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A new method for combining handling systems with passive orientation devices

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ABSTRACT

The development of flexible and cost-saving handling systems is within the scope of ongoing research. In the present work, a parallel robot is extended with a passive orientation device to enhance its mobility. Additional actuators, which are usually used for active orientation, are deliberately excluded to reduce costs and weight. Passive motions are thus caused by accelerations of the parallel robot in conjunction with the inertia coupling between both structures. This contribution presents methods to connect the control of the orientation device with the overlaid handling task. Validation of the process is done in simulation and experimentally.

1. Introduction

In recent years, reconfigurable manufacturing systems have become a key issue in a new manufacturing paradigm: unpredictable market changes e.g. caused by fluctuations in demand and product mix, together with changes in the product design, have led to the introduction of flexible manufacturing systems (FMS) where modularity is essential for rapid adaptions and cost-effectiveness [1]. Material handling systems are subsystems of common FMS, which determine the material flow between workstations. The delta robot is a common structure in handling systems and it is widely used in the packaging industry or in the assembly of electronic products to achieve pick and place operations (PPO) at very high speeds. To meet the need for a higher number or different types of degrees of freedom, current systems in academic and industrial research are augmented with an additional rotational axis to achieve *Schoenflies* motions. A famous example thereof is *FlexPicker* from *ABB Robotics*. By contrast, *M-3iA* from *Fanuc Robotics* can achieve at least six degrees of freedom, owing to three additional rotational axes. Both examples illustrate that additional axes require additional motors or powertrains, the integration of which into the basic robot system (BRS) becomes a challenge and which must be considered precisely. Fast motions require high performance motors, which usually come with high inertias. In such cases, the performance of the BRS will be impaired in terms of increasing mechanical stress and drive torque. A brief overview of existing robot designs with additional orientation axes is presented in [2] along with analyses that consider the impact of different extension mechanisms on the dynamics of a delta structure. Passive, i.e. unactuated, mechanical systems (UMS) that can be attached to the BRS as a module may provide an interesting solution to this predicament. Excluding actuators reduces costs and weight and will significantly enhance the maintenance of the entire system. Such a passive device together with the BRS will then yield an underactuated system, where the dynamics of both systems are coupled through inertia. The mechanical stress of the BRS will then be less and no extra motor controller is needed.

In the following, the role of underactuation in handling systems is shown and the proposed system is introduced. An orientation task is then designed, taking into account the developed control strategy and a fitting procedure to match the trajectory of the UMS to the trajectory of the PPO. Simulation and experimental results are shown to illustrate the benefits of this approach.

2. Underactuated handling system

The kinematics of handling systems can be classified by the number n_{t} of generalized coordinates and the number of actuators n_{a}: $n_{\mathrm{a}} > n_{\mathrm{t}} \rightarrow$ redundant, $n_{\mathrm{a}} = n_{\mathrm{t}} \rightarrow$ fully actuated (active), $n_{\mathrm{a}} < n_{\mathrm{t}} \rightarrow$ underactuated or $n_{\mathrm{a}} = 0 \rightarrow$ unactuated (passive), where the latter type is irrelevant for stand-alone systems. While systems of the first and second class, like 7-axis or 6-axis articulated robots, are in wide use and commercially available from robot manufacturers, underactuated manufacturing systems are much less common. A current trend in research is the combination of underactuated grippers/robotic hands with actuated systems. In this context, the idea of underactuation is "*. . . the distribution of the motion of a prime mover to two or more d.o.f. . . .*" [3]. For example, the motion of the links of a passive gripper is imposed by the object shape. In particular, this can lead to simpler controls. The implications of underactuation in the present case are more difficult. The motion of the passive links is transmitted by inertia

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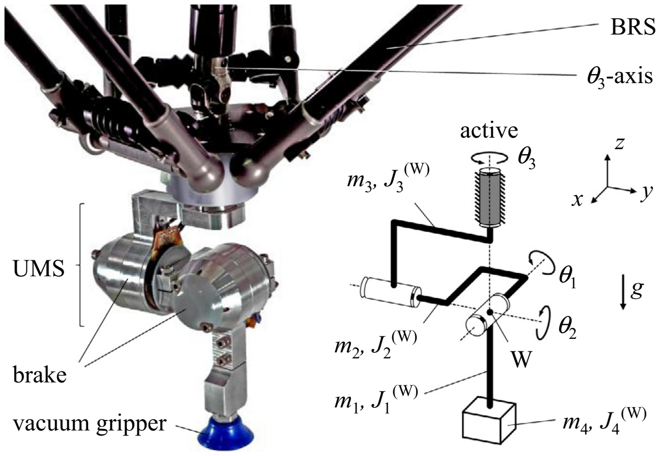

Fig. 1. The UMS attached to the BRS (left) and the corresponding schematic structure with the active joint of the BRS (right).

coupling, which represents the indirect actuation of the passive joints by means of inertia moments caused by the acceleration of the active joints.A promising approach of an underactuated system that uses inertia coupling is the pick and place robot SAMARA [4]. This robot performs a steady rotation with the first axis. The main proportion of energy used for the motion cycle is stored for the following cycles. A passive axis is used to provide nullspace motions, which causes a standstill of the gripper to grasp objects, and underactuated motions to move the gripper from any initial to any desired point. The power consumption is reduced to 43% compared to a conventionally articulated robot. Apart from manufacturing applications, underactuated pendulum systems can be found in literature for use in control engineering or for research in nonlinear control and robotics [5]. In this context, swing-up tasks with stabilization and motion analysis are predominant. A well-known example is the cart-pole structure, which can be classified as handling system such as in the example of a crane [6].

The proposed system is a technical realization of the cart-pole structure. Here, the BRS and UMS represent the cart and the pole respectively. The specifications of the BRS are based on the robot *FlexPicker*. To obtain a workspace with maximum orientation, or configuration space C, three serially arranged joints are required. In [7], five appropriate spherical kinematic chains were found. Since the BRS itself has one rotational axis, a workspace with full orientation can be achieved by (1) extending this axis to yield the Euler wrist or by (2) adding a cardan joint. The latter is used for the proposed UMS as shown in Fig. 1. θ_1 and θ_2 are passive axes; θ_3 denotes the active rotational axis of the BRS, point W the pivot of the axes and g the gravity vector. $m_{1,2,3,4}$ and $J_{1,2,3,4}^{(W)}$ are masses and moments of inertia with respect to W. Each passive axis is equipped with a brake to guarantee rest positions. In addition, a vacuum supply for the gripper is integrated in the structure to avoid using stiff vacuum hoses [8]. In general, the design is compact; it features easy sensor integration and strong inertia coupling for each passive axis with the BRS. Besides, it does not lead to kinematical redundancies, thus reducing the control effort compared to the Euler wrist [7]. For the sake of reconfigurability, the chosen structure features a modular design. Hence, the delta robot is only one option of possible BRS. The underlying idea can also be adopted for other robotic systems.

3. Process design

The proposed process is illustrated in Fig. 2. The aim is to match the trajectories of the swing maneuvers of the passive axes to the trajectory of a subordinate PPO in time and path as well as possible. After picking an object, the UMS will simultaneously be moved along z_p and rotated about z by ξ so that the θ_1-axis is perpendicular to the path of the PPO (y_p). The pivot W will then be accelerated along y_p to achieve a single swing of the θ_1-axis from its start angle to the desired angle. In doing so, the brake of the θ_2-axis is engaged. The θ_1-axis reaches its desired set-point with zero velocity to avoid influences of the braking process. Similarly, the θ_2-axis will subsequently be adjusted perpendicular to y_p and swung to the desired set-point. After the brake is engaged, the UMS will be moved along z_p and rotated about z to achieve the desired angle for θ_3 and position to place the object. In addition to this sequential process, it is also possible to execute both swing maneuvers simultaneous with a coupled motion in x- and y-direction.

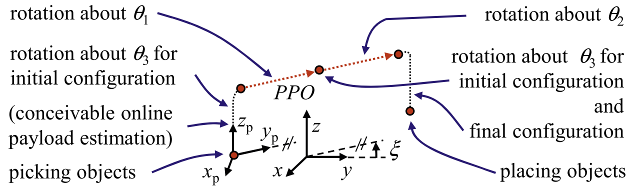

Fig. 2. Simplified design and steps of the process.

3.1. Control strategy

In literature, different approaches can be found for the control of underactuated systems. A review of feasible control techniques for different underactuated systems is given in [5,9]. This article focuses on energy-based control. As previously mentioned, the proposed system is comparable with a spatial pendulum on a cart in terms of the structure. In this case, energy-based swing-up control can be easily implemented and no trajectory planning is needed. However, the system properties make the application of commonly used energy-based control strategies impractical:

- The potential energy does not depend on the direction of rotation. Thus, as a result of mechanical interferences, angular boundaries are not considered.
- The inertias of both axes are coupled and vary during motion.
- Varying payload makes offline planning impractical.

Control is done by taking the kinetic T and potential U energy of the passive links 1, 2 and 4 into account, cf. Fig. 1. Link 3 is active and link 4 is attached to link 1. Usually, energy-based control aims at achieving a total energy of the system $E = T + U$, which corresponds to the desired unstable upright equilibrium of the pendulum with zero velocity so that $E_d = T_d + U_d$ becomes zero (desired: index $(\cdot)_d$). The control then switches to a linear balancing controller to stabilize the linearized system dynamics. In the present form, $C|_{\theta_{1d} \leq |\pi/2|, \theta_{2d} \leq |\pi/2|}$ is constrained through the set-points θ_{1d} and θ_{2d} so that the potential and kinetic energy levels are $U_d \neq 0$ and $T_d = 0$ respectively. This yields $E_d \neq 0$ and conventional techniques must be adapted. Nevertheless, the first steps are almost identical. To find an appropriate control law, Lyapunov method is applied. A possible Lyapunov function candidate is $V = (E - E_d)^2/2$, where its derivative should be negative in every respect to drive $(E - E_d)$ to zero, see Eq. (1). Substitution of $\mathrm{d}E/\mathrm{d}t$ and $\ddot{\theta}_{1,2}$ then yields Eq. (2), with Eq. (3).

$$\frac{\mathrm{d}V}{\mathrm{d}t} = (E(\theta_{1,2}, \dot{\theta}_{1,2}) - E_d) \cdot \frac{\mathrm{d}}{\mathrm{d}t} E(\theta_{1,2}, \dot{\theta}_{1,2}, \ddot{\theta}_{1,2}) \overset{!}{\leq} 0 \tag{1}$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = (E - E_d) \cdot \begin{pmatrix} s\theta_2 \cdot s\theta_1 \cdot \dot{\theta}_1 - c\theta_1 \cdot c\theta_2 \cdot \dot{\theta}_2 \\ c\theta_1 \cdot \dot{\theta}_1 \end{pmatrix} \cdot \begin{pmatrix} \ddot{x} \\ \ddot{y} \end{pmatrix} \tag{2}$$

$$E_d \begin{cases} E_{1d}(\theta_2, \dot{\theta}_2)|_{\theta_{1d}, \dot{\theta}_{1d} = 0}, & \text{for } \ddot{y} \\ E_{2d}(\theta_1, \dot{\theta}_1)|_{\theta_{2d}, \dot{\theta}_{2d} = 0}, & \text{for } \ddot{x} \end{cases}, \tag{3}$$

Here, c(·) and s(·) denote cos(·) and sin(·) respectively. To attain stability, the accelerations in x- and y-direction, which are the control inputs, must be chosen such that the Lyapunov function decreases. This is difficult, since θ_{1d} and θ_{2d} are arbitrary in C. This is different from the commonly used upright equilibrium. Thus, E_d does not take a specific value, it rather follows an almost circular