Optimizing Energy Consumption of a Parallel Robot with Elastic Elements via Equilibrium Position Adjustment

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ABSTRACT

1 Introduction

Industrial robots are essential for modern industries due to their efficiency in performing repetitive and dangerous tasks better than humans. Studying their energy consumption has become crucial for increasing profits and reducing carbon footprints. Natural motion exploitation appears as a strategy that combines hardware and software enhancements to reduce the energy consumption of mechatronic systems during cyclic tasks [1]. Natural motion is defined as the system's response due to the conversion of potential energy into kinetic energy, and several works implementing this strategy are reviewed and classified in [2]. The objective is to add springs to the system so that their design parameters and the trajectory of the actuators align with the task.

The springs' parameters are calculated along with a trajectory increasing the energy efficiency of a Delta robot in [3]. As the method is applied to scenarios where the pick-and-place positions are previously fixed, a major deviation from these positions could cause a rise in energy consumption because the springs' design is linked with the task specification. This is addressed in [4] by simultaneously updating the springs' equilibrium position and the manipulator's trajectory. However, the designed trajectories do not fully meet smoothness requirements for dwell times because the zero jerk condition is not specified at the pick-and-place positions. Moreover, updating the parameters of the multi-point trajectory and the equilibrium position of the springs requires an optimization problem with several decision variables. This contribution brings together the mentioned publications and deals with two principal challenges. First, a set of necessary border conditions to incorporate dwell times in the task, namely zero velocity, acceleration, and jerk in the stop positions, is implemented in the trajectory planning. Second, point-to-point trajectories are implemented in motion planning along with adjusting the equilibrium positions of the elastic elements to reduce energy consumption while maintaining a simple optimization problem with fewer decision variables.

2 Method, Results, and Discussion

The parallel robot studied is a planar five-bar linkage actuated by two rotational servomotors at the frame joints. Natural motion is exploited by incorporating two torsional springs parallel assembled in these joints. Additionally, the trajectories are defined in joint space as point-to-point polynomial trajectories (P2P), meaning they do not include intermediate control positions, or multi-point piecewise polynomial trajectories that consist of time-equidistant intermediate control positions. The trajectory definition makes the system kinematically determined by providing a driving function for each degree of freedom. This allows the equations of motion to be solved numerically to obtain the actuation torques. The energy consumption can be estimated following [4].

A typical packing industrial scenario is studied, where the pick position is fixed, and a place square grid is considered as shown in Fig. 1a). The spring parameters are calculated based on a nominal task, defined by the mentioned fixed pick position and the centroid of the squared grid as the placement position. Additionally, a nominal P2P trajectory can be defined between those positions as shown in Fig. 1a). The point-to-point trajectories are calculated with seventh-order polynomials considering the required zero velocity, acceleration, and jerk border conditions at the pick-and-place positions. The minimum energy multi-point trajectories (ME) are also calculated using seventh-order polynomials that include the mentioned required border conditions and five control positions as shown in Fig. 1a). Moreover, P2P trajectories are implemented when adjusting the equilibrium positions of the springs. Both minimum energy trajectory and equilibrium position updates can be formulated as optimization problems. In this formulation, the cost function is the energy consumption while the decision variable χ corresponds to the control intermediate positions for calculating a minimum energy multi-point trajectory, and a 2-element vector for adjusting the equilibrium position of the springs.

Fig. 1 presents the results for the two types of trajectories implemented, namely P2P and ME. In the case of the P2P trajectories, the motion was simulated for the manipulator extended with springs (wS) and without them (woS). The trajectory named P2P wS θ_0 corresponds to an update of the equilibrium position of the springs. As shown in Fig. 1b), when there are no springs the energy consumptions of the P2P trajectories are always above the energy consumptions obtained using the ME trajectories. On the other hand, when the nominal springs are incorporated and P2P trajectories are implemented, energy consumption is reduced in certain regions. In other regions, the energy consumption increases above the ME trajectories without springs as presented in Fig. 1c). In

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this case, it will be more beneficial to remove the springs; however, the presented method manages to further reduce energy consumption by updating the equilibrium position of the springs through the optimization problem solution. As shown in Fig. 1d), when a P2P trajectory is implemented with the adjusted equilibrium positions, the energy consumptions are always below the trajectories with the fixed nominal equilibrium positions. These observations are also obtained by analyzing Fig. 1e-f), which are sections of the surface for constant values of the y position $y = 0.4$ and $y = 0.5$, respectively. The importance of performing this adjustment becomes evident due to the varying order of the four energy curves.

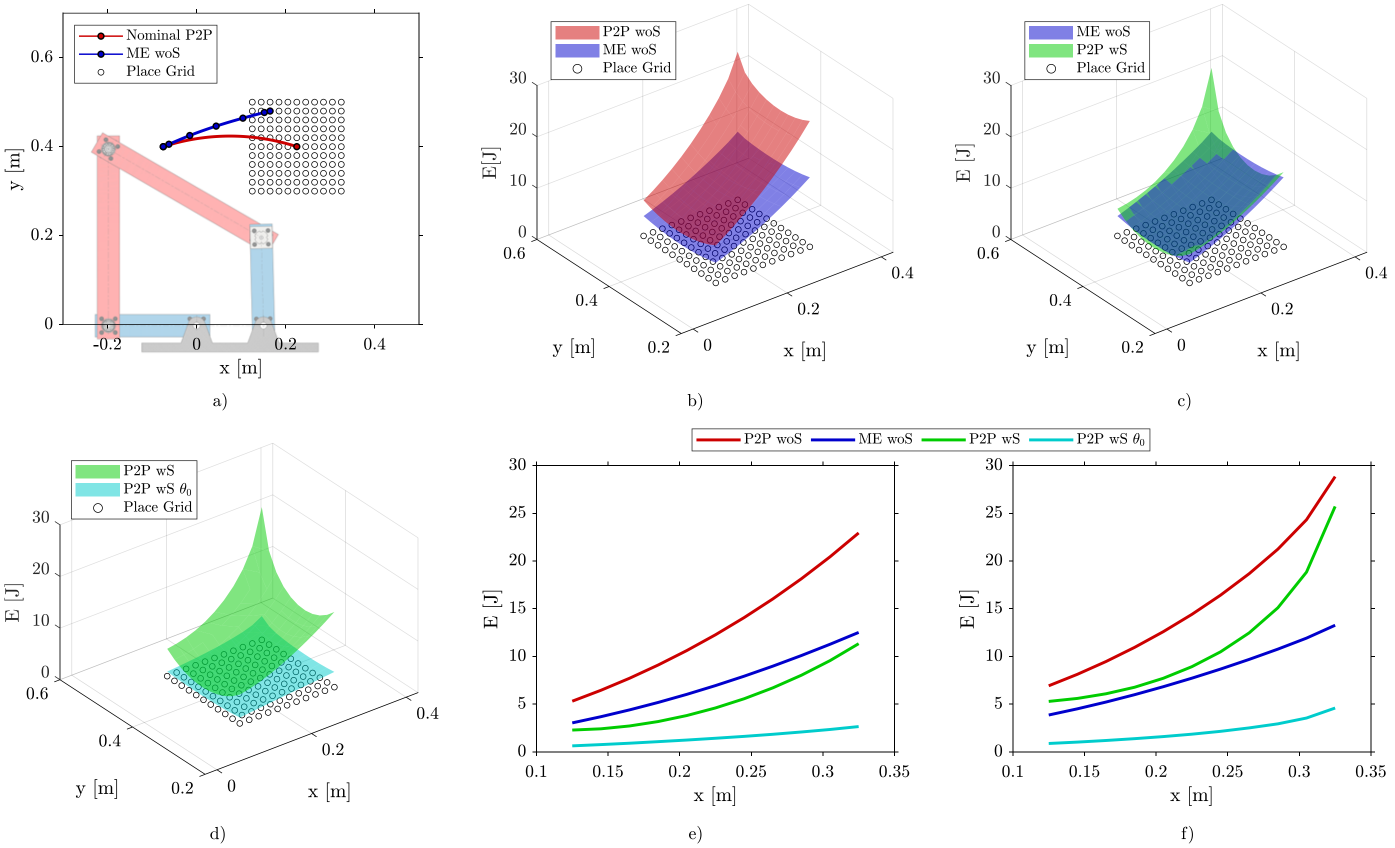

Figure 1: a) Task specification, b-d) Energy surfaces related to the place grid, e-f) Section analysis for a constant value of y.

3 Conclusion and Future Work

P2P and ME trajectories including necessary border conditions for dwell times are evaluated for a manipulator with and without springs, demonstrating that using springs and exploiting natural motion reduce energy consumption for pick-and-place tasks. The solution of a minimum-energy optimization problem allowed multi-point trajectories to outperform P2P trajectories if no springs were used. However, if nominal springs are assembled and used with P2P trajectories, energy consumption is reduced around the nominal task region compared to the ME trajectories without springs. Moreover, further energy reductions are achieved within a wider region by adjusting the equilibrium position while maintaining fewer decision variables than the ME optimization formulation. Although the method was implemented for a planar five-bar linkage it can be applied to other robots extended with elastic elements. Special attention will be paid to the selection of the nominal task and the cycle time in future work.

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