Closure to “Discussion of ‘Kinematics of a New High-Precision Three- 
Degree-of-Freedom Parallel 
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Background

The manipulator discussed in the paper titled “Kinematics of a New High-Precision Three-Degree-Of-Freedom Parallel Manipulator” [1] is a three-degree-of-freedom simplification of a six-degree-of-freedom parallel manipulator, which is protected by a US patent [2]. Between 1991 and 1995, late Professor Lung-Wen Tsai and I published several papers on various aspects of this six-degree-of-freedom manipulator [3–8]. It is important to note that all of these papers [3–8] were published prior to each and every reference mentioned by the commentary of Carretero et al.

Having used the six-degree-of-freedom manipulator [2–8] for some optical alignment tasks, I came across other applications in which only tip, tilt, and piston motions are important (e.g., alignment of Fabry-Pérot interferometers). So, the manipulator in US Patent No. 5279176 [2–8] was simplified to obtain tip, tilt, and piston outputs using only three base-mounted linear actuators (instead of three bidirectional drivers for the six-degree-of-freedom version) [1].

Responses to Commentary

I was not aware of the papers published by Carretero et al. [9–11]. The kinematics portions of these papers are similar to each other. If I knew of Ref. [11], I would have referred to it in Ref. [1].

In their commentary, Carretero et al. object to the term “new” in the title of Ref. [1] and claim that their work in Refs. [9–11] is “seminal.” However, in the “Mechanism Architecture” section of Ref. [10], Carretero et al. admit that “The architecture can be viewed as a 3-dof version of the 6-dof mechanism proposed by Tahmasebi and Tsai 1995, obtained by constraining the actuators to move radially from a point on the base plane.” In my opinion, as long as the six-degree-of-freedom manipulator is protected by a US patent [2], referring to it or its three-degree-of-freedom simplification as new is appropriate. I respect the views of those who may not agree with my opinion. It is important to note that although Refs. [9–11] discuss kinematics and optimization, Carretero et al. refer only to the paper, which discusses stiffness of the six-degree-of-freedom manipulator [3], and do not mention the much more relevant papers in Refs. [4–6].

It is well known that the direct kinematics of a parallel manipulator is much more difficult to solve than its inverse kinematics. A good discussion of this topic can be found in Ref. [12]. Researchers have published numerous papers in obtaining closed-form solutions for direct kinematics of parallel manipulators. Many good examples are cited in Refs. [1,4]. The purpose of Ref. [1] is to present closed-form solutions for the direct and inverse kinematics of the three-degree-of-freedom simplified manipulator. It is important to note that in Refs. [9–11], Carretero et al. have not offered any closed-form direct kinematics solution. In fact, in their Forward Kinematics subsection of Ref. [9], Carretero et al. state that “This problem is more complicated than the inverse kinematics problem because (a) it usually has no closed form solution and so requires the use of iterative numerical methods for its solution, and (b) it admits multiple solutions.” Obviously, it has been shown in Ref. [1] that the three-degree-of-freedom simplified manipulator has a closed-form direct kinematics solution.

The article published by Tsai et al. in 2003 [13], which is cited in Ref. [1], presents a closed-form direct kinematics solution for a 3-PRS parallel manipulator in which ball screws are used to move the lower ends of the legs perpendicular to the base platform (similar to Merlet’s MIPS (Miniature In-Parallel Positioning System) design [14,15]). The manipulator analyzed in Ref. [1] has a different architecture. Namely, the lower ends of its legs (limbs) can only slide on its base plane. The closed-form direct kinematics solution in Ref. [1] has been obtained independent of what is presented in Ref. [13]. It is important to note that back in 1992, Tahmasebi and Tsai used a methodology similar to that used in Ref. [1] for obtaining the closed-form direct kinematics solution of the six-degree-of-freedom minimanipulator [4]. It is not clear to me why one would want to transform the formulation in Ref. [13] to make it possibly work for the manipulator in Ref. [1], as suggested by Carretero et al.

In their commentary, Carretero et al. criticize the term high precision that is used in Ref. [1]. They also state that the small unavoidable twist and decenter (lateral) outputs of the manipulator are not discussed in detail. The high precisions of the manipulator discussed in Ref. [1] as well as the six-degree-of-freedom minimanipulator covered in Refs. [2–8] are due to the fact that their limbs are inextensible and their actuators are base mounted. As mentioned in Ref. [1], “The prismatic actuators move the lower ends of the limbs on the fixed base. Large movements at the lower ends of the limbs are needed to generate smaller movements at the top ends of the limbs, which are connected to the moving platform. This ‘motion reduction’ feature results in higher mechanical advantage.” Regarding the twist and decenter motions, the Introduction section of Ref. [1] states clearly that “The manipulator that is being analyzed in this paper is suitable for optical (and other types of) alignment applications where only tip, tilt, and piston motions are significant (e.g., alignment of segmented spherical mirrors, alignment of Fabry-Pérot interferometers).” This means that for such applications, the twist and decenter outputs are acceptable/tolerable. Again, the purpose of Ref. [1] is to present closed-form direct and inverse kinematics of the three-degree-of-freedom simplified manipulator, not to dwell on the small twist and decenter motions.

In my opinion, it was not appropriate to refer in Ref. [1] to all the workspace, dexterity, stiffness, and calibration papers that Carretero et al. refer to as “overlooked” in their commentary. Twenty nine books and papers, which are related to the closed-form kinematics topic of Ref. [1], are cited in it. In a single paper, one cannot discuss all the interesting topics that are related to parallel mechanisms.

Finally, Carretero et al. claim that the MIPS design of Merlet has been overlooked in Ref. [1]. This is not accurate. I have a lot of respect for the work of Merlet and in Ref. [1] I have referred to portions of his book [14] and one of his presentations [15] that discuss the MIPS mechanism.

References


