Adaptive Balancing by Counterweights of Robots and Mechatronic Systems

Liviu Ciupitu and Luige Vladareanu

***Abstract*—Present paper is dealing with the adaptive static balancing of robot or other mechatronic arms that are moving in vertical plane and whose static loads are variable, by using counterweights. A simple passive and approximate solution is proposed and an example is shown. The active and exact solution by using adaptive real time control in the case of unknown variation of static loads is simulated on VIPRO platform developed at Institute of Solid Mechanics of Romanian Academy.**

***Index Terms*—Adaptive; static balancing; counterweight; robot; mechatronic system.**

I. Introduction

Static balancing of a mechanical system is one of the first demanding steps in the design process of any mechanical system which is moving with relatively small accelerations and which is overcoming relatively large forces, in order to match first of all the need of energy consumption, and it is also an important aspect of the overall performance of it [1].

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 [1], [2]. 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, and its actuators are not required to overcome the static loads. 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.

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 of static balancing operation then the mechanical system is called *gravity compensate*. Also 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 remains constant or approximately constant and the center of gravity of mechanical system remain fixed with respect to a referential frame or is moving along a horizontal direction or into a horizontal plane with respect to Earth. Another important observation and hypothesis is that due to the small displacements of the centers of gravity of mechanical system bodies, with respect to the distance from the center of the Earth to each body mass centers, then the weight forces are constant. In this case the actuators of mechatronic system are not required to sustain the weight of its moving elements.

But, in the case of a manipulation robot for example, as is also the case of cranes too, the manipulation weight could be variable in steps. As is presented in article [5] for the case of an industrial robot [9] which is designed to manipulate payloads of 16 kg maximum mass, balanced by springs for a middle weight mass of 8 kg, the forces induced in actuating system are amplified about 4 times when the weight is increasing or decreasing from the mean value. In fact, in terms of resistance moments (torques) at shafts of rotating actuators, as is shown in Fig. 1.a for the most frequent case of an articulated arm, this variation occurs (and has a cosine variation) even the payload has constant weight $\boldsymbol{G_p}$. In case the load has variable weight (as is the case of oil pump-jack systems for example [21]) then a more complex variation is possible (Fig.1.b – solid curve line 1). A special situation is the one when the variation is known and it is repeating during one cycle. In this case the adaptive solution could be a passive one (i.e. not actuated). Otherwise the balancing system should adapt in real time by using a local and supplementary actuation system and by aid of a controlling system and the required sensors and transducers [3].

Many other mechanical systems, which are automatized more and more in these days, becoming in this way mechatronic systems, have to overcome variable payloads or resistant forces during the functioning. Beside the manipulation robots used in palletizing for example [10]-[14], articulated cranes [15]-[17] pump-jack oil pumps [18], [19], and a large category of ergonomic manipulators [9] are facing the variable payload and have to adapt to this condition.

By balancing, another moment which is opposing the load moment (Fig.1.b – dotted curve line 2) should be induced in order to compensate or eliminate the effect of load. If the difference between the load moment and the balancing moment is zero then the system is perfect (exact) balanced in all positions from its work field [6]. If there are only some positions where the difference is zero (Fig.1.b–discontinuous curve line 3) then an approximate balancing is obtained [7].

In order to compensate the effects of static loads that depend to displacements then forces which depend also to displacements should be used. The main candidates are the weight forces represented by counterweights and the elastic

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forces of springs or gases. Industrial robots are using both of these solutions [11]. Even in the case of static balancing by using counterweights the overall mass of the mechanical system is increased and from dynamics point of view the situation could become worst than in the case the mechanical system is even unbalanced, this solution is still useful and widely used in engineering because of the simplicity and for mechanical systems which are manipulating large loads and which are operating at low or moderate dynamics.

II. Adaptive 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 [6]. Some of the mechanical systems [1] accept this method because of operating at low or moderate dynamics, from security reasons or in cases where the right spring is difficult and costly to be obtained [2], or the spring balancing solution is too complicated to be fitted to [4]. Anyway, an internal mass redistribution so that parts of mechanical systems (actuators, electric motors, other transmission mechanisms) to act as counterweights like in the case of industrial robots [4], [5], is first step when the static balancing problem starts [3].

Variation of gravitational moment given by the weight force of the rocking arm ① (Fig. 1.a) $\boldsymbol{G_1}$ and by the variable payload $\boldsymbol{G_p}$ has the expression:

$$\boldsymbol{M}_g(t) = -\boldsymbol{G}_1\, OC_1 \cos\varphi(t) - \boldsymbol{G}_p(t)\, OP \cos\varphi(t) = \boldsymbol{f}_1(t)\cos\varphi(t) \quad (1)$$

where:

$$\boldsymbol{f}_1(t) = c_1 + c_2\, \boldsymbol{G}_p(t) \quad (2)$$

with:

$$c_1 = -\boldsymbol{G}_1\, OC_1 = \text{const. and } c_2 = OP = \text{const.} \quad (3)$$

Then the balancing moment should be:

$$\boldsymbol{M}_b = \boldsymbol{M}_b(t) = \boldsymbol{f}_2(t) \quad (4)$$

so that:

$$\boldsymbol{f}_2(t) \cong -\boldsymbol{f}_1(t)\cos\varphi(t) \quad (5)$$

Let suppose the case the rocking arm ① is gravity compensated for its weight $\boldsymbol{G_1}$ and for the weight of constant part from the variation of payload $\boldsymbol{G_{pc}}$ (Fig. 2) by a counterweight mounted fixed on the rocking arm ① at a proper distance on the opposite side according to origin point O (not represented in the following). In this case:

$$c_1 = -\boldsymbol{G}_1\, OC_1 - \boldsymbol{G}_{pc}\, OP = \text{const.} \quad (6)$$

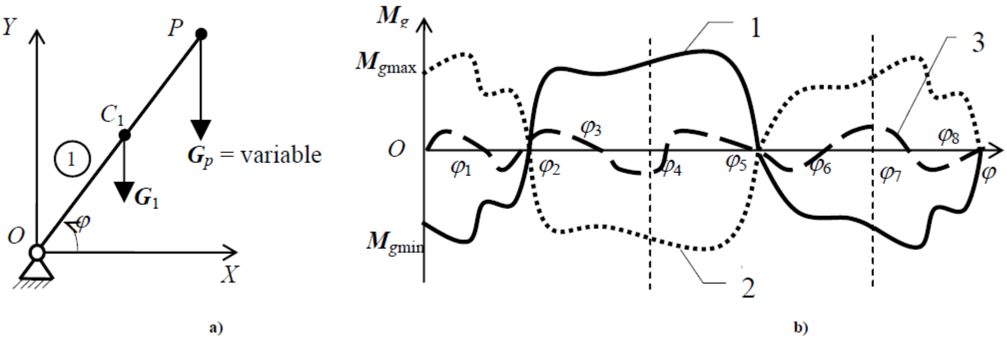


Fig. 1. Gravitational moment variation of the weight forces acted on an articulated arm.

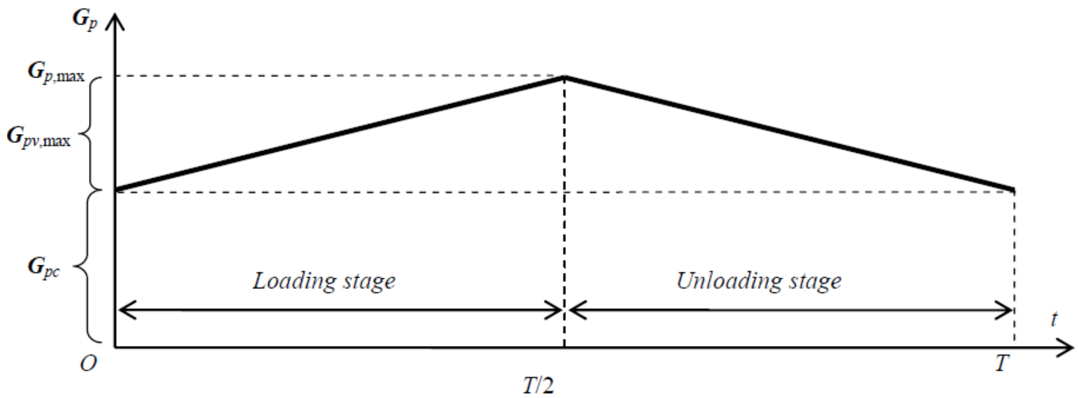


Fig. 2. Theoretic variation of a cyclic payload.

Without cutting the generality of the problem let suppose the variation of payload is known and cyclic with a linear variation (Fig. 2):

$$\boldsymbol{G}_p(t) = \boldsymbol{G}_{pc} + \begin{cases} \dfrac{2G_{pv,\max}}{T}t, & t \in \left[0, \dfrac{T}{2}\right] \\ 2G_{pv,\max}\left(1 - \dfrac{t}{T}\right), & t \in \left[\dfrac{T}{2}, T\right] \end{cases} \quad (7)$$

In order to gravity compensate the variable component $\boldsymbol{G_{pv}}$ by using also counterweight then 2 possibilities could be taken into consideration: a variable weight of the additional counterweight or a movable counterweight with a fixed weight.

To make a variable weight for the counterweight is not impossible but is complicated and in order to compensate a continuous variation then liquid weights are needed, which are complicating much more the system and the dynamics became also very important. From practical point of view the changing of the location of the additional counterweight on the balanced element (as is the studied rocking arm ① in Fig. 1.a) is a feasible solution.

There are also 2 possible ways of moving the additional counterweight relatively to the balanced element: by translating onto it (Fig. 3.a) or by rotating around a point which is becoming a joint on it by using an additional bar (Fig. 3.b).

Despite of the pretentious prismatic joint the solution with translating counterweight became very popular [21] due to the better dynamics of the multi-body system and due to the simplicity of the transmission of the supplementary actuator.

In case of a known cyclic variation of payload, as it is represented in Fig. 2, then a passive adaptive solution is possible to be used. The simplest solution is presented in [20] by linking the counterweight to the mechanism base through a simple bar connected by 2 joints as is shown in Fig. 4.

In Fig. 4.a is presented the symmetric solution which is leading to a reduced number of exact balancing positions (maximum three). In this case the gravitational moment which has to be compensated is:

$$\boldsymbol{M}_g(t) = -\boldsymbol{G}_{pv}(t)\, OP \cos\varphi(t) = c\, \boldsymbol{f}_3(t), \tag{8}$$

where:

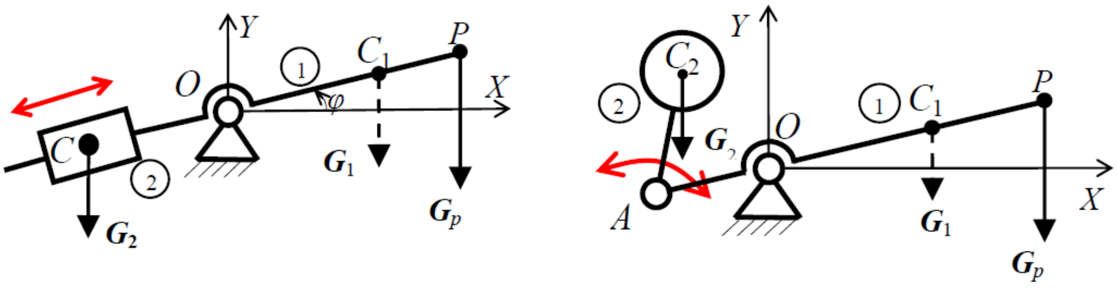
$$c = -\frac{2\, OP\, \boldsymbol{G}_{pv,\max}}{T} \tag{9}$$

and:

$$\boldsymbol{f}_3(t) = \begin{cases} t\cos\varphi(t),\, t \in \left[0, \dfrac{T}{2}\right] \\ (T-t)\cos\varphi(t),\, t \in \left[\dfrac{T}{2}, T\right] \end{cases}, \tag{10}$$

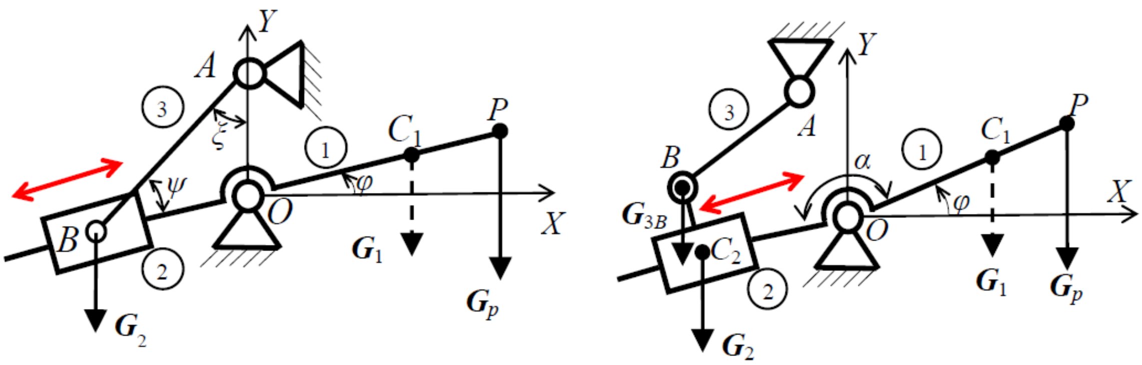
The balancing moment of counterweight ② has the expression:

$$\boldsymbol{M}_b(t) = \boldsymbol{G}_2\, OB(t) \cos\varphi(t), \tag{11}$$



a) b)

Fig. 3. Movable counterweight in order to compensate variable payload.



a) b)

Fig. 4. Translatable counterweight in passive solution.

where in the weight $\boldsymbol{G}_2$ could be count the part of the weight of the connecting bar ③ concentrated in point B (fig. 4).

The position of the counterweight on the balanced arm ① has the expression:

$$OB(t) = \sqrt{AB^2 - OA^2 \cos^2\varphi(t)} - OA \sin\varphi(t) \tag{12}$$

or:

$$OB^2 = OA^2 + AB^2 - 2\, OA\, AB \cos\xi \tag{13}$$

where:

$$\xi = \frac{\pi}{2} - \varphi - \psi \quad \text{and} \quad \sin\psi = \frac{OA}{AB}\cos\varphi \tag{14}$$

Another passive solution which is leading to a increased number of exact position where the arm ① is statically balanced is presented in Fig. 4.b.

In this case the mathematical model which has to be solved is represented by the following equation:

$$\boldsymbol{G}_{pv}(t) OP\cos\varphi_i + \boldsymbol{G}_2 OC_2 \cos(\varphi_i+\alpha) + \boldsymbol{G}_{3B} OB\cos(\varphi_i+\alpha-\beta) = 0 \tag{15}$$

where:

$$OB(t) = \sqrt{BC_2^2 + OC_2^2} \tag{16}$$

$$\sin\beta(t) = \frac{BC_2}{OB} \text{ and } \cos\beta(t) = \frac{OC_2}{OB} \tag{17}$$

Position of the counterweight ② on the balanced arm ① - distance OB - results by the kinematics analysis of the passive group with 2 elements of second variant i.e. the dyad RRT [8] (Rotation-Rotation-Translation).

The kinetostatics synthesis problem has the following design variables (fig. 4.b):

- co-ordinates of point A: X_A and Y_A ;
- length of the bar ③: AB ;
- distance BC_2 ;
- angle α ;
- mass of the counterweight ②: m_2 .

In this way the Equation (15) is wrote for 6 positions from the workfield (φ_i , $i = \overline{1, 6}$) making an un-linear system with 6 equations and 6 unknowns which could be solved by a numerical method (Newton-Raphson for example [8]).

III. Active Balancing by Counterweights

Active solution requires an additional actuating system to move the counterweight in order to adapt to the variation of payload. The main problem is the controlling system of the supplementary actuating system so that to respond to the variation of the payload. Also beside the actuating system and the controlling system of it, a supplementary sensorial system is also required.

As for the controlling system in the case of adaptive systems two main methods are used:

1) Model reference adaptive controller (MRAC)

2) Model identification adaptive controller (MIAC)

Before the design and the real manufacturing of the controlling system, a computer simulation is very useful. A more real and exact simulation is obtain into VIPRO software environment which is based on the virtual projection method [22]-[24] which is a versatile, intelligent, portable robot platform with control systems in adaptive networks (Fig. 5).

The VIrtual PROjection method is a method for simulation and testing control laws and mechatronic devices for demonstrating and validating research results. The results obtained by using the Virtual Projection Method helped us in proving the researched control methods.

As for the validating of the active solution in order to balance a variable load by adapting the position of a counterweight, 2 pairs of connected motors (Fig. 6) are used:

- one pair, MS1-AS1, to simulate the movement of balanced element (for example the arm ① from Fig. 4.a) which is loaded with a variable load;

- second one, MS2-AS2, to simulate the movement of the counterweight (for example the translatable counterweight ② from Fig. 4.a) used for balancing.

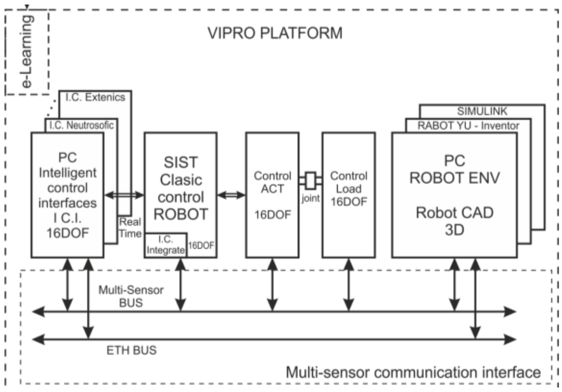


Fig. 5. Diagram of VIPRO platform.

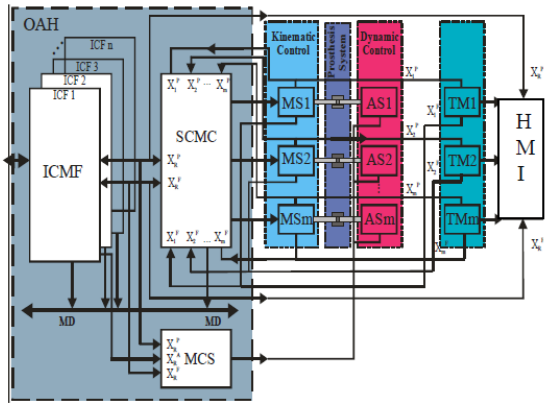


Fig. 6. Structure of VIPRO controlling system.

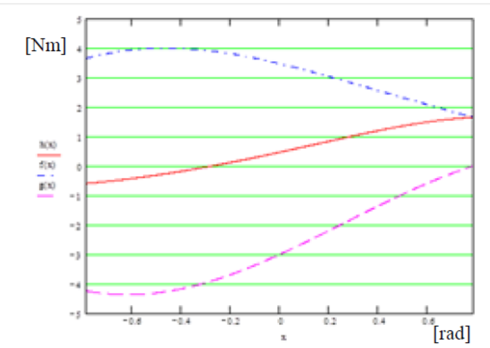


Fig. 7. Variation of weight moment of variable load - $g(x)$, of counterweight which is translating - $f(x)$, and the unbalancing moment - $h(x)$.

While the motors MS1 and MS2 are simulating the movement of actuators, the correspondent coupled motors AS1 and AS2, respectively, are used to simulate the mechanical resistance.

Mathematical model of mechanical system expressed by Eqs. (1) – (17) is used by controlling system to simulate the functioning and to produce controlling signals for all motors [25]-[27].

IV. Results and Conclusions

In the case of solution from Fig. 4.a, where the big and constant mass of the arm ① with the constant part $\boldsymbol{G}_{pc}$ of the variable payload is static balanced by a fixed counterweight which is not represented, let suppose that the variable part of payload has the maximum value $\boldsymbol{G}_{pv,\max}$ = 3 N and is acting at distance OP = 1 m while the workfield of balanced arm ① is symmetric with respect to the horizontal axis: $\varphi \in [-\pi/4, \pi/4]$. Suppose that the counterweight ② has the weight $\boldsymbol{G}_2 = 2$ N and the connecting road ③ has the length $AB = 2$ m and is articulated on vertical direction at distance $OA = 1$ m.

In this situation the maximum unbalancing moment has the value 1.646 Nm (represented by function $h(x)$ plotted in red color in graph from Fig. 7).

In the case of the simplest symmetric solution, presented in Fig. 4.a, a very good approximate adaptive balancing is obtained. The solution from Fig. 4.b will lead to better results due to increased number of exact static balancing positions, while the workfield of balanced arm ① could be non-symmetric with respect to horizontal axis.

By an adaptive control the unknown variation of the payload could be overcome but active solution is required i.e. the motion of the counterweight should be done by a controlled supplementary actuator and a specific mechanical transmission which in the case of industrial robots could complicate the manipulator mechanism.

A passive adaptive solution could solve at minimum cost and energy-free the static balancing problem.

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