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ADAPTIVE BALANCING OF ROBOT MECHANISMS

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Abstract: *Static balancing of a mechanical system can be regarded as the total or partial cancellation of the mechanical effects (force or moment) of static loads to the actuating system of it, in all configurations, respectively in a finite number of configurations, from functioning domain, under quasi-static conditions. Adaptive balancing is taking into consideration the variation of static loads during the functioning of mechanical systems. As a consequence the adaptive balancing requires an adaptive controlling system and, in the case of active or semi-active balancing, supplementary energy is required too. Present paper is continuing the article [1], by surveying some aspects of the adaptive static balancing problem in the case of robots.*

Key words: *adaptive balancing, static, counterweight, spring*

1. Introduction

Static balancing of a mechanical system is an important aspect of the overall performance of it and one of the first demanding steps in the design process of any mechanical system, to match the needs like energy consumption and working accuracy for the production requirements.

Static balancing can be regarded as the total or partial cancellation of the mechanical effects (force or moment) of static loads to the actuating system of mechanical system, in all configurations, respectively in a finite number of configurations, from functioning domain, under quasi-static conditions. The effect of this action is the maintaining of the mechanical system in a rest state at any configuration or at a finite number of configurations respectively, from working field. The movement inside working field can be done with a power-less actuating system which consumes energy only for overcoming the friction forces and balancing errors. The friction forces are dependent on the motion sense and are opposed to the movement, contributing in this way to the maintaining of the mechanical system in a rest state. Although the balancing forces are exerted during the motion of mechanical system, the motion is slow, the term ñstatic balancingò being quite natural.

The main static load is given by gravitational field of Earth, i.e. the *weight forces* of all bodies that compose the mechanical system. In the case that weight forces are the only static loads then the static balanced mechanical system is called *gravity compensate*. The effect of these loads to the actuating system is present only in the case that the mechanical system is not working in horizontal plane with respect to gravity field. Consequently, the potential energy of mechanical system

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remains constant or approximately constant and the center of gravity of mechanical system is fixed with respect to a referential frame or is moving in a horizontal direction or in a horizontal plane with respect to Earth. Due to small displacements of the centers of gravity of mechanical system bodies, with respect to the radius of the Earth, then the weight forces are constant.

Theoretically, any other conservative force can be counted as static load and can be statically compensated, but the other possible static loads, which can affect the actuating system of a mechanical system which is working on the Earth, are:

- *buoyant forces* in case that the mechanical system is working immersed total or partial into a liquid;
- *electro-magnetic forces* that appear in mechanical systems made of ferromagnetic, ferrimagnetic or paramagnetic materials that are working into electro-magnetic fields.

Buoyant forces are also constant and act in opposite direction to the weight forces of corresponding immersed bodies, contributing to the compensation of the weight forces. Because buoyant forces depend on the volume of bodies which compose the mechanical system, a simple solution to compensate their effect is to design the shape of each body so that its volume responds to a weight of liquid equal with the weight of body. But there are mechanical systems which during one functioning cycle are working with some parts which in one phase are immersed and in other phase are working outside liquids (like grabs for dredging for example). In this case the buoyant forces are variable and adaptive balancing systems that adapt to these different functioning conditions should be found.

Electro-magnetic forces could have any direction according to the field lines of electro-magnetic field. These forces are not constant, but they depend on the position of ferromagnetic links with respect to the electro-magnetic field. So, the overcoming of these forces should be done by using forces of the same nature whose variation should be based on the configuration of mechanical system. Elastic forces of elastic bodies are the simplest forces that can be used for such a task (note that springs are usually made of ferromagnetic materials).

Adaptive balancing is taking into consideration the variation of static loads during the functioning of mechanical systems. This variation could be discrete, in case of manipulation of a load during one step from the cycle as is the case of industrial robots, or could be variable during one functioning cycle as is the case of oil pump systems [2] for example. As a consequence the adaptive balancing requires a control system and, in case of active balancing, supplementary energy is required too. So the problem of energy efficiency of the balancing operation becomes also very important. A new *efficaciousness coefficient*, as the one defined in [3], is defined as following:

$$\varepsilon = 1 - \frac{E_b + E_a}{E_u} \quad (1)$$

E_b – energy consumed by actuating system of the balanced robot;

E_a – supplementary energy consumed by an additional actuating system in order to obtain active balancing of robot;

E_u – energy consumed by actuating system of the unbalanced robot.

In the case of this definition the efficiency of the balancing operation is better when the value of ε is close to 1. If the value of ε is close to 0 then the balancing system is consuming almost the same energy than in the case of unbalancing and then the balancing system becomes un-useful and costly. If the value of ε is negative then the balancing system is consuming more energy than in the case of unbalancing, and the balancing system should be reconsidered.

2. Static Balancing of Robots

In order to compensate the static loads, which effect to actuation system depend to their positions, then forces which effect depend also to positions should be used.

The main candidates are the weight forces represented by counterweights and the elastic forces of springs or gases [4].

Many industrial robots manipulators [4, 5] are using both methods in order to obtain the optimum balancing.

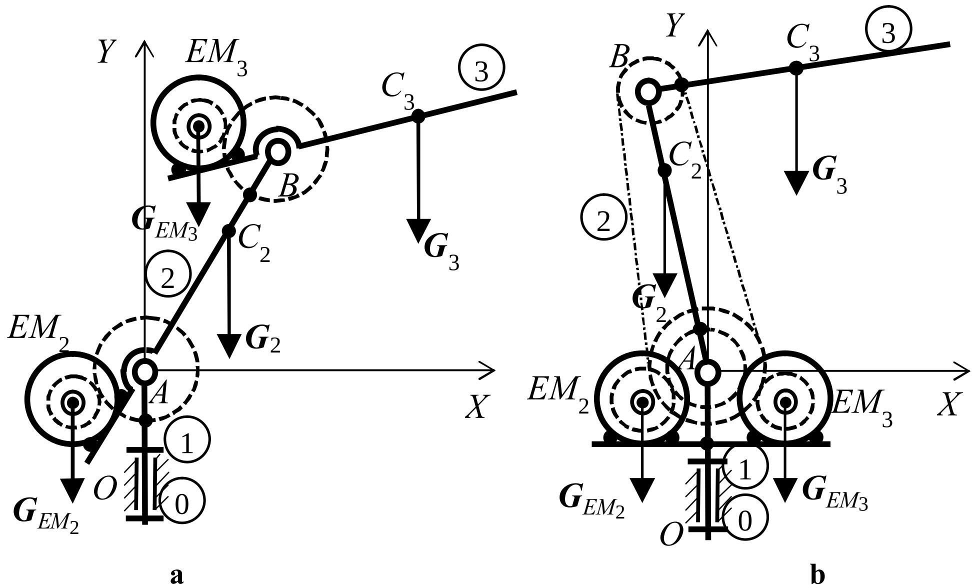


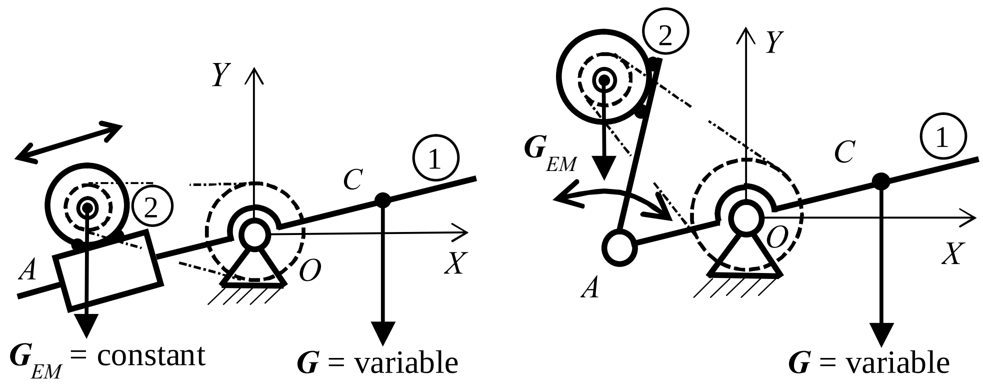
Fig. 1**.** *Internal mass redistribution in the case of robot manipulator by using electric motors as counterweights*

2.1. Static balancing by using counterweights

The method of adding the counterweights involves the increasing of moving masses, overall size, inertia and the stresses of the mechanism links [3]. Some of the mechanical systems [2] accept this method because of slow or rare movement of actuating mechanisms, from security reasons or in cases where the right spring is difficult and costly to be obtained, or the spring balancing solution is too complicated to be fitted to. Anyway, an internal mass redistribution [6] so that parts of mechanical systems (actuators, electric motors, other transmission mechanisms) to act as counterweights [4, 5], is first step when the static balancing problem starts (Fig. 1).

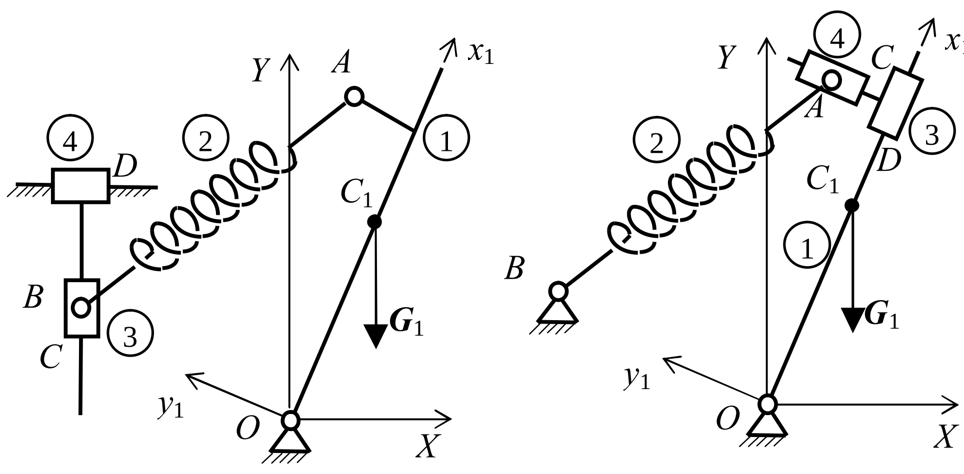
If the static loads are variable then the masses of counterweights should be variable or, as is solved in practice, the counterweights should be movable by using supplementary energy from the actuating system of mechanical system or from outside the mechanical system. There are 2 main solutions: translation of the counterweight along the swinging element [2] (Fig. 2.a) and rocking of counterweight around a medium balancing position (Fig. 2.b).

In case when electric motors which are actuating the robots are used like counterweights then mechanical transmissions should be designed in such a manner to be able to transfer the motion to the end-effectors (Fig. 2).



a **b**

Fig. 2**.** *Replacing the fixed position of the counterweight (electric motor) by a movable one*



a **b**

Fig. 3**.** *Replacing the articulation points of helical spring by movable ones*

Lacasse et. al. are proposing in [7] an interesting solution to adjust the position of the counterweight (Fig. 2.b) by using a simple hydraulic circuit instead of a complicate mechanical transmission. Bales is proposing in [8] a solution to balance the walking beam of a pump jack mechanism, which is using a fluid as counterweight in order to obtain continuous balancing, by adjusting the position of oscillating counterweight (Fig. 2.b). But in the case of the hydraulic solutions there are always problems with seals and leakages.

2.2. Static balancing by using springs

In case of applying the deformation energy of deformable bodies, in order to exchange it with the potential energy of mechanical system, bodies with high elasticity should be considered for large functioning field. Candidates are springs of different kinds (helical, spiral, torsion, bar etc.) and gases [4].

In the case of an industrial robot for example, which is manipulating payloads of different weights, the influence of the variation of static loads to the actuation system is very big. In paper [9] is shown an increasing of actuation forces of 4 times when the manipulated loads of a APR20 robot are from 0 to 16 kg, while the robot was static balanced by springs for a payload with mass of 8 kg. So the simplest solution of hanging the load or to sustain the load by the aid of a helical spring joined to a fixed point should be reconsidered either by changing the stiffness of elastic system or the joining points of it to become movable (Fig. 3).

In [10] authors proposed a solution to move the *B* end joint of spring balancing system (Fig. 3.a) along vertical *OY* axis. The same idea is proposed in [11] by using dual adjusters. Briot and Arakelian are proposing in [12] a passive balancing system which is moving one end of a spring in a very complicated solution, like the one proposed in Fig. 3.a.

In [13] authors proposed a couple of solutions in order to move both joints of spring balancing system by using a *simultaneous displacement concept* so that the length of spring to not change during the moving of springôs joints.

An interesting solution with cam and compression springs is presented in [14]. The required adjustment is made discretely by hand on vertical direction only. Another interesting solution is presented in [15] where a gas-spring is used and the moving of joint *B* (Fig. 3.a) is on an arch of circle by using a servomotor with ball-screw controlled by Arduino development board (with AVR microcontroller).

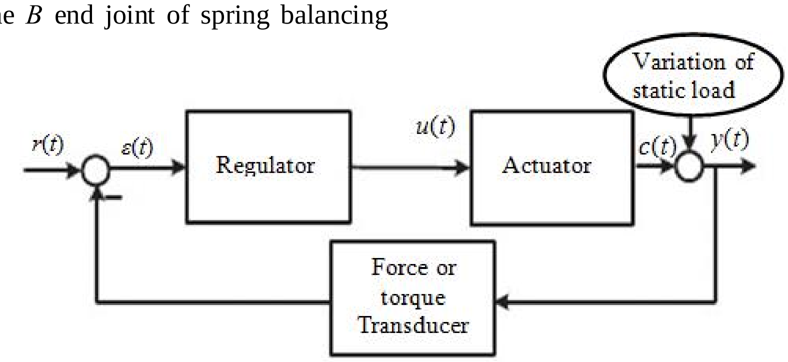


Fig. 4. *Controller scheme*

3. Control Systems of Adaptive Active Balancing

Adaptive active balancing under the static conditions requires the following components (Fig. 4):

- An actuator which is moving the counterweight (by translating or by rotating) or which is moving one of the coupling joints of the elastic system;
- A sensor which is sensing and measuring on-line the unbalance of the system;
- A controller [2, 11, 15] which is able to send in real-time the commands in terms of position with respect to information from the force (or torque) sensor.

4. Conclusions

In this paper a new *efficaciousness*

coefficient (1) was defined in order to appreciate the energy efficiency of the adaptive active static balancing. Two solutions were proposed: one for the case of counterweight balancing by using motors or other transmission parts of actuating system like counterweights (Fig. 2), and the other for spring balancing, by making movable one of the elastic system joints (Fig. 3).

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