# Optimal static balancing of a spatial palletizing robot

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**Abstract**

Static balancing of a mechanism is achieved if its total potential energy is made invariant for any admissible pose. In such an instance, actuators are not required to sustain the weight of the mechanism moving parts. The compensation of gravity loads is an important strategy for reducing the motor loads in serial manipulators and it has been widely studied [1]. Indeed the majority of the industrial robotic arms features some kind of balancing devices, the most common being counterweights, springs or hydro/pneumatic cylinders.

This work deals with the static balancing of a commercial 4-DOF spatial manipulator (Fig. 1). It is primarily conceived for palletizing tasks, the maximum payload being about 150 kg. *Actuator 1* provides rotational motion around a fixed vertical axis to the end effector, namely a palletizing gripper. A planar 2-DOF closed kinematic chain, driven by two actuated prismatic joints (*Actuator 2* and *Actuator 3*), permits the translation of the end effector on a vertical plane. *Actuator 4* controls the gripper orientation around a mobile vertical axis.

The studied manipulator presents some issues concerning the overload of the motors (in particular *Actuators 2* and *3*) during the execution of some specific tasks. Since the current system is not statically balanced and since its typical working conditions are characterized by low/moderate dynamics, gravity compensation appears a viable strategy for enhancing the robot operation. This research aims at developing a gravity compensated variant of the robot as well as at optimizing the balancing solution in order to minimize potential drawbacks.

Due to the presence of the closed kinematic chain featuring translational actuators, gravity compensation methods specifically conceived for parallel linkages are required (such as [2]), whereas the approaches commonly adopted for industrial robotic arms are not directly applicable. Gravity compensation is analytically achieved by making constant the total potential energy of the mechanical system. Motions generated by *Actuators 1* and *4* do not vary the mechanism gravity potential energy. Therefore the static balancing problem can be reduced to the gravity compensation of a planar 2-DOF closed-loop linkage. Invariant total potential energy is obtained by introducing counterweights and/or springs (both tension and/or compression ones), which add terms to the expressions of the mechanism gravity and elastic potential energy respectively. Various feasible solutions featuring different combinations of balancing devices are designed and investigated (e.g. the robot variant presented in Fig. 1, which includes one counterweight and one tension spring). The parameters characterizing the balancing devices of each proposed solution are determined by imposing equal to zero all the partial derivatives of the total potential energy.

The optimization of the proposed balancing solutions is performed by assessing the effects of compensation for the nominal working conditions of the manipulator. The dynamic motor loads required for moving the end effector and the payload along trajectories between two generic points of the workspace, with velocity and acceleration laws commonly imposed for the robot operation, are evaluated through simulations. The inverse dynamic analysis is carried out by using a numerical model based on the Lagrange equations of motion. The most critical trajectories, i.e. those characterized by the highest rms and/or peak absolute values of the motor actions, are taken into account for the optimization process. Indeed, even if the effects of the weight of the mechanism members (which are preponderant for the unbalanced robot) are cancelled by balancing, the dynamic actuator loads are still affected by the payload and by the inertial actions related to the robot operation. The expressions of the dynamic motor actions (which include the balancing parameters to be optimized) are adopted as objective functions of the optimization algorithm. A multi-objective constrained optimization problem is therefore defined [3]. Each balancing solution is optimized independently of each other. In fact, while gravity compensation by using only springs is expected to

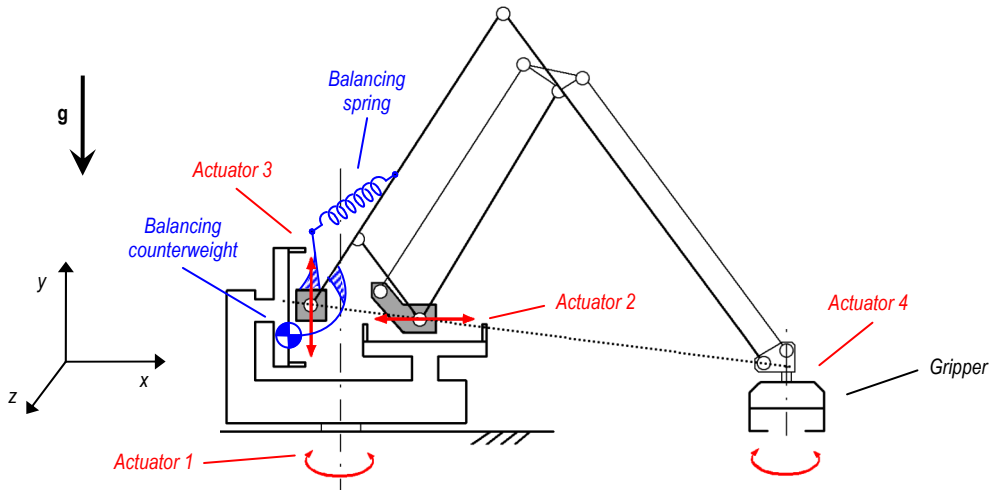


Figure 1: kinematic scheme of the palletizing robot and of a feasible static balancing solution.

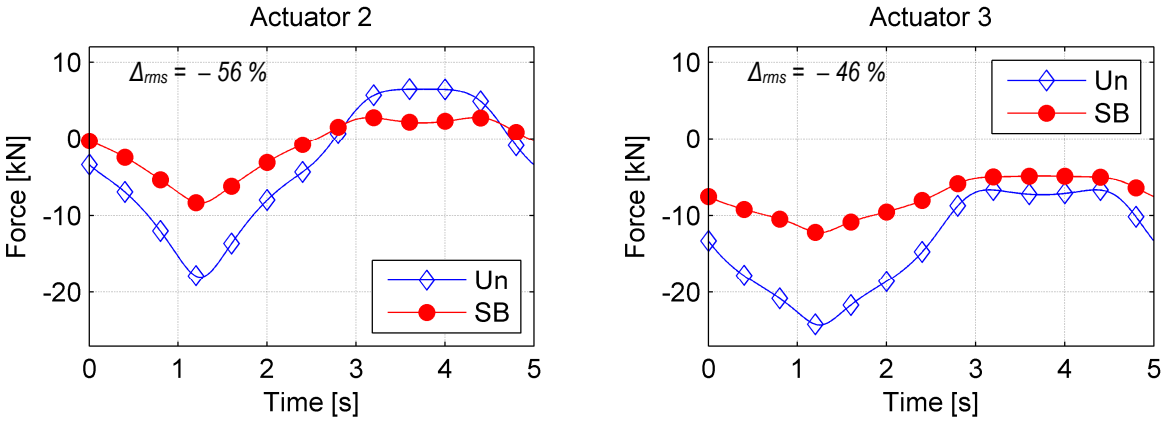


Figure 2: motor forces over one of the tested trajectories, with maximum payload, for the unbalanced robot (Un) and one of its gravity compensated variants (SB).

be always more profitable in terms of dynamic loads (due to the lower inertia added to the robot), balancing solutions involving counterweights may be still convenient depending on the design constraints concerned with the practical implementation of the balancing devices.

The first results provided by the optimization process are promising. All the examined balanced variants of the robot exhibit enhanced working performance in terms of both rms and peak absolute values of the motor loads. Some results concerning the balancing solution featuring one counterweight and one tension spring are reported in (Fig. 2). The force rms value appears significantly reduced, thus a remarkable increment in the robot energy efficiency being reasonably expected. A rather sizeable decrement in the peak motor actions is also achieved. Such result may permit not only to solve the experienced overload issues but also to increase the nominal maximum payload of the manipulator.

**References**

[1] S.K. Agrawal, A. Fattah. Gravity-balancing of spatial robotic manipulators. Mechanism and Machine Theory, Vol. 39, No. 12, pp. 1331–1344, 2004.

[2] A. Martini, M. Troncossi, M. Carricato, A. Rivola. Static balancing of a Parallel Kinematics Machine with *Linear-Delta* architecture. In Proceedings ASME 12th Biennial Conference on Engineering Systems Design and Analysis (ESDA), Copenhagen, Denmark, 2014.

[3] S. Ruzika, M.M. Wiecek. Approximation Methods in Multiobjective Programming. Journal of Optimization Theory and Applications, Vol. 126, No. 3, pp. 473–501, 2005.