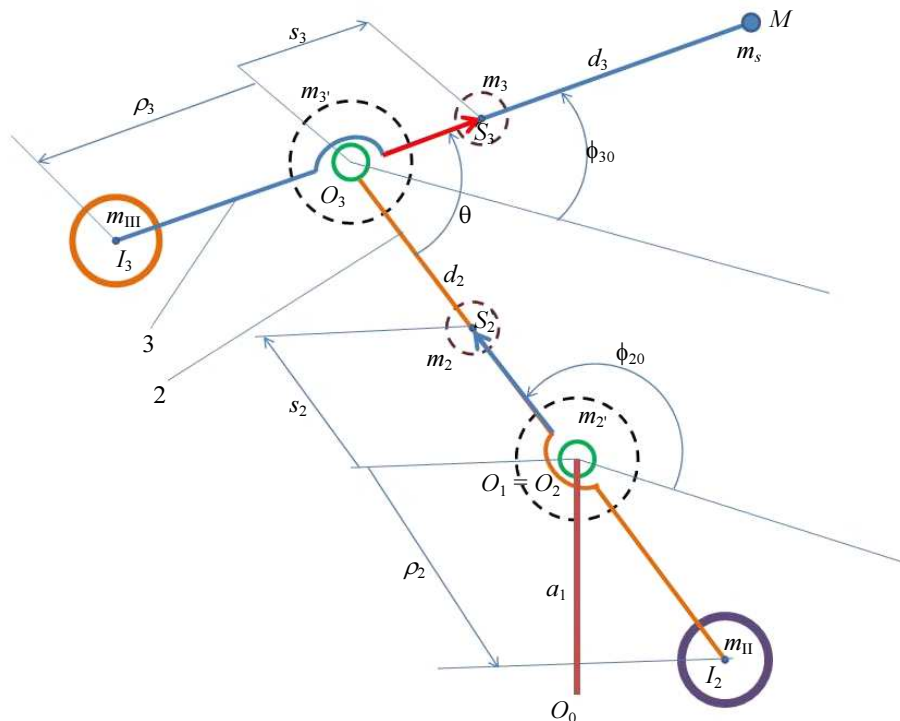


Fig. 3: Balancing the plan cinematic chain

Generally choose the m_{II} balancing mass and calculate the mounting distance, ρ_2 (relationship 5):

$$\rho_2 = \frac{m_3 \cdot d_2 + m_2 \cdot s_2}{m_{II}} \quad (5)$$

After balancing the mass of the entire planar kinematic chain (consisting of elements 2+3) is concentrated in the O_2 joint and gets the value m_2 given by the relationship (6):

$$m_2 = m_3 + m_2 + m_{II} \quad (6)$$

Theoretical justification of the method used:

The forces whose moments must be written against a joint (fixed or mobile) are all parallel to each other, oriented vertically downwards (or upwardly with negative values) and have the value (module) given by the product between that mass and the gravitational acceleration.

If in moments relation we simplify everywhere with g , then this sum of moments appears as a sum of masses amplified each with the arm of that force.

But also the arms of the forces are similar to the distances from the point where the mass is concentrated to the articulation against which the moments of the weight forces are written, so that all arms of the weight forces can be replaced with the respective distances.

Finally, the relation of the moments of the weight forces to the joint will be the sum of the mass products away. This is more convenient, but it can only be used after appropriate theoretical justification.

Results (Kinetostatic of Balanced Plan Cinematic Chain)

The kinetostatic of the balanced plan cinematic chain means the determining of forces from this chain.

Cinetostatic means the study of the distribution of the forces of a kinematic chain by analyzing them on the whole kinematic chain, or on modules (element or several elements interconnected) considered each separately.

The study of all the forces acting within the kinematic chain is instantly made in the form of a picture of the cinematic chain in a certain position (similar to the kinematic study, which deals only with the study of the positions, velocities and accelerations of the cinematic chain instantly photographed in a certain position considered).

The forces and moments that occur in the unbalanced mechanism are more and more dispersed, but in general the mechanisms used in practice are already balanced for the sake of good functioning, so that the cinematic study of a fully balanced cinematic chain is more justified.

Starting from the well-balanced kinematic chain shown in Fig. 3, the torsion of the forces existing on this cinematic chain is instantly photographed at any position, as shown in Fig. 4.

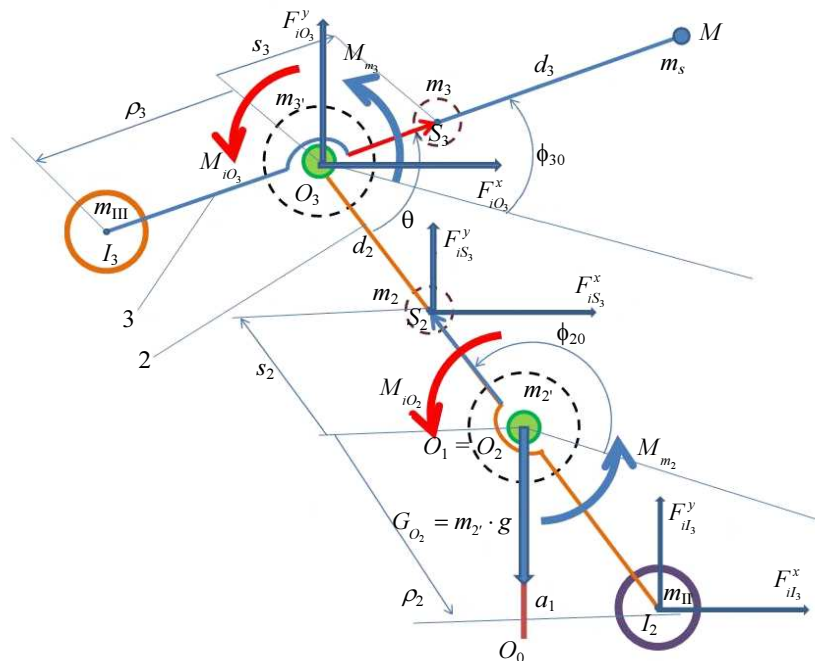


Fig. 4: The kinetostatic of the balanced plan cinematic chain

For the beginning, the cinetostatic element of the second element, which also carries the mass m_3 'of the element 3, so that the element 2 supports the effect of the whole balanced kinematic chain, considered welded (similar to a platform), the element 3 being replaced by the mass m_3 , inertia and weight forces of the mass m_3 .

Since the mechanism has already been balanced, weight forces no longer produce effects and they are removed from subsequent calculations to make drawing and relationships more difficult. It is considered to be only the final result of the weight of the entire balanced kinematic chain, G_{O_2} , which no longer produces any moment on this point, but only generates a vertical component of the O_2 coupling reaction.

Only the inertial forces will be considered in the following cinematic calculations, with the important statement that the total static balancing actually annihilates the effects of the inertial forces, so that the study aims to present these forces to their knowledge, observing (checking) towards the end of the calculations that and their effects have been canceled by the total balancing already done.

We recall, from the kinematic study, the accelerations of the O_3 point (the last two system relationships 7 positions, speeds and accelerations):

$$\begin{cases} x_{O_3} = d_2 \cdot \cos \varphi_{20}; & y_{O_3} = d_2 \cdot \sin \varphi_{20}; \\ \dot{x}_{O_3} = -d_2 \cdot \sin \varphi_{20} \cdot \omega_{20}; & \dot{y}_{O_3} = d_2 \cdot \cos \varphi_{20} \cdot \omega_{20}; \\ \ddot{x}_{O_3} = -d_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2; & \ddot{y}_{O_3} = -d_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 \end{cases} \quad (7)$$

With the help of the relations (7) the inertia forces from the inertia torch (8) of point O_3 are written:

$$\begin{cases} F_{iO_3}^x = -m_3 \cdot \ddot{x}_{O_3} = -m_3 \cdot (-)d_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2 \\ = m_3 \cdot d_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2 \\ F_{iO_3}^y = -m_3 \cdot \ddot{y}_{O_3} = -m_3 \cdot (-)d_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 \\ = m_3 \cdot d_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 \\ M_{iO_3} = -J_{O_3} \cdot \varepsilon_3 \end{cases} \quad (8)$$

From the inertia torque of the point O_3 given by the system relations (8), we are currently interested only in inertial forces at the point O_3 oriented on the axes x and y (basically the scalar components of the inertial force given by mass m_3 '), they producing the effect on element 2. We intend to write the sum of the forces acting on the 2-3 kinematic chain separated on the x and y -axes as well as the sum of the moments of the torques produced by the inertial forces on the chain from the O_2 point. In addition to O_3 , we also have the inertial forces given by mass m_2 from point s_2 (system relations 9) and the inertia

forces given by the equilibrium mass m_{II} in point I_2 (system relations 10):

$$\begin{cases} F_{is_2}^x = -m_2 \cdot \ddot{x}_{s_2} = m_2 \cdot s_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2 \\ F_{is_2}^y = -m_2 \cdot \ddot{y}_{s_2} = m_2 \cdot s_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 \end{cases} \quad (9)$$

$$\begin{cases} F_{iI_2}^x = -m_{II} \cdot \ddot{x}_{I_2} = -m_{II} \cdot \rho_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2 \\ F_{iI_2}^y = -m_{II} \cdot \ddot{y}_{I_2} = -m_{II} \cdot \rho_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 \end{cases} \quad (10)$$

We have prepared the inertial forces acting on element 2 and we can begin to study the equilibrium forces equations for element 2 (but also taking into account the effects of element 3). First we write the equilibrium of the forces on the horizontal axis, x (relations 11), from which the horizontal component of the O_2 coupling reaction will finally be determined:

$$\begin{cases} \sum F_{(2)}^x = 0 \Rightarrow m_3 \cdot d_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2 + m_2 \cdot s_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2 \\ -m_{II} \cdot \rho_2 \cdot \cos \varphi_{20} \cdot \omega_{20}^2 + R_{O_2}^x = 0 \\ \Rightarrow (m_3 \cdot d_2 + m_2 \cdot s_2 - m_{II} \cdot \rho_{II}) \cdot \cos \varphi_{20} \cdot \omega_{20}^2 + R_{12}^x = 0 \\ \text{but } m_3 \cdot d_2 + m_2 \cdot s_2 - m_{II} \cdot \rho_{II} = 0 \text{ dueto balanced} \\ \Rightarrow R_{O_2}^x \equiv R_{12}^x = 0 \end{cases} \quad (11)$$

Next, a force (equilibrium of forces) projected on the vertical axis, y , on element 2 (but also with respect to the loads on element 3) is made and determine the vertical component of the fixed coupling reaction (considered fixed) O_2 (relationships 12):

$$\begin{cases} \sum F_{(2)}^y = 0 \Rightarrow m_3 \cdot d_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 + m_2 \cdot s_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 \\ -m_{II} \cdot \rho_2 \cdot \sin \varphi_{20} \cdot \omega_{20}^2 - m_2 \cdot g + R_{12}^y = 0 \\ \Rightarrow (m_3 \cdot d_2 + m_2 \cdot s_2 - m_{II} \cdot \rho_{II}) \cdot \sin \varphi_{20} \cdot \omega_{20}^2 - m_2 \cdot g + R_{12}^y = 0 \\ \text{but } m_3 \cdot d_2 + m_2 \cdot s_2 - m_{II} \cdot \rho_{II} = 0 \text{ dueto balanced} \\ \Rightarrow R_{O_2}^y \equiv R_{12}^y = m_2 \cdot g = G_{O_2} \end{cases} \quad (12)$$

It can be seen that the loads in the couplings are minimal precisely due to balancing.

The effect of inertial forces (couples produced by these forces) is canceled (due to balancing). Couples by weight are also canceled due to balancing.

Balanced final weight also produces only one effect on the kinematic chain, a vertical load (causes a vertical reaction) in the fixed coupler.

At full balancing, even horizontal load from the fixed coupler disappears.

The only remaining load is constant and therefore it does not pose a high risk of wear, it does not create dynamic shocks, the mechanism has a normal (quiet) running behavior.

It will also write a sum of moments relative to the fixed joint on element 2 (but also considering the effects on element 3), (relations 13):

$$\left\{ \begin{array}{l} \sum M_{O_2}^{(2)} = 0 \Rightarrow M_{m_2} - F_{iO_3}^x \cdot d_2 \cdot \cos\left(\varphi_{20} - \frac{\pi}{2}\right) \\ -F_{iO_3}^y \cdot d_2 \cdot \sin\left(\varphi_{20} - \frac{\pi}{2}\right) - F_{iS_2}^x \cdot s_2 \cdot \sin\varphi_{20} - F_{iS_2}^y \cdot s_2 \cdot \cos\varphi_{20} \\ + F_{iI_2}^x \cdot \rho_2 \cdot \cos\left(\varphi_{20} - \frac{\pi}{2}\right) + F_{iI_2}^y \cdot \rho_2 \cdot \sin\left(\varphi_{20} - \frac{\pi}{2}\right) + M_{iO_2} = 0 \\ \Rightarrow M_{m_2} - m_3 \cdot d_2^2 \cdot \omega_{20}^2 \cos\varphi_{20} \sin\varphi_{20} + m_3 \cdot d_2^2 \cdot \omega_{20}^2 \sin\varphi_{20} \cos\varphi_{20} \\ - m_2 \cdot s_2^2 \cdot \omega_{20}^2 \cos\varphi_{20} \cdot \sin\varphi_{20} + m_2 \cdot s_2^2 \cdot \omega_{20}^2 \sin\varphi_{20} \cdot \cos\varphi_{20} \\ - m_{II} \cdot \rho_2^2 \cdot \omega_{20}^2 \cos\varphi_{20} \cdot \sin\varphi_{20} + m_{II} \cdot \rho_2^2 \cdot \omega_{20}^2 \sin\varphi_{20} \cdot \cos\varphi_{20} \\ - J_{O_2}^* \cdot \varepsilon_2 = 0 \Rightarrow M_{m_2} - J_{O_2}^* \cdot \varepsilon_2 = 0 \Rightarrow M_{m_2} = J_{O_2}^* \cdot \varepsilon_2 \end{array} \right. \quad (13)$$

$J_{O_2}^*$ (the momentum of mass or mechanical inertia of element 2, plus the influence of the mass of element 3), is calculated by the relation (14):

$$J_{O_2}^* = J_{O_2} + m_3 \cdot d_2^2 = m_2 \cdot s_2^2 + m_{II} \cdot \rho_2^2 + m_3 \cdot d_2^2 \quad (14)$$

It follows that from the momentary equilibrium to the fixed coupler on the element 2 and considering the influence of the element 3, it is possible to determine the necessary motor moment, which must be generated by the actuator 2, mounted in the coupling O_2 (relation 15).

$$M_{m_2} = J_{O_2}^* \cdot \varepsilon_2 = (m_2 \cdot s_2^2 + m_{II} \cdot \rho_2^2 + m_3 \cdot d_2^2) \cdot \ddot{\varphi}_{20} \quad (15)$$

Observation. The motor torque 3 only acts on the element 3 broken by the element 2 (i.e., it is an action of 3 relative to 2, or more precisely the element 3 is actuated by the element 2 by this motor moment 2). Nor was the moment of inertia considered for the same reasons. It acts only on element 3 considered separately (broken by 2). The influence of the mass m_3 'on element 2 is shown by the final mass m_2 , which also contains the mass m_3 .

This is followed by the separate cinetostatic study of element 3 broken by element 2. To make this study much easier, the following considerations will be taken into consideration: All the forces of weight and inertia acting on element 3 are already balanced so that they no longer influence the dynamics element. Neither the gravitational forces nor the inertial forces no longer couples at the O_3 reduction point, as these couples are all canceled due to element balancing. Making the sum of the moments of all forces on the element 3 relative to the mobile O_3 , (relation 16) we will observe that the motor moment M_{m_3} of the actuator 3 is only balanced with the M_{O_3} moment of inertia:

$$\begin{aligned} \sum M_{O_3}^{(3)} = 0 \Rightarrow \\ M_{m_3} + M_{iO_3} = 0 \Rightarrow M_{m_3} - J_{O_3} \cdot \varepsilon_3 = 0 \Rightarrow M_{m_3} = J_{O_3} \cdot \varepsilon_3 \quad (16) \\ \Rightarrow M_{m_3} = (m_s \cdot d_3^2 + m_3 \cdot s_3^2 + m_{III} \cdot \rho_3^2) \cdot \ddot{\varphi}_{30} \end{aligned}$$

The vertical component of the inner cup O_3 reaction is determined by realizing the equilibrium projections on the y -axis of all the forces acting on the element 3 (relation 17):

$$\left\{ \begin{array}{l} \sum F_{(3)}^y = 0 \Rightarrow -m_3 \cdot g + R_{23}^y = 0 \\ \Rightarrow R_{23}^y = m_3 \cdot g \\ \Rightarrow R_{32}^y = -R_{23}^y = -m_3 \cdot g \end{array} \right. \quad (17)$$

The horizontal component of the reaction from the mobile kinematic couple O_3 is null ($R_{23}^x = -R_{32}^x = 0$).

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

Conclusion

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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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