

Improving Dexterity and Workspace for 3-DOF Spherical Motion Telemanipulators

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Abstract

Telemanipulators are devices that consist of two main components: a control part (master) and an execution part (slave). They are widely used in various fields where remote control is necessary to manipulate objects or tools within a specific work area. The efficiency of a telemanipulator is often assessed by its degrees of freedom. In this study, starting from a telemanipulator featuring 3 degrees of freedom of pure spherical motion (previously presented by the authors), we propose three different mechanisms—both parallel and serial, spatial and planar—that, when appropriately combined with the spherical telemanipulator, can significantly expand the overall system's workspace. This expansion enhances efficiency and comfort for the operator. Finally, we compare the various systems based on their mechanical characteristics.

Keywords: Mechanisms, Spherical Motion, Telemanipulators, Minimally Invasive Surgery

1. Introduction

Telemanipulators have been used in various fields [1-3], especially in robotic-assisted and minimally invasive surgery (MIS) [4]. These systems consist of a master unit controlled by an operator and a remote slave unit that performs the tasks. These two units can feature a direct mechanical connection, which allows prompt action of the end-effector and inherent force feedback. On the other hand, the design and construction could be challenging.

We have recently presented a new master-slave device that features spherical motion with 3 degrees of freedom (DOFs) of rotation at the terminal tool [5]. These characteristics increase the efficiency of the operator, in particular for MIS applications, where the surgeon is requested to perform small rotation tasks with a fixed position of the end-effector. However, in this context, several applications require an additional device to guide and control the 3-DOF master-slave device position and orientation with respect to the object of the manipulation, which can be a general material or, in the case of MIS, the patient to be operated on.

In this paper, we present solutions that allow additional DOFs and control of the pose of the telemanipulator tool with respect to the frame. The general idea is to add a passive or active mechanism with 5 or 6 DOFs, which guides the tool frame. The main features of the master-slave

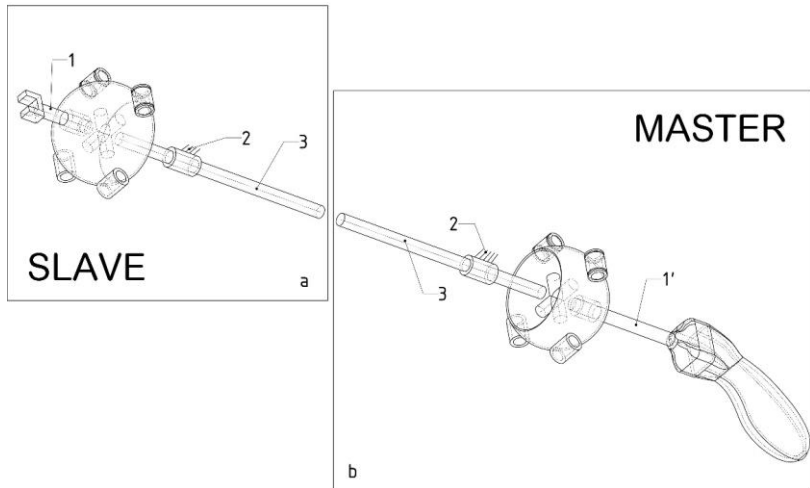


Fig. 1 Schematic of the master-slave mechanism

device are briefly recalled. Then, three different solutions of the positioning mechanism for the telemanipulator are presented, which satisfy different requirements on the tool guidance.

2. Master-slave device

In this section, we will revisit the device described in [5] as an example of a master-slave telemanipulator with 3-DOF spherical motion. However, alternative solutions can also be considered. Referring to Fig. 1, the telemanipulator primarily consists of two components: a master and a slave. Fig. 2 shows the slave component, which features two rollers (5 and 6) with mutually orthogonal axes that act on a sphere (4), allowing it to rotate around its center. This design enables the unit vector \mathbf{u} of the end effector (1), orthogonal to the sphere's surface, to be oriented within a cone that has an opening angle of approximately 75 degrees. The movement of the rollers is performed and controlled by the operator via a corresponding master sphere. As the operator rotates this master

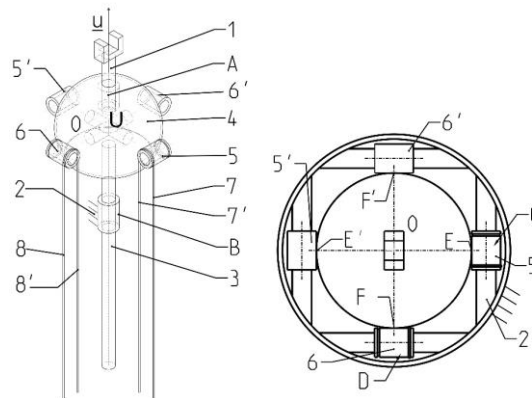


Fig. 2 Schematic (a) and top view (b) of the mechanism slave part. The master part is specular.

sphere, it generates the rotation of the two associated master rollers. These rotations are then transmitted through cables to the rollers 5 and 6 of the slave component.

A second part of the telemanipulator includes a double Cardan joint, with the centers of the crosses of the two Cardan joints aligned with the respective centers of the master and slave spheres. The intermediate shaft (3) connecting the two joints is fixed to the device's frame (2) by a revolute joint (B). The angular position of the input shaft of the master Cardan joint is controlled by the operator, while the output shaft of the slave Cardan joint is connected to the slave sphere via a revolute joint (A).

Link 1 serves as the terminal organ of the telemanipulator. Consequently, when the operator adjusts the input shaft (1'), he can transmit three independent rotations around three axes that pass through the center of the slave sphere. Thus, the system provides 3 DOFs of spherical motion that are directly controlled by the operator (master).

3. Guiding device

The operator must be able to control the position of the spherical center O (Fig. 2) in space. To facilitate the operator's work, it is also appropriate that the tool body, link 2 of Fig. 1, can be oriented with 2 DOFs, to avoid uncomfortable positions for the operator's hand. The guiding device, to be combined with the 3-DOF spherical motion telemanipulator, must, therefore, have 5 DOFs, i.e., 3 DOFs of translation and 2 DOFs of orientation. Decoupling between translations and rotations facilitates manipulability and allows these components to be controlled separately. In the following, unless otherwise specified, telemanipulator means the mechanism comprising the 3 DOFs spherical telemanipulator and the guiding device defined above.

3.1 Spatial parallel mechanism

A viable solution involves utilizing a translational parallel robot, which features a Cardan joint on the platform to control the orientation of link 2 in Fig. 1. Among the various translational robots available, the Tsai platform [6], also known as the 3-UPU parallel mechanism, is a convenient choice.

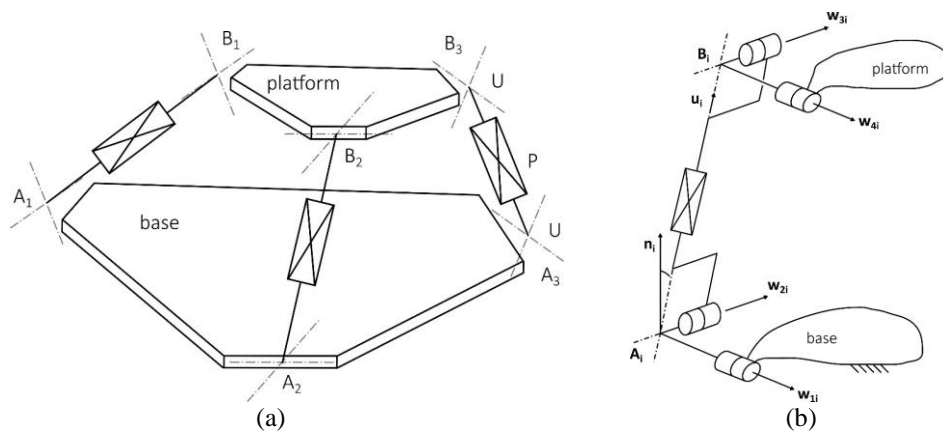


Fig. 3 Schematic of the Tsai 3-UPU manipulator (a), and *i*-th UPU leg

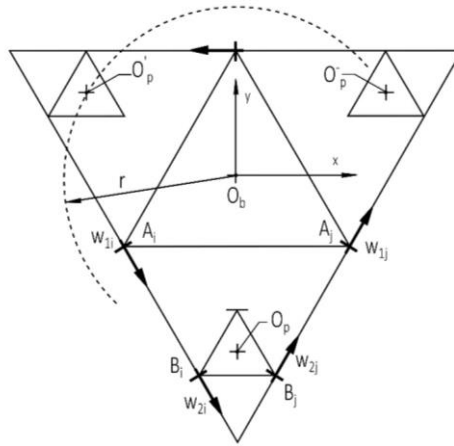


Fig. 4 Singularity positions. Singularity cylinder directrix of radius r and center O_b

The Tsai manipulator presents an interesting symmetric topology (Fig. 3a): both the base and the platform are equilateral triangles, $A_1A_2A_3$ and $B_1B_2B_3$, respectively, interconnected by three independent serial legs of type UPU, where U stands for universal and P for prismatic joint. The arrangement of these legs ensures the pure translation of the platform, provided that specific manufacturing and assembly criteria are met. These conditions dictate that in each leg, the axes of the two intermediate revolute pairs must be parallel to each other, and similarly, the axes of the two terminal revolute pairs must also be parallel (Fig. 3b).

It is important to highlight the workspace of the platform that is free from singularities. Referring to Fig. 4, which shows a top view of the Tsai mechanism, it can be demonstrated that the mechanism is in singularity when the axes of two revolute pairs of the mobile platform are projected onto the corresponding axes of the two revolute pairs of the base, namely when the center O_p of the mobile platform is at the three different positions O_p , O'_p , and O''_p [7]. Furthermore, when the point O_p is projected inside the circumference of diameter $2r$, defined by the three points O_p , O'_p , and O''_p , the mechanism is free from singularities. This condition does not depend on the distance of the mobile platform from the base, indicating that the space within the right cylinder of diameter $2r$ represents a singularity-free workspace. In reference to Fig. 5, frame 2 of the spherical telemanipulator with 3 DOFs depicted in Fig. 1 can be connected to the mobile platform of the Tsai mechanism using a Cardan joint (U). Consequently, point O (shown in Fig. 2), which represents the spherical center of motion of the slave part of the telemanipulator in Fig. 1, can be positioned at the desired point in space using the 3 DOFs of the Tsai mechanism. The orientation of link 2 can be adjusted by the operator through joint U, resulting in a 5-DOF guiding device. Additionally, the telemanipulator in Fig. 1 retains 3 DOFs that enable pure spherical motion. Thus, the overall system can be viewed as a telemanipulator with a total of 8 DOFs, featuring a terminal link with pure spherical motion.

This solution meets the proposed requirements. However, it is important to note that in this system, the axial translation of the tool is not independent of the movement of the platform. This may be a limitation in certain applications, as some telemanipulation devices require the capability for free axial translation of the tool following positioning relative to the target.

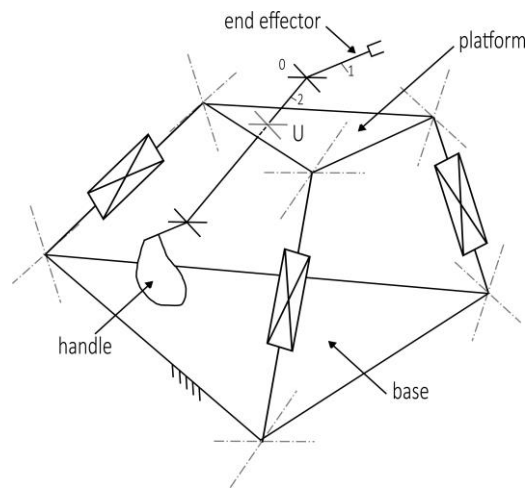


Fig. 5 Telemanipulator with 3 translational (3-UPU), 2 rotational (U) and 3 spherical motion (3R) DOFs of the end effector 1

3.2 Planar mechanism

To address the issue mentioned at the end of the previous section, a second solution involving a planar mechanism, either parallel or serial, can be utilized.

3.2.1 Planar parallel mechanism

In reference to Fig. 6, a 6R planar mechanism can be utilized, where R denotes a revolute kinematic joint. Link 3 of this mechanism has 3 DOFs relative to frame 6. By connecting link 2 of the telemanipulator shown in Fig. 1 in series with link 3 of the 6R mechanism using a Cardan joint U and a prismatic joint P, with P oriented orthogonally to the plane of the 6R mechanism, a telemanipulator that incorporates a total of 9 DOFs can be created.

It is important to note that during the operation of the telemanipulator, the rotation of link 3 represents a redundant rotation. This redundancy must be compensated by adjusting the rotation of

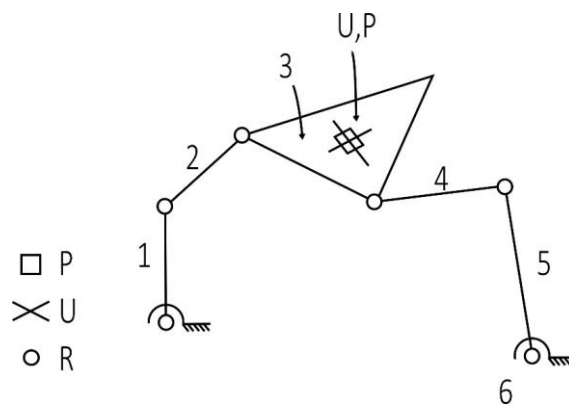


Fig. 6 Telemanipulator with 3 planar (6R), 2 rotational (U), 1 translational (P), and 3 spherical motion (3R) DOFs of the end effector 1

the knob (shown in Fig. 5) of the telemanipulator in Fig. 1. In other words, the rotations of link 3 of the 6R mechanism and of link 3 of the spherical telemanipulator in Fig. 1—specifically, the intermediate shaft of the double Cardan joint—provide the same rotational DOF.

The problem can be addressed using a corresponding 5R mechanism and connecting frame 2 of the spherical telemanipulator to link 2 of the 5R mechanism. However, a potential drawback is that the translation of the spherical device is linked to a complex motion of the 5R mechanism.

3.2.2 Planar serial mechanism

Instead of using the parallel mechanism 6R shown in Fig. 6 (or the corresponding 5R), we can opt for a serial mechanism of type RR that has similar kinematic properties. In this design, the second mobile link (akin to link 2 of the 6R mechanism in Fig. 6) possesses 2 DOFs relative to the frame. By connecting frame 2 of the telemanipulator illustrated in Fig. 1 to link 2 of the RR mechanism using a P and U joint, we can achieve the desired telemanipulator configuration. This setup results in a total of 8 DOFs, thereby eliminating the redundancy in the system's rotations that was present in the previous configuration.

A notable difference between the parallel and serial solutions is that the parallel mechanism exhibits greater stiffness, while the serial mechanism offers a larger workspace.

3.3 Planar translational mechanism

To eliminate the redundancy of the two rotations highlighted in the solutions presented in the previous section while maintaining a simple motion of the link connected with the spherical device, a planar translational mechanism can be used to be appropriately integrated with the telemanipulator in Fig. 1. Also in this case, a parallel or serial mechanism can be used.

3.3.1 Planar parallel translational mechanism

In reference to Fig. 7, a parallel mechanism can be utilized that consists of a mobile link (the platform of the mechanism) connected to the frame by two branches, each featuring two parallelograms (Pa)

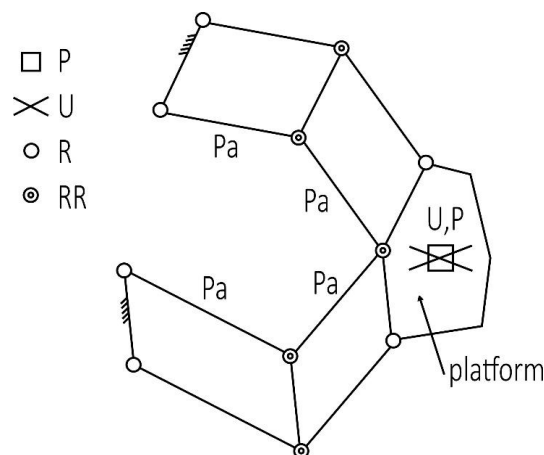


Fig. 7 Telemanipulator with 2 planar (2-PaPa), 2 rotational (U), 1 translational (P), and 3 spherical motion (3R) DOFs of the end effector 1.

in series. This mechanism can be classified as a 2-PaPa type planar parallel mechanism. It is straightforward to verify that the mobile platform of the mechanism possesses 2 DOFs that allow for pure translational movement within the plane of the parallelograms.

Additionally, the connection of frame 2 of the telemanipulator (Fig. 1) to the platform of the 2-PaPa mechanism—configured in series with a P and a U joint—achieves a system similar to that described in the previous section. However, this setup eliminates the issue of redundancy associated with the two rotational movements.

3.3.2 Planar serial translational mechanism

As in the previous section, the 2-PaPa parallel mechanism can be replaced by a serial PP mechanism that is kinematically equivalent. The telemanipulator shown in Fig. 1 can be connected in series to the terminal link of the PP mechanism using a P and U joint, as described earlier. This setup results in a telemanipulator with the necessary characteristics, utilizing 5 additional DOFs alongside the 3 DOFs of the telemanipulator in Fig. 1. In this arrangement, there are no redundant DOFs.

From a kinematic perspective, this system is equivalent to the one depicted in Fig. 6, but it differs in the positioning of point O (Fig. 2). Here, the center of the spherical motion of the telemanipulator's terminal link is achieved through three P joints that enable completely decoupled motion.

As with the previously discussed cases, a significant distinction between the parallel 2-PaPa mechanism and the serial PP mechanism lies in their stiffness and workspace. The parallel mechanism has greater stiffness, while the serial mechanism offers a larger workspace. Additionally, the solution featuring PaPa legs uses preferably revolute joints.

4. Conclusions

In this study, three different solutions were proposed to enhance the workspace of a telemanipulator with 3 DOFs of pure rotation. These solutions aim to promote a more efficient and comfortable user experience.

The mechanical characteristics of these proposed solutions were compared synthetically. The 3-DOF telemanipulator with spherical motion, which serves as the reference for this work, was introduced in a previous study by the authors. The three new solutions, which utilize both planar and spatial mechanisms—incorporating appropriate parallel and serial connections with the telemanipulator—constitute the original contribution of this study.

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