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Energy efficiency evaluation of an underactuated robot in comparison to traditional robot kinematics

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Abstract

An underactuated serial kinematics industrial handling robot using high torque direct drive motors combined with slip rings is presented. Pick and place tasks are performed through combining the underactuated motion with a null-space motion enabling the kinetic energy to be conserved within the system. This system is benchmarked against linear axis systems with belt and ball screw drives respectively and also against a conventional robot system regarding energy efficiency proving performance improvements.

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Keywords: robotics; underactuated motion; energy efficiency; nullspace motion

1. Introduction

Pick and place tasks represent a major field of robotic applications. In this regard, technology developments in this field have been an interested area of academic and industrial research. Speed and accuracy are considered as the dominant criteria in defining the efficiency of the pick and place robots. However energy consumption has been also a considerable criterion in design of specialized robots for this type of tasks.

The predominant designs in this field have achieved higher efficiency by considering features that improve their specialty for pick and place tasks. The key feature of parallel robots is to reduce the weight of the moving parts in order to reduce the dynamic inertia, energy consumption and their negative effects on accuracy [1]. SCARA designs tend to reduce the gravity effects through horizontal planner motion and to reduce the inertia of the moving parts by locating the motors in the stationary base of the robot [2].

In this paper an underactuated planar robot is introduced which applies a momentum conservation concept in order to achieve a higher efficiency in pick and place tasks. The acceleration and deceleration forces are mainly obtained from interactions of dynamic forces between the robot linkages rather than from electric motors. Accordingly, this concept enables to achieve faster robots despite considerably lower energy consumption.

An underactuated robot is characterized by having more degrees of freedom than actuated axes. For more than two decades there have been efforts towards recognition of underactuated mechanisms as controllable robot manipulators. Use of dynamic coupled forces and application of brakes for position control were suggested in several research [3,4,5]. Some researchers recommended use of properties of special structures of manipulators [6,7,8]. The study of control schemes for the underactuated planar manipulators reveals that they are more controllable at high dynamics conditions [9]. This suggests that underactuated manipulators are more suitable for fast robot applications.

There has been also some research on the controllability of underactuated manipulators through offline trajectory planning methods [10,11]. Several studies by Brett [12,13], proved the theoretical advantages of an underactuated design in pick and place tasks. Accordingly, a serious step towards introduction of an industrial underactuated robot was taken in Technical

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University of Berlin at the Department of Machine Tools and Factory Management [13].

A prototype of a 3 DOF planar underactuated manipulator with an offline trajectory planning method was built in this project in order to do experimental performance tests on a real scale mechanism. The laboratory results of the prototype proved the idea of industrializing an underactuated manipulator to be practical. It also showed its privileges over conventional robots in terms of energy consumption.

2. Trajectory generation and simulation

Brett and Quiel [12] developed a multi objective optimization procedure based on an evolutionary algorithm in order to generate optimized trajectories. This procedure relies on simulation of multi body dynamics of the robot for estimation of the procedure objectives. Figure 1 shows the DH parameters of the simulated robot model. The third axis, A3, is regarded as the non-actuated degree of freedom of the robot. Power consumption and accuracy are considered as the objectives of the optimization procedure so that the resulting trajectories represent the minimized integral of the energy required for traveling between pick and place configurations.

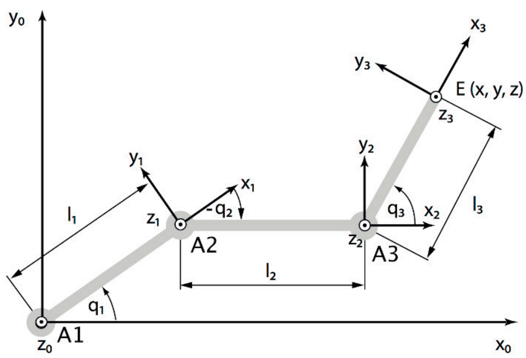

Fig. 1. 2D representation within the simulation.

Nomenclature	
3P3W	3 phase 3 wire measurement
3P4W	3 phase 4 wire measurement
A1, A2, A3, E	1st, 2nd, 3rd and endeffector axes
DOF	degree of freedom
L1, L2, L3	1st, 2nd and 3rd links
l1, l2, l3	link lengths
PTP	point to point
T	cycle time

A typical trajectory comprises two null-space motions, in which the end effector experiences a stationary position while the robot linkages are in motion, and an underactuated trajectory connecting the null-space motions. Pick and place operations take place during the null-space motions. This enables conservation of robots kinetic energy by eliminating the need for braking and energy loses thereof. Figure 2 represents a typical trajectory generated by the mentioned algorithm.

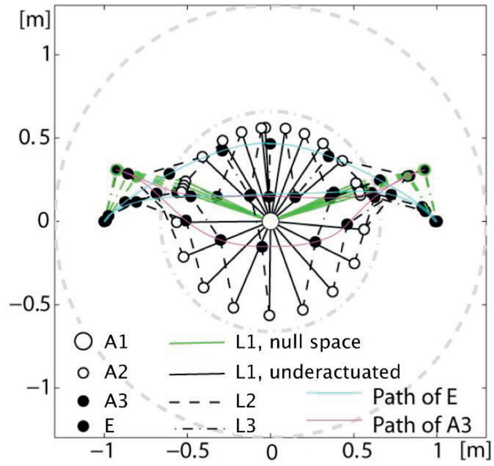

Fig. 2. Underactuated motion, null-space motion parts marked green [13].

3. Robot prototype

The prototype consists of three direct drive servo motors, and absolute encoders corresponding to axes A1, A2 and A3. In spite of the underactuated nature of the robot a motor is located at the third axis in order to compensate for deviations of the simulation parameters from the real world which would result in instability of the motions.

The continual rotation nature of the robot arms necessitates application of slip rings for transferring the power and signals through the rotating axes. The slip rings and the encoders are embedded in the axes of the robot with a concern on keeping the robot height as low as possible. Figure 3 shows the prototype in a top down mounting configuration. The control system consists of state of the art Beckhoff® AX5000 power drives controlled by TwinCAT®.

Fig. 3. Prototype of the underactuated robot.

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