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Research paper

The dynamics of a parallel Schönflies-motion generator

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A R T I C L E I N F O

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A B S T R A C T

A parallel architecture was recently proposed to generate Schönflies motions. The CR-RHHRRC closed kinematic chain offers a symmetric single-loop architecture, isostatic design, and high rotatability[1] of its gripper. This pick-and-place robot uses an innovative cylindrical drive, which is a realization of a two-degree-of-freedom cylindrical actuator. The authors report the kinematics and dynamics analysis of the above-mentioned Schönflies-motion generator, developed at McGill University's Centre for Intelligent Machines. This analysis is intended to optimize the robot design. Validation of the mathematical model was conducted experimentally. The results reveal the accuracy of the model.

1. Introduction

Manipulation tasks can be classified into different categorises based on the degree of freedom (dof) and type of motion, like trajectory-tracking and pick-and-place. Pick-and-place operations (PPO) consist of grabbing a payload and moving it from its starting pose to its destination pose, regardless of the poses visited in-between. PPO have many industrial applications, like moving parts between workstations. The focus of this paper is on pick-and-place robots that produce Schönflies motions, the pertinent robots being termed Schönflies-motion generators (SMG). The Schönflies subgroup of the algebraic group of rigid-body displacements [1] comprises four dof, translation in three independent directions and rotation about one axis of fixed orientation, usually vertical. The motion is similar to a waiter's tray, which is not allowed to tilt about any horizontal axis. The tray can only rotate about the vertical axis and translate in three independent directions. Various designs and architectures have been proposed, including serial and parallel architectures [2–4]. A serial architecture has a larger workspace and a longer reach when compared to a parallel architecture with the same overall size. However, the load-carrying capacity of a serial robot is lower than that of a parallel robot. The first SMG, with a serial architecture, was developed in the 1980s. It was termed SCARA (Selective-Compliance Assembly Robot Arm) [5–7], supplied with one prismatic and three revolute joints. In 2000, Angeles et al. came up with a novel design for the production of Schönflies motions [8], which employed two identical SMGs.

Closely related to SMGs, a parallel pick-and-place robot, known as Delta, was first disclosed by Clavel and patented in 1990 [9]. A Delta architecture was proposed with three identical limbs aimed at generating three-dof translational motions of its moving plate (MP) [10]. One additional rotational motion, proposed in Clavel's patent, was produced at the robot base

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[1] The industry-adopted test cycle calls for a rotatability of at least a half-turn. Any SMG capable of rotating its moving platform by more than a half-turn is termed here of high rotatability.

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Nomenclature

r	Arm length
l	Forearm length
p	C-drive screw pitch
p_p	Peppermill screw pitch
h_i	Vertical distance of peppermill screw joint and ith C-drive
$\mathbf{x}$	Trajectory of prescribed path of peppermill centre
u_i	Position of the ith C-drive collar
b	Vertical position of each C-drive
θ_i	Orientation of the ith C-drive collar
λ_i	Orientation of the ith forearm
x_C	X-position of peppermill centre
y_C	Y-position of peppermill centre
z_C	Z-position of peppermill centre
ϕ	Rotation of peppermill about Z-axis
ψ_{iR}	Rotation of the ith C-drive motor coupled to the right-hand screw
ψ_{iL}	Rotation of the ith C-drive motor coupled to the left-hand screw
τ_{iR}	Torque of the ith C-drive motor coupled to the right-hand screw
τ_{iL}	Torque of the ith C-drive motor coupled to the left-hand screw
$\mathbf{J}$	PMC Jacobian matrix
$\mathbf{J}_c$	C-drives Jacobian matrix
$\mathbf{v}_i$	Velocity vector of ith body c.o.m
$\boldsymbol{\omega}_i$	Angular-velocity vector of ith body
$\mathbf{f}_i$	Force vector acting on ith body
$\mathbf{n}_i$	Moment vector acting on ith body
$\mathbf{t}_i$	Twist exerted on ith body
$\mathbf{w}_i$	Wrench exerted on ith body
$\mathbf{T}_i$	Twist-shaping matrix of ith body
$\mathbf{w}_i{}^G$	Gravitational wrench on ith body
$\mathbf{w}_i{}^E$	External wrench on ith body
$\mathbf{w}_i{}^D$	Dissipative wrench on ith body
$\mathbf{W}_i$	Angular-velocity dyad of ith body
$\boldsymbol{\Omega}_i$	Angular-velocity matrix of ith body
$\mathbf{M}_i$	inertia dyad at of ith body c.o.m.
$\mathbf{I}_i$	Inertia tensor at of ith body c.o.m.
ΔK_i	Change of ith body kinetic energy
ΔU_i	Change of ith body potential energy

and transmitted to the MP by a telescopic Cardan shaft. Currently, the IRB 340 FlexPicker, manufactured by ABB Robotics, is a hybrid (serial-parallel) SMG based on Clavel's patent.

Current parallel architectures have four identical limbs and corresponding actuators, with each limb connecting its base plate (BP) to its MP. Schönflies motions are produced by means of these four limbs. One major challenge of the four-limb architecture design is limb interference. Since all four limbs converge in order to be connected to a small MP, they can collide each other when producing the rotational motion. However, the robot controller is programmed to avoid any collision between the limbs, but this in turn limits the robot rotatability. Several control methods have been implemented to achieve the best performance of the above-mentioned parallel architectures [11]. On the other hand, various architectures for the articulated MP have been proposed, such as: H4, I4L, I4R, Heli4 and Par4, to amplify the rotational motion generated by the limbs [12]. An amplification mechanism was implemented by the use of a gear train and a belt-pulley transmission [12–17]. The Quattro s650H, from Adept Technology Inc., is the best-known example of parallel architecture with four limbs and a H4 mechanism. The concept was invented and patented by Pierrot et al. [18].

Other researchers have proposed a two-limb SMG design intended to reduce the complexity of the parallel architecture. Angeles and his team developed a two-limb SMG dubbed the McGill SMG [19]. Recently, Lee and Lee [20,21] proposed two-limb parallel SMG architectures to eliminate some disadvantages of the parallel architecture, including the overall complexity and the requirement of a transmission to produce the rotary motion. The advantages of these new architectures include isostaticity, high rotatability of the MP, and a fully symmetric layout [22]. What plays the role of the MP is a rod carrying two coaxial screw joints with different pitches; it is dubbed “the peppermill”, because of its similarity, both formal and functional, to the long, Italian peppermill. Recently, Angeles and his team picked one of three different design variations of the Lees’ architectures [20,21] and researched on the mechanism feasibility and kinematics [22]. The Isostatic Schönflies