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Design of a compensation mechanism for an active cardiac stabilizer based on an assembly of planar compliant mechanisms

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Résumé :

Dans cet article, nous présentons la conception d'un mécanisme de compensation pour un stabilisateur cardiaque actif, composé de mécanismes compliant plans et d'actionneurs piézoélectriques. L'utilisation de mécanismes compliant plans facilite leur fabrication et favorise la compacité du dispositif. Recourir à des architectures parallèles pour la conception de mécanismes compliant permet généralement de disposer de propriétés de rigidité intéressantes. Cependant, la configuration plane des manipulateurs parallèles est souvent singulière. C'est pourquoi deux approches de conception de mécanismes compliant plans sont exploitées dans cet article. Une première approche consiste à explorer le voisinage de la singularité en introduisant des asymétries lors de la fabrication. Une seconde approche consiste à profiter de la singularité afin d'obtenir des architectures originales de mécanismes. Le dispositif complet à base de mécanismes compliant plans est présenté, et ses performances sont discutées.

Abstract :

In this paper we present the design of a compact active cardiac stabilizer based on planar compliant mechanisms and piezoelectric actuators. Considering an assembly of planar manufactured structures helps to simplify the manufacturing process and may increase the compactness. Parallel architectures constitute interesting solutions for their intrinsic stiffness properties, but in a planar configuration parallel manipulators often exhibit kinematic singularities. Two design approaches for planar parallel compliant mechanisms are presented in this paper. One design approach consists in designing a passive compliant mechanism in a configuration close to the singularity by introducing some asymmetries during the manufacturing process. The second design approach consists in taking advantage of the singularities of parallel manipulators to obtain non-trivial solutions. The new proposed active stabilizer, composed of planar compliant mechanisms, is introduced and its performances are discussed.

Keywords : Compliant mechanism ; active cardiac stabilizer ; mechanism design

1 Introduction

Surgical robotics helps to increase the surgeon's accuracy and limits the invasiveness of the surgery. The complexity of an operation room implies to design surgical devices that are as compact as possible and that can be easily sterilized. One interesting design approach is to combine compliant mechanisms, which have a monolithic structure, and piezoelectric actuators [11, 4]. Based on this approach, a robotic device for minimally invasive coronary artery bypass grafting has been proposed previously in our laboratory [1]. It is composed of a shaft with two fingers in contact with the heart at one end, and an actuated compensation mechanism at the other end. The latest prototype, the *Cardiolock II*, is illustrated in figure 1. This device successfully helps to increase the stabilization of the beating heart surface during the surgery but its compactness needs to be increased for an optimal integration in the operation room.

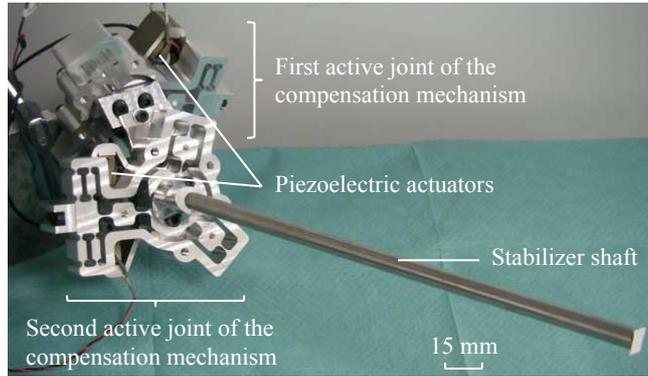


FIGURE 1 – The *Cardiolock II*.

One possibility is to reduce the size of the compensation mechanism by considering an assembly of planar manufactured structures. This helps to simplify the manufacturing process and may increase the compactness. Lamina emergent mechanism (LEM) [10] and ortho-planar mechanisms [12] are based on this principle. Compliant mechanisms can be designed with a so called kinematic approach, which consists in first selecting in the literature an architecture that answers to the kinematic requirements and then replacing each joint by a compliant joint using the pseudo-rigid body modeling [8]. In this paper, we follow this design approach. Therefore, in a first section, the kinematic scheme of the new compensation mechanism compatible with a planar decomposition is introduced. The joints are then designed as compliant structures, trying to use parallel compliant architectures for their intrinsic stiffness properties. In planar configurations, parallel manipulators often exhibit kinematic singularities [5]. To deal with these singularities, we consider in the first section two design approaches. One design approach consists in designing a passive compliant mechanism in a configuration close to the singularity by introducing some asymmetries during the manufacturing process. The second design approach consists in taking advantage of the singularities of parallel manipulators. The integration of the different components for the design of a compact device is presented in the second section. Finally, the active cardiac stabilizer composed of planar compliant mechanisms is presented and discussed in a third section.

2 Design of the different components of the active cardiac stabilizer

The stabilizer must be able to produce, similarly to the *Cardiolock II* device, displacements along the directions normal to the shaft axis to compensate for the flexibilities of the device and its mounting system. It is therefore a two degrees of freedom (DOF) mechanism, that will be actuated with piezoelectric actuators. One way to take advantage of the oblong geometry of the shaft is to decompose the compensation mechanism by distributing the mobilities into two planes, P_1 and P_2 , close enough to provide a high displacement amplification ratio. Thus, we propose to use the kinematic scheme represented in figure 2. The shaft is oriented with a spherical joint in O_2 and actuated with two prismatic joints in O_1 . A coupling mechanism composed of a universal joint and a prismatic joint allows to link the orientation and actuation mechanisms. Given the application requirements, the distance O_1O_2 must be less or equal to 12 mm. This constrains the design of the device components presented in the following part of the section.

2.1 Vicinity of singularities for the design of a planar compliant orientation mechanism

For the design of the passive compliant spherical joint in P_2 , we choose the architecture of the 3-RRR parallel spherical manipulator proposed by [7]. In the planar configuration, this manipulator is however in a singular configuration of type 1 and type 2 [2]. One approach used for LEMs in [9] is to design the 3-RRR compliant mechanism in the planar configuration and then to extract it to

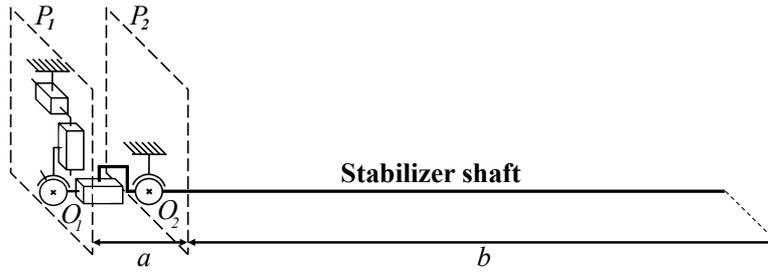
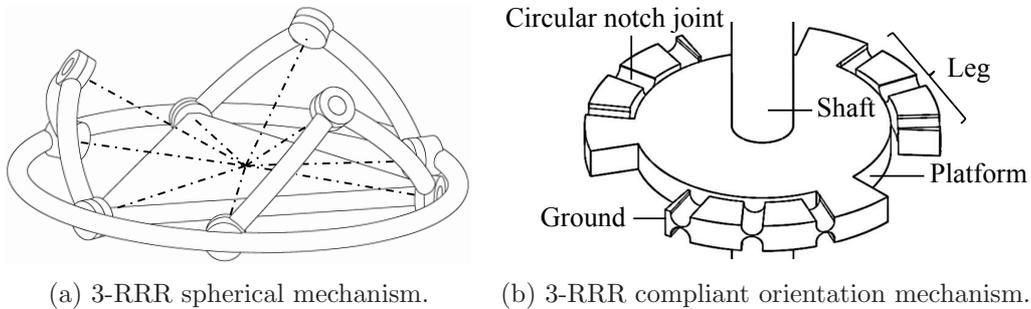


FIGURE 2 – Planar decomposition, kinematical scheme

its working configuration. The extraction process seems complex, since the mechanism needs to be precisely positioned in a configuration that is close to the planar configuration. We prefer to design a passive compliant mechanism in the configuration illustrated in figure 3a but close to the singularity by manufacturing the second revolute joints of each leg slightly out of the mid-plane. The modeling and the pre-dimensioning of the 3-RRR compliant orientation mechanism, illustrated in figure 3b, have been addressed in [16].



(a) 3-RRR spherical mechanism.

(b) 3-RRR compliant orientation mechanism.

FIGURE 3 – Planar compliant orientation mechanism obtained from a 3-RRR spherical mechanism.

2.2 Parallel singularities for the design of a planar compliant mechanism with RRP mobilities

For the design of the coupling mechanism in P_1 , we need two rotations (RR) around the in-plane axes in O_2 and one translation (P) along the shaft axis. We therefore choose the architecture of the 3-US parallel manipulator, illustrated in figure 4a, considered for foldable mechanisms in [13]. In the planar configuration, the 3-US parallel manipulator has the desired mobilities but is in a singular configuration of type 2. It means that the end-effector of the manipulator loses stiffness while its actuators are blocked. As compliant mechanisms only work around a given configuration, this loss of stiffness can be used to produce the required mobilities. The use of this kind of singularity has been considered for the design of 1-DOF compliant mechanism in [3, 14]. Here we want to obtain three mobilities from the singular configuration of the 3-US manipulator. The singularity analysis of the 3-US manipulator has been performed in [15] and has shown that a 3-UU planar mechanism, illustrated in figure 4b, has locally the desired RRP mobilities. Finite element analysis (FEA) shows that in-plane stiffnesses are 200 times greater than the out-of-plane stiffness, and the torsional stiffness is 400 times greater than the other rotational stiffnesses. The equivalent 3-UU compliant mechanism, illustrated in figure 4c, exhibits RRP mobilities.

2.3 Selection of an actuation mechanism

The coupling mechanism must be integrated in one of the two planes. As the 3-RRR compliant orientation mechanism will be integrated in the first plane, the coupling mechanism will be integrated in the second one. Therefore, the coupling mechanism will be integrated in the actuation mechanism.

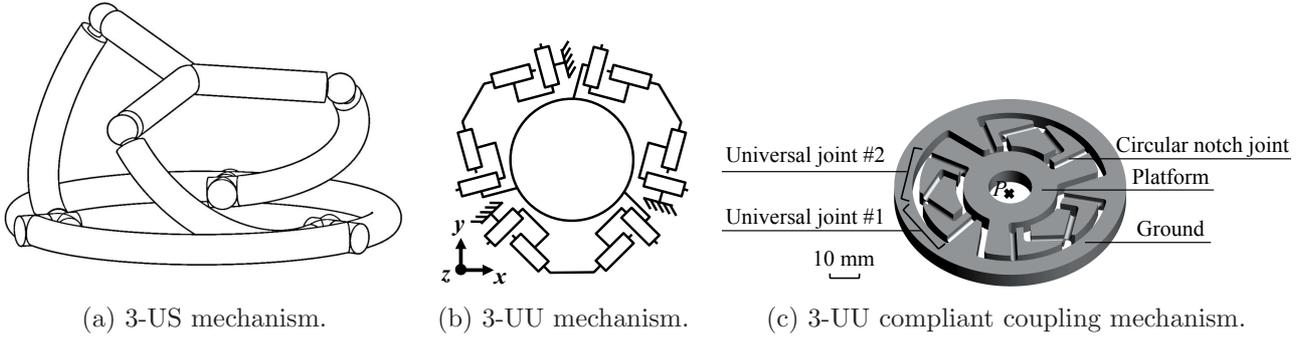


FIGURE 4 – Compliant coupling joint with RRP mobilities obtained from the singularity analysis of a 3-US parallel manipulator.

Among the 2-DOF planar parallel mechanism proposed in the literature, the 2PRR-RR mechanism proposed by [6] is particularly relevant : it has a planar geometry and it can integrate the coupling mechanism in its platform. As it will be actuated by piezoelectric actuators, it will only work around a given configuration. Considering q_1 and q_2 the actuators positions and x and y the cartesian coordinates of the platform point O_2 , the configuration illustrated in figure 5 allows, locally for small displacements, a decoupling and a direct transmission of the actuators to O_2 as shown by the Jacobian matrix in equation 1. As the ratio between the actuators displacements δx , δy and the distance B_3O_2 is high, the induced rotation $\delta\theta$ of the platform remains of small amplitude, and is therefore not a concern for the application.

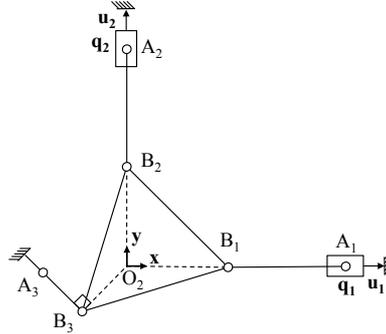


FIGURE 5 – Chosen configuration for the 2-PRR 1-RR actuation mechanism

$$\begin{pmatrix} \delta x \\ \delta y \\ \delta\theta \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ \frac{-\sqrt{2}}{2B_3O_2} & \frac{\sqrt{2}}{2B_3O_2} \end{pmatrix} \begin{pmatrix} \delta q_1 \\ \delta q_2 \end{pmatrix} \quad (1)$$

3 Integration of the three mechanisms in the two planes

The different components of the compensation mechanism must be integrated in only two planes. In the first plane, only the orientation mechanism must be integrated in contrary to the second plane which contains the coupling mechanism and the actuation mechanism. Therefore, we propose, in addition to the 3-RRR compliant mechanism, to integrate the two piezoelectric actuators in the first plane. Since the piezoelectric actuators need obviously to be linked to the actuation mechanism, the two compliant prismatic joints of the actuation mechanism are decomposed in two parts designed in the two planes with connecting elements in order to transmit the actuator forces from the first plane to the

second plane. This is illustrated in figure 6a, where the first machined plane is illustrated. It contains the 3-RRR compliant mechanism for the shaft orientation, the two locations for the piezoelectric actuators and the two half compliant prismatic joints for the force transmission with the second plane. In the second machined plane, illustrated in figure 6b, we can find the actuation mechanism with the embedded 3-UU compliant coupling mechanism. The two planes are assembled and maintained in position with dedicated connecting elements, screws and nuts.

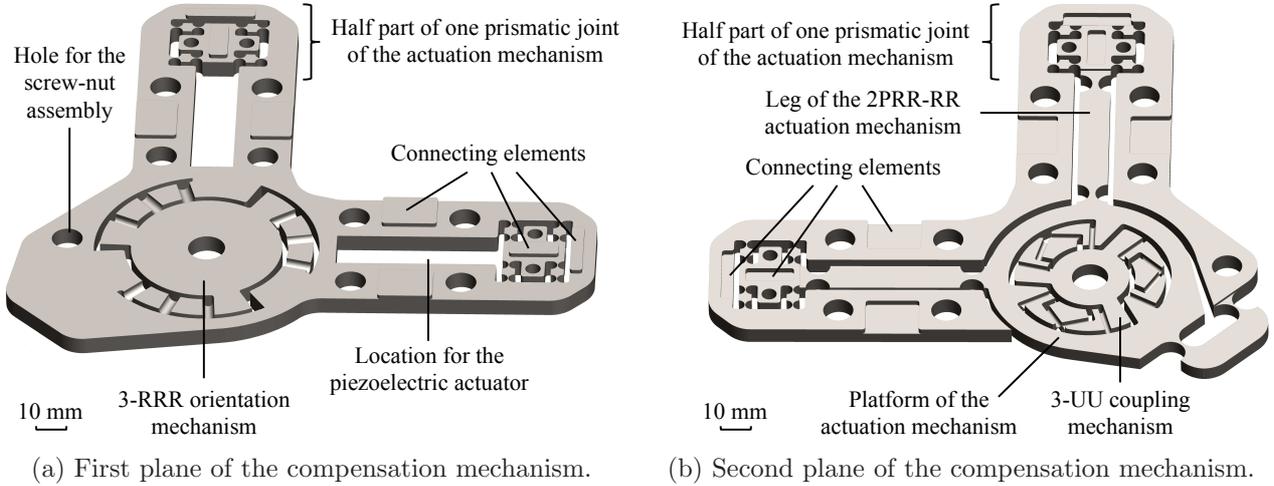


FIGURE 6 – Integration of the planar compliant mechanisms.

4 Results and discussion

The assembled device with its piezoelectric actuators is illustrated in figure 7a. It is first interesting to outline that the device is four times more compact than the previous one as illustrated in figure 7b. After a simple trial and error pre-dimensioning of the whole mechanism using FEA, we furthermore already obtain interesting performances. The presented design allows us to produce a displacement of 0.7 mm which is sufficient to compensate for the flexibilities of the device and the mounting system, according to [1].

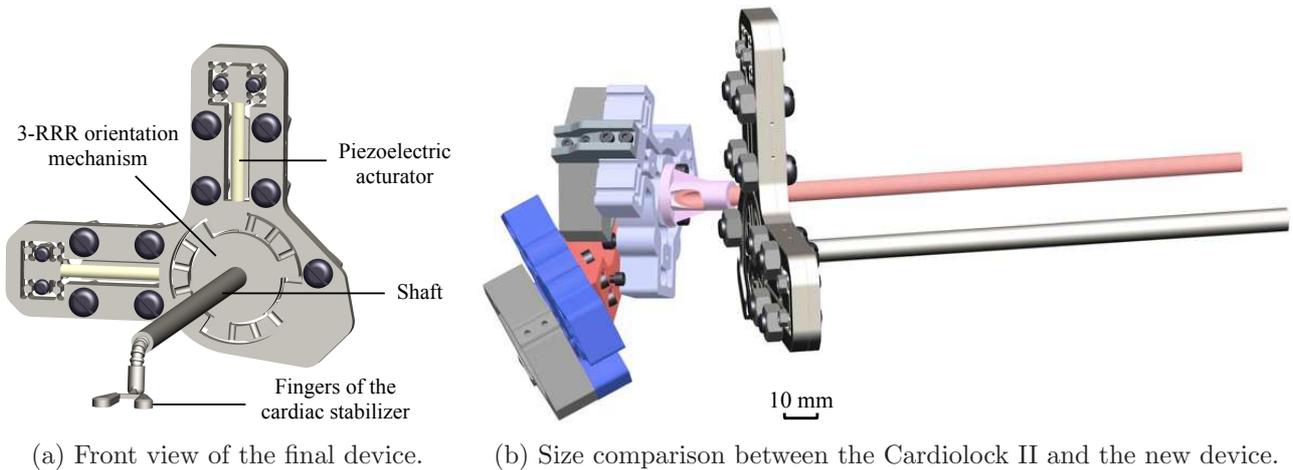


FIGURE 7 – Compensation mechanism based on planar compliant mechanisms.

5 Conclusions

In this paper we have presented the design of a 2-DOF compensation mechanism for an active cardiac stabilizer based on planar compliant mechanisms. To maximize the device compactness, planar structures are of interest. For parallel architectures, it may conduct to singular configurations. Two design

approaches are thus considered in this paper. Singularities are once avoided by introducing asymmetry in the manufacturing of the compliant structure. We have then taken advantage of the singularities to design a passive parallel architecture with interesting stiffness properties. The new proposed device has been presented, with encouraging performances and a significant improvement in the compactness as expected. Global modeling of the device needs now to be achieved in order to optimize the level of performances, as well as further experimental work.

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