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Letter to Editor

Comments on "Design and analysis of a totally decoupled 3-DOF spherical parallel manipulator" by D. Zhang and F. Zhang (Robotica, Available on CJO 19 Nov, 2010, doi:10.1017/S026357471000652)

D. Zhang and F. Zhang[1] addressed the issue of designing and analyzing totally decoupled 3-DOF spherical parallel manipulators (SPMs) and concluded that the SPMs in Figs. 5(a) and 5(b) of ref. [1] are completely decoupled and fully isotropic (see Abstract, Section 5, and Conclusions in ref. [1]). This topic is of great interest to researchers working in the general area of parallel mechanisms. However, we disagree with the authors of ref. [1] on their conclusion. The supporting arguments are detailed below.

First, we will show that, for the presented SPMs, the following set of *linear* input–output kinematic equations (see p. 6 in ref. [1]), on which the conclusions in ref. [1] are based, is incorrect, although the first equation of this equation, namely $\theta_1 = \alpha$, is correct.

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} \alpha \\ \psi \\ \varphi \end{bmatrix}, \qquad (1)$$

where θ_1, θ_2, and θ_3 are the actuator joint angles and α, ψ, and φ form a set of Euler angles representing the orientation of the end effector (output).

In fact, it is noted that the SPM in Fig. 5(a) of ref. [1] is identical to the Agile Eye[2,3], while the SPM in Fig. 5(b) of ref. [1] is a nonoverconstrained variation of the same robot[4,5]. The latter may be useful in certain cases. It has been shown in the literature (see refs. [6–9], for example) that the Agile Eye has a set of *nonlinear* input–output kinematic equations. Even though one may derive a formula that produces a unique current solution to the forward displacement analysis [9], the set of input–output kinematic equations of the Agile Eye is still nonlinear. The solutions given in refs. [7, 9] have been verified and implemented in the control of the Agile Eye in the Robotics Lab at Laval University, Canada. Accordingly, the linear relation in Eq. (1) does not hold for the Agile Eye and the alike. The misconceptions at the basis of Eq. (1) might be due to the misunderstanding or misuse of Euler angles by the authors of ref. [1]. They correctly found that $\alpha = \theta_1$ by setting $\mathbf{w}_1 \cdot \mathbf{v}_1 = 0$, but from here they also inferred that $\psi = \theta_2$ and $\varphi = \theta_3$ (p. 6 of ref. [1]), which is wrong. By expanding $\mathbf{w}_2 \cdot \mathbf{v}_2 = 0$ and $\mathbf{w}_3 \cdot \mathbf{v}_3 = 0$, they would have derived the correct set of nonlinear equations. Although the authors of ref. [1] mention that "The decoupled motion has been validated by the simulation conducted in Pro/Engineer (PTC) as shown in Fig. 7" (p. 6 of ref. [1]), the Euler angles might not have been measured in the simulation since no relevant data on the Euler angles are given in ref. [1]. Otherwise, they should have found that Eq. (1) is wrong.

Then, we will prove that the SPMs in Figs. 5(a) and 5(b) of ref. [1] are neither completely decoupled nor fully isotropic. From the literature (see refs. [10–17], for example) on fully decoupled and isotropic parallel manipulators, we learn that one necessary condition for a parallel manipulator to have decoupled and constant input–output velocity transmission ratios is that it must exhibit a set of linear input–output kinematic equations. However, as shown above, the set of input–output kinematic equations of the Agile Eye and the alike is nonlinear. Therefore, with reference to the SPMs in Figs. 5(a) and 5(b) of ref. [1]: (a) the motion is not decoupled; (b) the Jacobian matrix is not unit (p. 6 in ref. [1]); (c) the workspace is not cubic (p. 7 and Fig. 9 in ref. [1]); (d) the stiffness matrix is not constant (Section 6 in ref. [1]); (e) the manipulator is not singularity-free (see Abstract, Introduction, and Conclusions in ref. [1]). It is clear from the above cited literature that the mechanisms of Figs. 5(a) and 5(b) of ref. [1] do not have such properties. Furthermore, the 3-DOF SPM in Fig. 5(c) of ref. [1] is improper, since the leg (or limb) composed of one revolute joint and one spherical joint degenerates into a spherical joint.

Indeed, when the output link has more than one rotational freedom and only holonomic joints are employed, it is impossible to generate decoupled and configuration-independent relations between the rates of the actuators and the components of the output-body angular velocity[17]. The best that one may attain is to achieve relations of this sort between the motor speeds and the time derivatives of the Euler angles describing the end-effector orientation, which is equivalent to converting the kinematics of a closed-chain rotational device into that of a serial spherical chain. However, while such a solution potentially rules out the singularities of the forward kinematics, it has no effect on the singularities of the inverse kinematics, which are inherent to the serial chain. In the case of the Agile Eye and thus of the wrist studied in ref. [1], the latter singularities occur when the axes of the revolute joints in any one of the legs become coplanar. In this situation, the platform looses one rotational freedom and it may resist a torque component with zero actions by actuators. This observation confirms that the input–output static relationships of the examined wrist *are not* invariant and that homogeneous stiffness is not achieved. Indeed, Gosselin and Lavoie[6] showed that this device is isotropic only in a limited set of configurations.

It is worth emphasizing that even those mechanisms that actually exhibit constant input–output transmission relationships are, *a priori*, neither characterized by uniform kinetostatic behavior nor free from singularities. In fact, while the forces and velocities produced by the actuators may be available on the end-effector unscaled and undistorted throughout the workspace, the same cannot be said in general for the forces and velocities transmitted within the mechanism, which may remarkably vary during the movement and even rise to unacceptable values in the proximity of an *increased-instantaneous-mobility* singularity[17].

Finally, recent advances in the type synthesis of parallel manipulators (see, for instance, the studies in refs. [5, 10, 15–19]) have been ignored by the authors of ref. [1]. It is well known that any synthesis approach that is exclusively based on *infinitesimal-mobility* criteria is ineffectual. It is a trivial task (by screw theory or elementary linear algebra) to arrange the joints of a manipulator in order to obtain, for a *specific* configuration, desirable forms of the Jacobian matrices of the forward and inverse kinematics. However, *nothing guarantees that the properties that hold for one configuration keep holding for full-cycle motions of the robot*. Indeed, passing from attributes of the infinitesimal motion to finite-displacement properties requires additional constraints and more complex arguments, unless special screw systems apply[20–22].

In summary, a number of claims in ref. [1] are incorrect and should be revised. Accordingly, the contribution of ref. [1] lies in the development of a nonoverconstrained variation of the Agile Eye[2,3], rather than in the design of fully decoupled and isotropic SPMs. The misconceptions in ref. [1] could have been avoided by a review of the relevant literature (see the list of references at the end of this letter) and/or a thorough verification of the kinematics of the prototype proposed by the authors.

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