Robotics and Computer-Integrated Manufacturing 38 (2016) 1–8

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Static performance improvement of an industrial robot by means of a cable-driven redundantly actuated system

Matteo Palpacelli

Department of Industrial Engineering and Mathematical Sciences, Polytechnic University of Marche, Ancona, Italy

ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form
14 August 2015
Accepted 4 September 2015

Keywords:
Cable-driven parallel manipulator
Redundant actuation
Parallel kinematics machine
Industrial robot
Kineto-static performance

ABSTRACT

Every industrial robot has a specific kinematics, which often results in anisotropic performance within its workspace in terms of force and velocity. A cable-driven system can be used to improve the force manipulability of a robot by introducing an actuation redundancy. Such system acts directly on the robot end-effector increasing its flexibility of use in applications where a higher and more uniform force performance is required. This work is focused on high-thrust operations, for example robotic friction stir welding or incremental forming, realized by means of a highly anisotropic industrial robot.

1. Introduction

Industrial robots are today employed in many manufacturing companies because of their versatility and ease of programming. Nevertheless, their use is often limited to applications like pick & place or packaging, where a large workspace is required and positioning accuracy is not a major factor. On the contrary, operations like machining or assembly are usually entrusted to Computer Numerical Control (CNC) machines, which have high accuracy, stiffness and thrust capacity, resulting in a better product quality. However their poor flexibility occurs in many industrial applications, where complex paths have to be realized by the tool and the request of small batches entails the need of a fast change of production.

Large-size robots with high static performances or Parallel Kinematic Machines (PKMs) represent a more flexible alternative to CNC machines [1], even though a force feedback is usually required at their machining tool [2]. However, the thrust capacity of industrial robots, defined here as the ability to push the machining tool against a workpiece, depends on their kinematics, mechanical design and drive power. This generally results in a strong anisotropy in terms of generalized velocities and forces developed within their workspace [3]. Notwithstanding the performance of industrial robots is suitable in a lot of conventional robot applications, many manufacturing processes require a more balanced force ability in order to guarantee a stable and precise operation, like for example incremental forming and friction stir welding [4,5].

Actuation redundancy, regarded in the present work as the use of additional actuated branches to an existing architecture, can be usefully adopted for parallel manipulators when greater static forces in certain Cartesian directions are required at the robot end-effector [6], even if that leads to a workspace reduction. Anthropomorphic robots need a more robust mechanical structure and an increase of the size of motors if compared to PKMs. Hybrid drive parallel arms driven by cables and cylinders were proposed to handle heavy material in construction and shipbuilding fields [7], as well as under-constrained or fully-restrained cable driven manipulators in large load applications, because of their high payload-to-weight ratio [8], besides their large workspace. Moreover, redundancy, also obtained by the composition of different robot architectures, can be exploited to improve the speed, stiffness and force capacity of the system choosing an optimized trajectory of the tool [9].

This paper deals with the application of a cable-driven device to an industrial robot in order to increase its static performance and stiffness by means of an actuation redundancy. The concept is shown in Fig. 1, where the moving platform of the cable-driven device is rigidly joined to the robot end-effector. After a kinematic and static modeling of the redundant system given by the cable-driven device and a generic robot, the concept is applied to the Tricept robot, a hybrid industrial robot that presents high force anisotropy.

2. Redundantly actuated system

The cable-driven device is thought of as a conventional cable-driven parallel manipulator (CDPM) where the moving platform is

E-mail address: m.palpacelli@univpm.it

http://dx.doi.org/10.1016/j.rcim.2015.09.003
0736-5845/

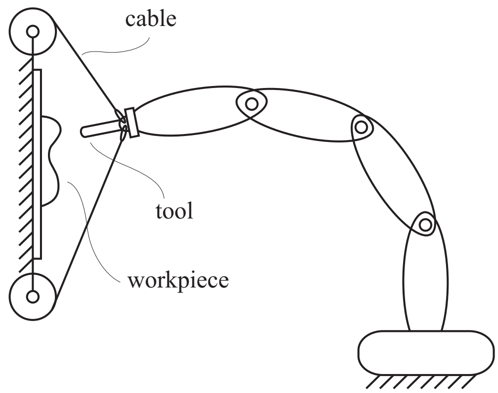

Fig. 1. Concept of the static performance improvement.

connected to the fixed base by means of several cables. The moving platform of the CDPM is connected to the industrial robot between its external flange and the tool, therefore the platform is subject to the robot motion.

The number of cables depends on the kind of action that is required at the robot end-effector, but the scheme proposed in the following is based on three cables. The fixed base is rigidly connected with the frame of the robot: at the edges of a triangle three idler pulleys allow to direct the corresponding cables toward the driving system, which provides their tension. Each pulley can rotate around a fixed axis orthogonal to the triangle plane in order to orient the median plane of the pulley toward the robot tool. The moving platform of the CDPM is assumed to be a single point where the three cables converge. Clearly such hypothesis simplifies the study, avoiding to take into account different points of connection that are needed in practice. However the offset between the three points will be designed as small as possible in real applications, tending to the proposed approximate solution.

According to the concept shown in Fig. 1, two problems need to be addressed: the first is the kineto-static analysis of the cable-driven system, once assigned its geometry, the second is the evaluation of its effect within a more complex system given by the industrial robot and the cable system itself. Together they become a redundantly actuated system.

2.1. Position kinematics of the CDPM device

The kinematics of the whole system, given by the industrial robot and the cable-driven device, can be easily solved once the pose of a reference frame fixed with the base of the auxiliary cable-driven device is known with respect to the robot base frame. At this time it is assumed that such a constant transformation is available with some accuracy, obtained by means of a suited calibration procedure, where the subscript b refers to the robot base frame and f to the cable-driven reference system. Many works have been already proposed in the literature with relation to cable-driven systems and their physical realization [10–13]. According to them the kinematic model of a CDPM is analyzed in the following. Fig. 2 shows the sketch of the cable-driven system, where a reference frame $\{O_f;\, x_f, y_f, z_f\}$ is fixed to the ground and a reference frame $\{O_m;\, x_m, y_m, z_m\}$ is instead mobile with the robot tool. As already mentioned the frame located at the CDPM moving platform is subject to the pose of the robot tool, therefore the position and orientation of the mobile frame can be considered known even if the auxiliary device is not a fully restrained CDPM. However a further constant transformation between the robot end-effector and the CDPM moving platform reference systems must be considered to relate the kinematics of the two devices. In the following a complete description of reference frames and their transformations for the whole system is given.

Several vectors are indicated in Fig. 2 where an index $i = 1, 2, 3$ is used to refer to one of the three kinematic chains: vectors $\mathbf{c}_i$ locate each pulley center C_i in the $x_f y_f$ – plane describing the edges of a triangle, angles φ_i set the direction of $\mathbf{c}_i$ with respect to the x_f-axis, vectors $\mathbf{r}_i$ of constant radius r define the point D_i of the pulleys where the cables unwrap from, vectors $\mathbf{u}_i$ originate in D_i and converge towards the origin of the reference frame located at the moving platform. Finally $\mathbf{p}$ is the oriented vector from O_f to O_m.

Three further reference systems for each kinematic chain, all centered in C_i, are useful to derive the kinematic equations of the CDPM: starting from the fixed frame a first constant rotation φ_i about the current z-axis defines the orientation of the system $\{C_i;\, x_{i0}, y_{i0}, z_{i0}\}$, a second rotation γ_i still around the current z-axis gives the system $\{C_i;\, x_{i1}, y_{i1}, z_{i1}\}$, whose $x_{i1}z_{i1}$ – plane coincides with the ith cable plane, and a further rotation θ_i about the current y-axis defines the last reference system $\{C_i;\, x_{i2}, y_{i2}, z_{i2}\}$, whose

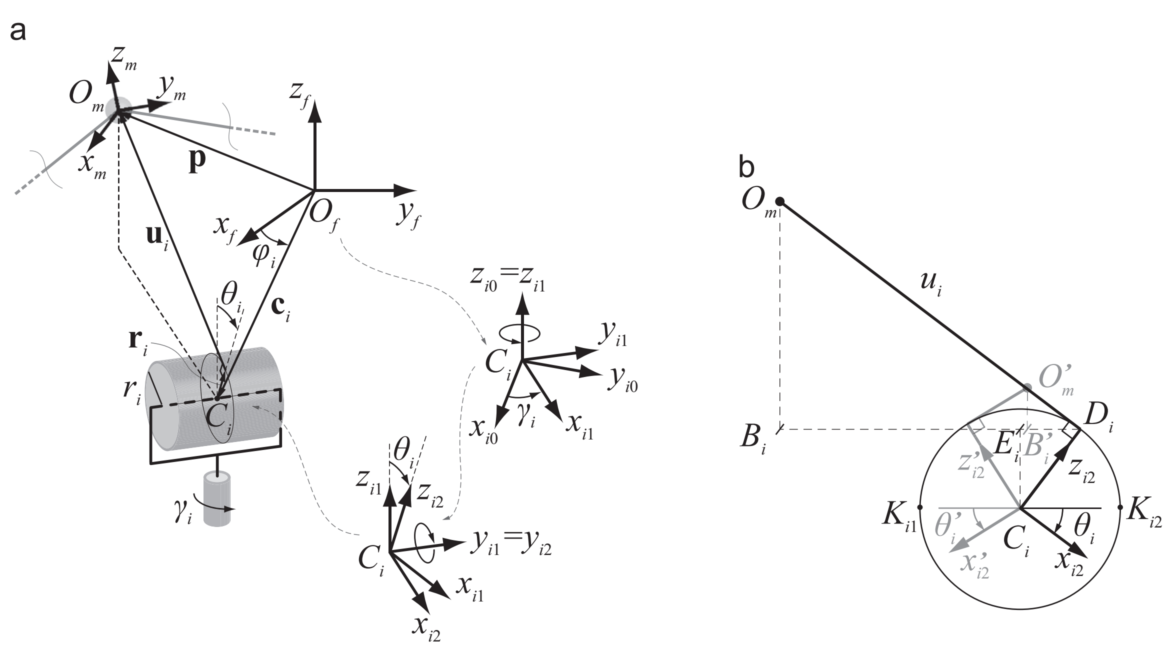

Fig. 2. Sketch of the cable-driven system. (a) Main reference systems and (b) plane of the ith pulley.