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Trajectory tracking controller of the hybrid robot for milling

Maciej Petko*, Grzegorz Karpiel, Konrad Gac, Grzegorz Góra, Konrad Kobus, Janusz Ochoński

AGH University of Science and Technology, Mickiewicza 30, 30-059 Krakow, Poland

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ABSTRACT

The paper presents a model predictive trajectory tracking controller for a five degree of freedom hybrid robot for milling. The construction of the manipulator is introduced, forward and inverse kinematics problems are solved in a closed analytical form, a simplified dynamic model, suitable for control synthesis is described. Control law of the computed torque type is proposed with modifications that improve the performance of trajectory tracking. The control algorithm is tested in experiments conducted on a robot material prototype without actual milling. The presented results are very good for the parallel part of the robot, but require improvement for the serial part. Finally, the conclusions and indications towards future investigations are presented.

1. Introduction

Recently, a growing interest in robots of parallel kinematics can be observed. They possess properties, which give them certain advantages over serial manipulators, in which the tool is placed on the end of an open kinematic chain. The most frequently emphasized [1–3] are higher stiffness, due to the presence of multiple closed kinematic chains and, as a result, higher natural frequencies, high payload capacity, fast movements and high accuracy. The disadvantages of parallel manipulators include difficulty in obtaining an analytical solution of the forward kinematics problem, thus resorting to numerical methods, which are prone to numerical errors and require intensive computations, mechanical properties, especially stiffness depending on the position, and a limited workspace, often filled with singularities, which imposes further limitation on the workspace size and causes additional problems with control and calibration [4–6].

Parallel manipulators are composed of a stationary base and a moving platform connected by several independent, serial kinematic chains (limbs) [7]. Only certain kinematic pairs in these chains are actuated and their number is usually equal to the number of degrees of freedom, which has the platform relative to the base. The advantages of parallel manipulators, such as low inertia, high stiffness, good dynamic properties, or an advantageous payload to weight ratio, attracted a lot of attention to this type of structures [7]. Most frequently used are configurations with six degrees of freedom, based on the construction of the Stewart-Gough platform [8] (hexapod type). Each limb of the structure consists of two links connected by an actuated prismatic joint. The limbs are attached to the base and/or to the moving platform by spherical joints. The Stewart-Gough platform has a high payload capacity and a small range of movement, at which the tool can take any orientation. Such a high mobility is not always necessary, thus configurations with fewer degrees of freedom are analyzed, as a potentially simpler and cheaper. The first construction of this type, which has been very successful commercially, thanks to excellent dynamic properties, is the Delta robot [9,10], based on parallelograms precisely made of special materials. It is characterized by high acceleration, and a relatively large workspace, but a small payload. It is used for very fast manipulation of very lightweight objects, mainly for palletizing. Later many other structures of manipulators having three degrees of freedom [1,11–13] were analyzed and almost all cause problems with obtaining analytical solution to the forward kinematics problem. A large part of the existing constructions of parallel manipulators uses spherical joints. Such joints still cause problems, are expensive, not durable enough, and their range of motion is limited [7].

By developing a new type of joint, which is at the same time the moving platform, and the use of linear direct drives, it was possible to construct a new type of a parallel manipulator with only one degree of freedom joints, comparatively large workspace,

* Corresponding author. AGH University of Science and Technology, Department of Robotics and Mechatronics, al. Mickiewicza 30, 30-059 Krakow, Poland. Tel.: +48 126173669; fax: +48 126343505.

E-mail addresses: petko@agh.edu.pl (M. Petko), gkarpiel@agh.edu.pl (G. Karpiel), kgac@agh.edu.pl (K. Gac), ggora@agh.edu.pl (G. Góra), kobus.konrad@gmail.com (K. Kobus), ochonski@agh.edu.pl (J. Ochoński).

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and high payload. In order to extend its motion capabilities, it was equipped with a tilt rotary table on the base, resulting in a hybrid five degree of freedom construction intended for high speed milling.

Milling requires accurate reproduction of a desired tool path – expected relative accuracy of trajectory tracking is of the order of 10^{-5} of the movement range [13]. In order to reach the goal, high sampling frequencies must be used [14]. For typical aluminum milling feed rates and accuracy better than 10 μm the sampling frequency should beat least 10 kHz. From the other hand, higher frequencies are unreasonable, as typical operating frequency of direct drive commutators is around 15 kHz.

In classical CNC milling machines, position PID servo controllers are used, working with trajectories that contain only desired positions in all axes in consecutive time samples. All axes are treated as independent SISO systems, which leads to problems with accuracy of desired contours reproduction [3]. An effective method of parallel manipulator control seems to be Computed Torque Control [5,9,15], especially the version described in [16], in which dynamic model of the manipulator is used for feedback linearization and for needed forces and torques prediction, and the PID component is applied for compensation of model inaccuracies and disturbances. Such a controller must get, in each sample period, a desired trajectory vector consisting of the position, velocity and acceleration in all joint space coordinates. In the case of milling, a task is defined in the global space, and, in order to meet technological demands, the desired trajectory is generated also in the global space. For transformation into the joint space, in which the controller works, the solution of the inverse kinematics problem is needed [17].

As in real devices hard nonlinearities, troublesome to modelling, are present, heuristic modifications are often introduced into the PID part of the control algorithm [18,19] – their task is to compensate effectively results of unmodeled phenomena, such as friction.

2. Construction of the manipulator

The developed 5-DOF (degrees of freedom) hybrid manipulator, shown in Figs. 1 and 2, is designed primarily for use as a support system for machining (drilling, milling, turning, laser cutting and waterjet cutting) but may be used, when equipped with the appropriate tool, also for handling and assembly tasks. The hybrid manipulator consists of two manipulators: a parallel one with three limbs, and a serial one in the form of the tilt rotary table, developed by CBKO Pruszkow – Polish manufacturer of machining equipment, mounted on the base of the parallel manipulator.

The parallel manipulator, with three translational degrees of freedom, has a structure, which is a compromise between the two dominant trends of parallel kinematics: derived from the Delta robot and Stewart-Gough platform. It is characterized by a relatively large workspace, high payload capacity and attainable high acceleration. In its construction, there are no spherical joints and parallelograms, expensive and troublesome in manufacturing and exploitation.

The manipulator has three limbs attached to the base and connected by a common triple joint (Fig. 3). The main triple joint serves as a moving platform, to which a tool (electrospindle) is mounted. Each of the robot limbs forms a kinematic chain of the structure RR$\underline{\text{P}}$RR (Fig. 4), in which the prismatic joint is actuated by a linear direct drive of the PMSM (permanent magnet synchronous motor) type, and its length is measured by a linear optical incremental encoder, whose resolution is 0.25 μm. The actuator is led by linear guides attached through revolute joints to the common base. The two joints connecting the linear guides to the base, as well as elements of the triple joint were constructed in such a way that they consist of a connections with only one degree of freedom. This construction provides ability of easy manufacturing, assembly and achieving the required accuracy.

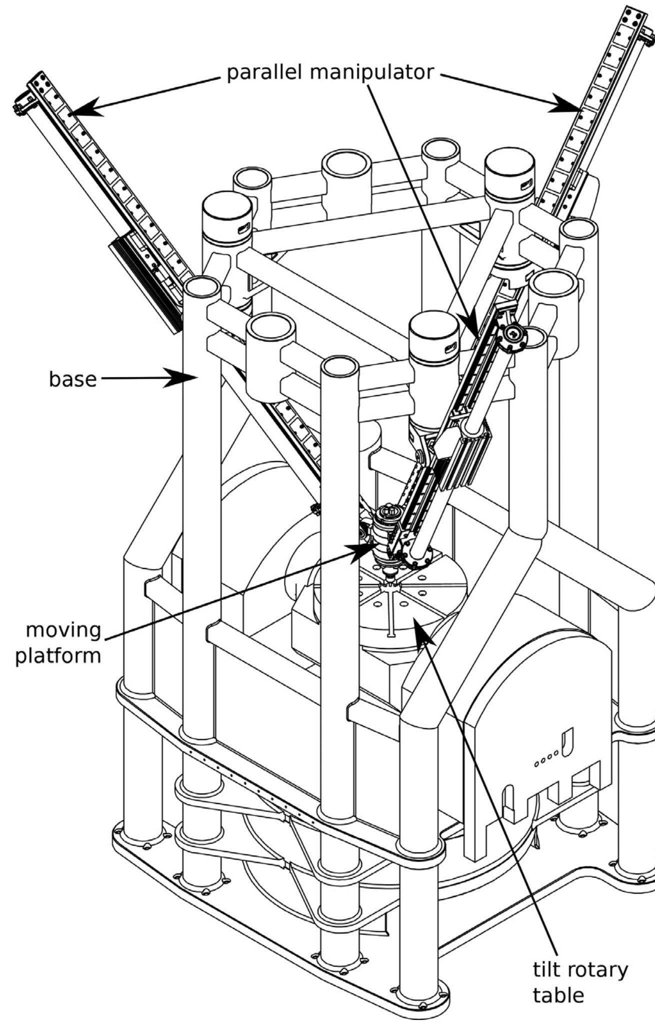

Fig. 1. Scheme of the 5-DOF hybrid manipulator.

The main joint axis is always perpendicular to the base, which is provided by appropriate location of revolute joints axes [20] and the original construction of the main triple joint [21]. Because the tool is attached directly to the main part of the triple joint, this has a direct impact on its orientation in space. The triple joint consists of one main and two auxiliary elements. Auxiliary elements are identical and inverted by 180 degrees. The arrangement allows rotation of elements around the main axis of the moving platform. To each element an additional revolute joint is attached with the axis rotated by 90 degrees and offset by a constant distance to the main axis. The use of such an arrangement with revolute joints significantly increases the ease of its manufacturing, and allows the use of standard rotating elements. The asymmetry of auxiliary elements and their respective positioning allows for attachment of three limbs at the same height. This has further effect on elimination of adverse bending torques and on simplification of the manipulator kinematics equations.

The tilt rotary table (Fig. 5) consists of a base, a tilting part and a rotary table. The tilting part is mounted on the base and can be inclined by ±180° from the horizontal position of the table. The ø 400 mm rotary table with an unlimited rotation angle is mounted in the tilting part. Both axes are actuated by PMSM direct drives and angular position is measured by optical absolute encoders of the 18-bit resolution.