GRAVITY COMPENSATION IN ROBOTICS – A REVIEW

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Abstract
Gravity compensation is a well-known technique in robot design to achieve equilibrium throughout the range of motion and as a result to reduce the loads on the actuators. Therefore, it is desirable and commonly implemented in many situations. Various design concepts for gravity compensation are available in the literature. This paper proposes an overview of gravity compensation methods applied in robotics. In order to classify the considered balancing schemes three principal groups are distinguished due to the nature of the compensation force: counterweight, spring or active force developed by an auxiliary actuator. The author believes that such an arrangement of gravity compensation methods allows one to carry out a systematized analysis and provides a comprehensive view on the problem. Particular attention has been given to the coupled Hand-operated Balanced Manipulator (HOBM) and Lightweight Robot (LWR). The aim of such a cooperation is to displace heavy payloads with less powerful robots.

Key words: *gravity compensation; balancing; actuator power; Hand-operated Balanced Manipulator (HOBM); effort minimization.*

INTRODUCTION

Many robotic systems are operated at low speed to ensure the different tasks. In this situation gravitational torques generated by the masses of links are often much greater than dynamic torques. Thus, gravity compensation is beneficial by which a robotic system can be operated with relatively small actuators generating less torque. The potential energy of such a robotic system is constant (or quasi-constant) for all possible configurations, which leads to the self-balancing of the mechanical system. Nature of the forces that must compensate gravity and its emplacement in the robotic systems may be diverse. In the present paper, the typical gravity compensation solutions are systematized and their effectiveness is considered.

It should be noted that the gravity compensation can also be achieved by optimal control of input torques. In this case the control law combines terms that cancel the gravity effects on the robot link dynamics with a PD-type error feedback on the motor variables *(Gosselin, 2008)*. However, in this survey, the mechanical solutions of the gravity compensation will only be reviewed.

The given systematization can be presented as follows *(Arakelian, 2016)*:

1. Gravity compensation by counterweights.
1.1. Gravity compensation by counterweighs mounted on the links of the initial system.
1.2. Gravity compensation by counterweights mounted on the auxiliary linkage connected with the initial system.
2. Gravity compensation by springs.
2.1. Balancing by springs jointed directly with manipulator links.
2.2. Balancing by using the cable and pulley arrangement.
2.3. Balancing by using auxiliary systems.
2.3.1. Balancing by using an auxiliary linkage.
2.3.2. Balancing by using a cam mechanism.
2.3.3. Balancing by using a gear train.
3. Gravity compensation by using auxiliary actuators.

1. GRAVITY COMPENSATION BY COUNTERWEIGHS

The use of counterweights has been applied to the design of mechanical systems for a long time. The classical approach consists in adding counterweights in order to keep the total centre of mass of moving links stationary. With regard to the several approaches employed for the redistribution of movable masses, the developed design concepts could be divided into two principal sub-groups.

1.1. GRAVITY COMPENSATION BY COUNTERWEIGHS MOUNTED ON THE LINKS OF THE INITIAL SYSTEM

It is obvious that the adding of the supplementary mass as a counterweight is not desirable that it leads to the increase of the total mass, overall size of the robot-manipulator and the efforts in joints. That is why in many constructions of industrial robots, for example KUKA R360 or PUMA 200, the masses of the motors are often used for gravity compensation. The review slowed that the gravity compensation by counterweights mounted on the links is more appropriate for serial and planar parallel manipulators. It is much more difficult for spatial parallel manipulators. Gravity compensation has been successfully applied on hand-operated balanced manipulators (HOBM). The balanced manipulator is a handling system with a simple mechanical system in which the manipulated object in any position of the workspace is balanced. Such a state of constant gravity cancellation allows displacements of heavy objects manually. The term "balanced manipulator" shows that in the operating procedure of these systems is very important to achieve an accurate compensation of gravity. Many studies and design concepts have devoted to the gravity compensation of these manipulators by counterweights. It was shown that for the balancing of these manipulators it is necessary to apply to the pantograph mechanism a sinusoidal balancing moment. The general approach for determination of balancing conditions was proposed by the study of the motion of the center of mass of the pantograph actuator. In many HOBM the balancing by counterweights is combined with actuators, which carried out an active balancing.

1.2. GRAVITY COMPENSATION BY COUNTERWEIGHTS MOUNTED ON THE AUXILIARY LINKAGE CONNECTED WITH THE INITIAL SYSTEM

At first, let us define an auxiliary linkage. We will use this term for any mechanical system that mounted between the balancing element and the initial structure of a robot. The goal of these linkages is to improve the compensation and design conditions via optimum location of balancing elements. There are also some solutions in which it is proposed to cancel the weight of the payload via a moving counterweight. The counterweight balancing of the mine detection vehicle with a pantograph manipulator has been developed. It has been shown that the robot arm with properly dimensioned balancing counterweights can efficiently actuated with very low power and energy consumption.

Many schemes illustrate the parallel manipulators comprising auxiliary systems equipped with counterweights. However, the industrial applications of such approaches are often quite complicated because of limitation of the overall size of manipulators and the possibility of collision of extended moving links carrying counterweights.

2. GRAVITY COMPENSATION BY SPRINGS

Firstly, let us disclose the properties of two types of springs that are used for gravity compensation in robotic systems: zero-free length and non zero-free length springs. The author believes that it is important to provide a comprehensible and short background on these two types of springs. It will be particularly useful for young scientists and engineers. Zero-free length spring is a term for a specially designed coil spring that would exert zero force if it had zero length. Obviously, a coil spring cannot contract to zero length because at some point the coils will touch each other and the spring will not be able to shorten any more. Zero length springs are made by manufacturing a coil spring with built-in tension, so if it could contract further, the equilibrium point of the spring, the point at which its restoring force is zero, occurs at a length of zero. In practice, zero length springs are made by combining a "negative length" spring, made with even more tension so its equilibrium point would be at a "negative" length, with a piece of inelastic material of the proper length so the zero force point would occur at zero length. It is important to emphasize that the use of a zero free length spring for complete gravity compensation is basically used when the spring is connected directly with the robot links and such a necessity mainly disappears when the spring is connected with the robot links via a cable or an auxiliary mechanism. To preserve the structure of the systematization adopted above, i.e. the first step of classification by the nature of compensation forces and the second step by the structural features, let us gather the spring compensators in following three sub-groups.

2.1. BALANCING BY SPRINGS JOINTED DIRECTLY WITH MANIPULATOR LINKS

In order to create springs with adjustable stiffness the “Jack spring” concept based upon the principle of adding and subtracting coils from a spring has been developed. Thus, with this method, by changing the number of coils in a spring, the actual or intrinsic stiffness of the spring is structurally changed. The gravity balancing of the leg was also solved. The gravity balancing mechanism, proposed in these studies, consists of two springs with the same stiffness coefficients: one compression and another extension connected with the shank of the leg and permitting the complete gravity compensation of the leg’s weight. In order to improve the gravity compensation quality the spring mass has been included in the balancing condition. It was shown that the mass of the balancing spring increases the unbalanced moment and it cannot be neglected. The numerical simulations showed that the error caused by neglect of the spring mass can be reached until 8%. Various design concepts have been also developed for adjustment of gravity equilibrators.

2.2. BALANCING BY USING THE CABLE AND PULLEY ARRANGEMENT

The adding of the cable and pulley allows full compensation of gravity by using non-zero free length spring. The gravity compensation with non-circular pulleys and springs has also been examined. After preliminary verification of the design methodology for a single pendulum system, the weight compensation mechanism has been extended to the two degrees of freedom parallel five-bar linkage arm. It has been shown that the introduction of the weight compensation mechanism reduces the maximum static torque up to 50-80%. The spiral pulley with spring are already succefully used.
It should be mentioned that the several error sources in the practical implementations decrease the efficiency of the gravity compensation with springs and pulleys. Errors are mainly caused by the non-linearity of the springs due to the manufacturing tolerance. Often the nominal values of the calculated springs are different to the real values. Therefore, the values of springs´ stiffness must be adjusted. Another error source is the radius of the pulleys.

2.3. BALANCING BY USING AUXILIARY MECHANICAL SYSTEMS

The auxiliary mechanisms have the same effect that the cables and the pulleys. In most cases, they allow the gravity compensation by using non-zero free length springs. The advantage of the adding of an auxiliary mechanism consist also in increase of free parameters of the system which allows one optimize the gravity compensation by applying the linkage synthesis methods. The known solutions can be arranged into three sub-groups: i) Balancing by using an auxiliary linkage that can be un four-bar, slider-crank or coulisse mechanism, the pantograph is also has been applied as an supplementary system. ii) Balancing by using a cam mechanism. In this case, by using the conservation of energy and balance conditions, the optimal profiles of cams can be found in order to compensate the gravity of links or a payload. iii) Balancing by using gear trains.

1. GRAVITY COMPENSATION BY USING AUXILIARY ACTUATORS

In this case, a pneumatic or hydraulic cylinder is connected with manipulator links or directly with the moving platform. There are also some approaches based on counterweights, which are fluid reservoirs connected with an auxiliary actuator. Continuous gravity compensation is achieved by the pumping of the fluid from the first reservoir-counterweight to the second. Electromagnetic effects were also used.
The gravity compensation of spatial parallel architectures is a complicated problem because it can be achieved either by unavoidable increase of the total mass of moving links or by a considerably complicated design of the initial parallel mechanism. It seems that an optimal approach is to combine an auxiliary linkage with pneumatic or hydraulic cylinders. An illustrative example of such a system developed at the INSA of Rennes *(Baradat et al., 2008)*, is shown in Fig. 1. The suggested approach involves connecting an auxiliary mechanism to the initial structure, which generates a vertical force applied to the manipulator platform. The minimization of the input torques was carried out by constant and variable

forces for static and dynamic modes of operation. It was shown that a significant reduction in input torques can be achieved by the suggested balancing mechanism: the reduction of the root-mean-square value of the input torque due to the gravitational forces is 99.5% and the maximum value is 92%.

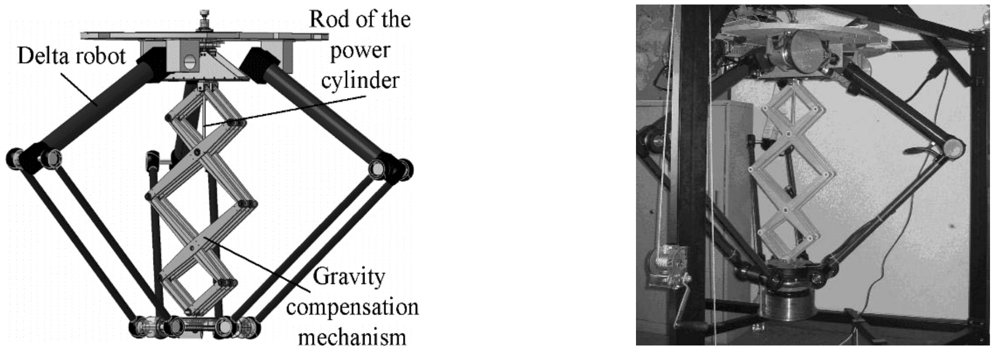

Fig. 1. CAD model and prototype of the balancing mechanism implemented in the structure of the Delta robot.

The positioning errors of the unbalanced and balanced parallel manipulators have been provided. It was shown that the elastic deformations of the manipulator structure due to the payload, change the altitude and the inclination of the platform. A significant reduction in these errors has been achieved by using the balancing mechanism (from 86.8% to 97.5%). The theoretical results obtained by numerical simulations were confirmed by experimental study carried out by means of the developed prototype.

It should be noted that the gravity compensation for the manipulators in which the vertical motion is decoupled from other Cartesian degrees of freedom has also been studied. In the latter situation, only one degree of freedom needs to be gravity compensated in order to eliminate actuator torque due to the weight of the moving parts and the payload. The specificity of this technique it is easy to see on the example of the PAMINSA manipulator developed at the INSA of Rennes. An energetic analysis shows that the gravity work of a body moving in the horizontal plane is equal to zero (the gravitational forces are always perpendicular to the displacements). But the work of the same force moving along the vertical axis is other than zero (the gravitational forces are parallel to the displacements). This phenomenon is used in the design of the hand operated manipulators, in which the horizontal displacements of the payload are carried out manually and the vertical displacements are actuated. This principle is also applied in the design of the parallel manipulators called PAMINSA (Parallel Manipulator of the INSA) *(Briot et al., 2009)*.

Let us consider the mechanical architecture of this manipulators. The aim was to develop a parallel architecture in which displacements of the platform in the horizontal plane are independent of its vertical displacements. For this purpose, the pantograph linkage is used as a leg. The pantograph is a mechanical system with two input points A_i and B_i and one output point C_i (Fig. 2a). These input points linearly control the displacement of the output point C_i. Thus, one linear actuator connected with input point B_i can control the vertical displacement of the output point C_i and one other linear actuator with horizontal axis is able to control its horizontal displacements. Please note that these motions are completely decoupled, i.e. they can be carried out independently.

Now let us connect three Scheiner pantograph linkages with the base and the platform as shown in Fig. 2b. In the obtained structure, one vertical actuator M_v controls the vertical displacement of point B_i of the pantograph linkages, resulting in the vertical displacement of joints C_i of the moving platform. The generation of motion in the horizontal plane is achieved by the actuators M_1, M_2 and M_3 moving the input joints A_i.

Among the obvious advantages of the suggested manipulator architecture, we would like to note the following:

(i) the decoupling of the control powers into two parts, making it possible to raise an important payload to a fixed altitude with powerful actuators and then to displace it on the horizontal plane with less powerful actuators;

(ii) a great accuracy in the horizontal positioning because the payload can be locked in the horizontal plane using mechanical architecture of the manipulator (in other words, if the position of the vertical actuator is fixed, the altitude of the platform cannot change);
(iii) the cancellation of the loads of gravity on the rotating actuators which displace the platform in the horizontal plane;
(iv) the simplification of the vertical control which is based on linear input/output relationships.

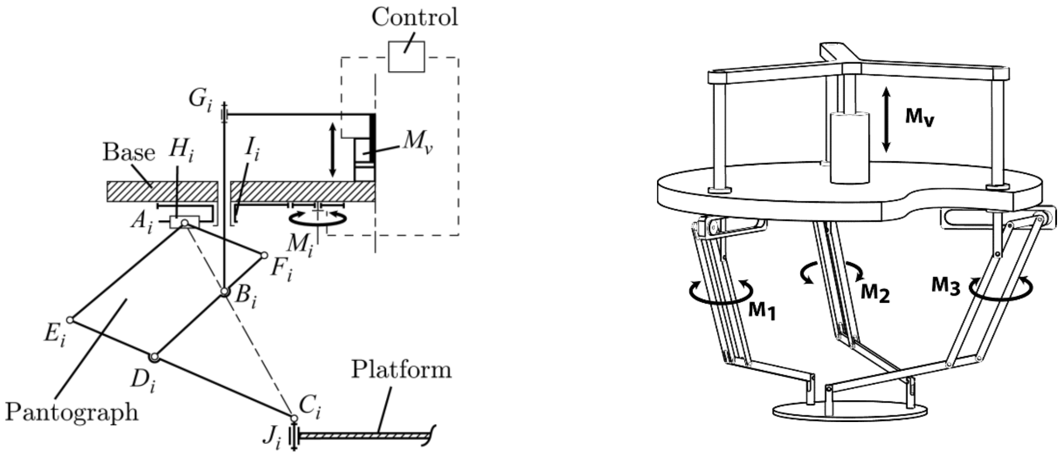

Fig. 2. PAMINSA: a) kinematic chain of each leg; b) 3D view.

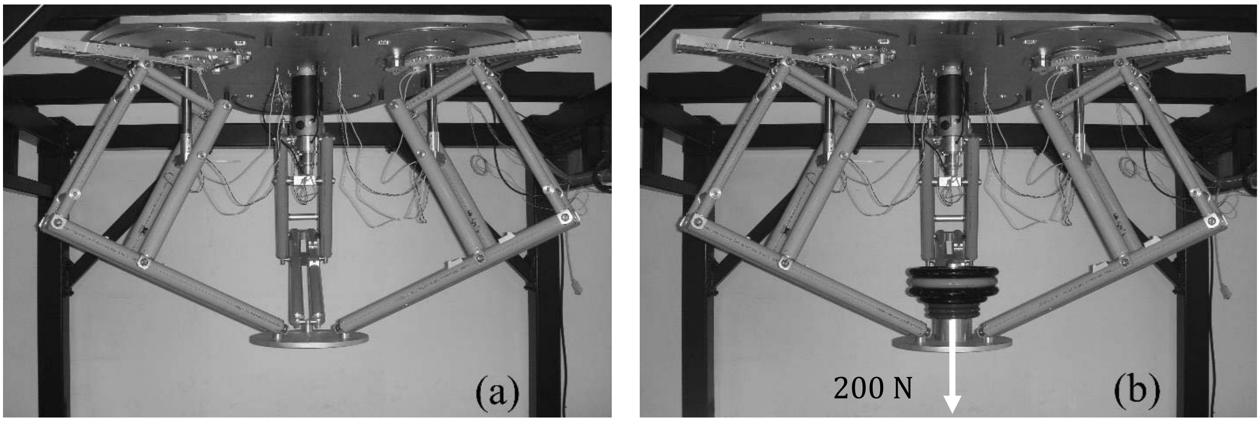

Fig. 3. The prototype of PAMINSA developed at the I.N.S.A. of Rennes.

The design concept has been validated via experimental tests carried out on the prototype (Fig. 3). The curves with and without payload (200N) for the 3 rotating actuators have been superposed. It has been shown that they are similar. Regarding the vertical actuator, it supports the payload and the increase of the input force is significant.
Workers in industries such as manufacturing and assembly, frequently manipulate heavy objects. However, manual processing is often repetitive and becomes tedious, it reduces efficiency and leads to back pains, injuries and musculoskeletal disorders. It is obvious that traditional robot installations can offer several benefits compared to manual operation: improved repeatability, increased precision and speed. However, industrial robots still have many weaknesses compared to humans. For example, currently industrial robots have a limited ability to perceive their surroundings, which requires costly safety arrangements in order to avoid serious injury. These safety arrangements are particularly important and costly when working with installations of large and powerful industrial robots. It is obvious that serial robots have a poor payload-to-weight ratio. For a six-degrees-of-freedom general-type serial robot, it is less than 0.15. For example, a robotic arm handling an object of $50kg$ must have a weight of at least $350\ kg$. The purchase, installation and operation of such a robot are quite expensive. In addition, the

heaviness of the robot and of the payload complicates the dynamics of the system, making it difficult to move accurately and quickly. This becomes especially noticeable during assembly processes, when heavy parts must be installed on a surface with guiding pins. In such a case, the robotic arm has to move smoothly and any sudden movement may damage the mechanical surface of the part.

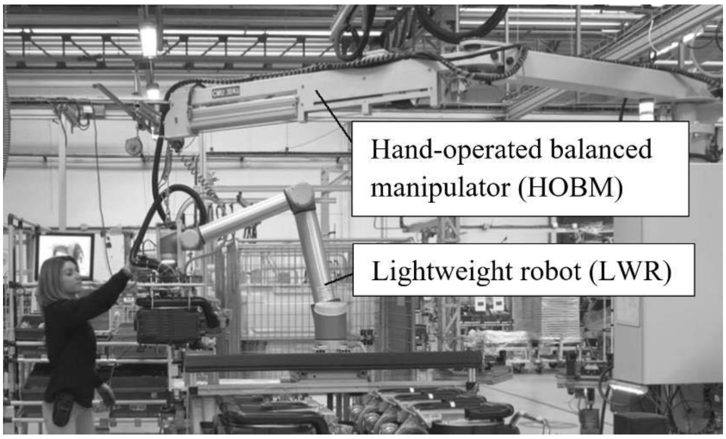

Fig. 4. Coupled «Balancer-lightweight robot» system.

Such a task is not easy to achieve. Thus, autonomous manipulation does not always provide expected reliability and flexibility. Balancer – robot systems such as power assist robotic systems may be perfectly used for heavy object manipulation. The combination of motion programming of a lightweight robot and simplicity of a hand-operated balanced manipulator (HOBM) may make the system far better than the application of an individual robot arm. Detailed descriptions of gravity compensation methods can be found in the monography *(Arakelian & Briot, 2015)*.

CONCLUSIONS

Despite its ancient history, gravity compensation methods continue to develop and new approaches and solutions are constantly being reported. It seems promising the development of new gravity compensation solutions for the exoskeletons, rehabilitation devices and walking assist devices. The use of active and passive actuations allows a significant reduction of the size and weight of walking assist devices with bodyweight support. However, the several error sources in the practical implementations decrease the efficiency of the gravity compensation in robotics systems. Errors are mainly caused by the non-linearity of the springs due to the manufacturing tolerance. Often the nominal values of the calculated springs are different to the real values. Other error sources are the manufacturing tolerances of equilibrator's links, their stiffness and clearance in joints. In the case of auxiliary linkages, the balancing is carried out for discrete positions due to the non-linearity of transmission characteristics, which leads to an approximate balancing.

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