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Torque minimisation of the 2-DOF serial manipulators based on minimum energy consideration and optimum mass redistribution

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A B S T R A C T

This paper deals with the analytically tractable solution for input torques minimisation of two degrees of freedom serial manipulators based on minimum energy control and optimal redistribution of movable masses. The minimisation problem is carried out in two steps: at first, the optimal trajectory of the manipulator is defined as a function, which leads to the minimisation of energy consumption. Then, by introducing the obtained trajectory into dynamic equations, the torques are reduced by using the optimal redistribution of movable masses, which is carried out via an adaptive counterweight system. For this purpose, the torques due to the dynamic loads of the counterweights are presented as a function of the counterweight positions. The conditions for optimal dynamic balancing are formulated by minimisation of the root-mean-square value of the input torque including the dynamic loads of the unbalanced manipulator and counterweights. The suggested approach is illustrated by numerical simulations carried out using ADAMS software.

1. Introduction

The loading of manipulator actuators depends on the distribution of mass in the links as well as the efficient motion generation. The first problem can be partially solved via gravity compensation, i.e. by static balancing. This means that potential energy is constant for all possible configurations, i.e. zero actuator torques due to the static loads are required. Previous works on the static balancing of robot mechanisms can be arranged in the following groups:

(a) Balancing by counterweights mounted on the links of the initial system [1–4]. Such balancing is very simple to realize. However, it leads to the important increase of the moving masses of the manipulator.
(b) Balancing by counterweights mounted on the auxiliary linkage connected with the initial system [5–9]. Articulated dyads [5–7] are used as the added systems for optimal displacements of the counterweights. In [9] the pantograph mechanism is used as an auxiliary linkage, which allows the generation of a vertical force applied to the manipulator platform. The balanced platform becomes a weightless link, and it can be displaced by low-power actuators.
(c) Balancing by springs jointed directly with manipulator links [10–15]. It was shown that complete static balancing can be achieved when the zero free length spring is applied and partial balancing for the non-zero free length spring. In the work [13] it was shown that the mass of the balancing spring increases the unbalanced moment and it cannot be neglected. Therefore a study to gravity balance considering the spring mass was developed.
(d) Spring balancing by using a cable and pulley arrangement [16–20]. Such an approach allows zero free length springs to be used, which is more favourable for realisation of complete balancing.
(e) Spring balancing by using an auxiliary linkage [21–31]. In these studies the articulated dyads, pantograph mechanism and parallelogram structure are used as the added systems for optimal displacements of the springs. It should be noted that many balancing methods carried out by springs are only applicable for planar manipulators.
(f) Spring balancing by using a cam mechanism [32–35]. In [33] was shown a balanced technique which uses springs in addition to the cam with Archimedean spiral curve.
(g) Spring balancing by using gear train [36–39].

It is obvious that such a balancing is very useful for static mode of operation of the manipulator. However, with the increase of the accelerations of moving links, the inertia forces become important and the complete static balancing in dynamic operation cannot be optimal. In this context another problem may be formulated: to

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