Toward an MR-compatible needle holder with adaptive compliance using an active tensegrity mechanism

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1 Introduction

The field of MR imaging has extended from diagnosis to guidance and control in a wide variety of interventional procedures [1]. Due to the lack of space and manipulability within the MRI scanner, there is an ongoing interest for robotic assistance in MR-guided interventions. Numerous MR-compatible robots have been proposed, especially for needle manipulation.

For needle insertion in the liver, patient-mounted robots are particularly interesting for the provided partial compensation of the breathing motion. The needle holder must however still fulfill two contradictory requirements: it needs to be stiff during the insertion and compliant afterwards, in order to avoid organ lacerations [2]. This led to the development of needle grasping systems that allow the needle to move freely between two insertion phases [3].

In this paper, an alternate approach is considered: a needle manipulation system with adaptive compliance is proposed that is based on so-called tensegrity mechanisms. Numerous challenges related to MR-compatibility and compliance control could be overcome thanks to this recent class of robots, as outlined in the following through the design of a first device for needle orientation control.

2 Toward a needle holder using tensegrity mechanisms

2.1 Tensegrity mechanisms

Tensegrity mechanisms are derived from tensegrity structures. These structures are self-stressed systems comprising a set of compressed bars in a set of tensioned cables [4]. In tensegrity mechanisms, cables are replaced by springs and some components, either bars or springs, are actuated to control the mechanism configuration.

The components of a tensegrity mechanism are only axially loaded, so they can be lightweight as well as the system. In addition, tensegrity mechanisms can exhibit high workspace to size ratio, as demonstrated by their use in different deployable systems. They can be remotely actuated using cables so as to ensure MRI compatibility. Previous MR-compatible systems using cable-driven robots have shown the interest of this approach [5, 6]. Since tensegrity mechanisms are prestressed systems, their compliance can be adjusted through the control of the spring prestress without changing their configuration. Moreover, the stiffness variation can be achieved even when using linear springs [7]. Tensegrity mechanisms constitute therefore an interesting class of mechanisms for the design of compact and lightweight needle holder devices with adaptive compliance. Such a use is original to the best of our knowledge.

The position of the needle entry point can be computed in a preoperative period and registered through the position of the device on the patient skin before the insertion. The control of the needle orientation before and during the insertion is on the contrary challenging. As a consequence, we focus here our attention on the design of a device with two degrees of freedom in orientation.

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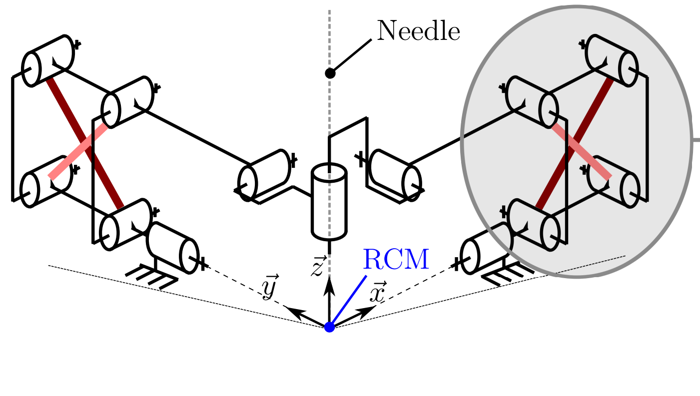
2.2 Design of a 2-DOF needle holder

In this application, four variables have to be controlled, namely the two DOF in rotation of the needle and the two angular compliances with respect to the rotation axes. For ease of use, a device with a Remote Center of Motion (RCM) is considered.

The kinematics of the proposed system are featured Fig. 1(a). The device is based on two perpendicular planar parallelogram linkages connected by a cylindrical joint. Each linkage controls one DOF in rotation of the needle, with a decoupling of the two DOF for an easy control.



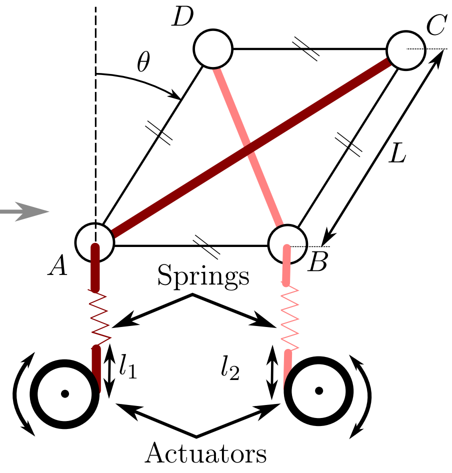


Figure 1: (a) RCM-based needle holder architecture, (b) Planar tensegrity mechanism based on parallelogram linkage.

As described in Fig. 1(b), each parallelogram linkage is a planar tensegrity mechanism articulated with cables connected in series with springs along the diagonals AC and BD. The configuration of the parallelogram, represented by the angle θ, is remotely controlled by changing the lengths (l_1, l_2) of the two cables. As two cables are used, the angle θ of the parallelogram is controlled together with the angular compliance through the springs prestress. In [8], an extreme case of this parallelogram mechanism is assessed using zero free length springs thus exhibiting a zero stiffness behavior.

In total, four cables are actuated providing four controllable variables for the entire device. The device is remotely actuated to ensure MRI compatibility.

The device geometry is being defined using an iterative design process. The length L is chosen equal to 70 mm in order to keep the device compact. The angular range is equal to $\pm 45°$. As a first step, only standard commercial linear springs are considered for the integration. The maximum compliance variation range is investigated by considering the maximum and minimum tensions in the springs for nominal working conditions.

3 Results and discussion

First simulation results show that a simultaneous control of the orientation and the compliance of the needle is feasible for the two DOF. Using standard commercial linear springs, the needle can be oriented on $\pm 45°$ along two directions, while modifying by more than 25% the level of compliance of the needle axis.

Such a compliance variation remains limited for the context. In order to improve the compliance range, an identification of adequate spring behavior is performed. Using non linear springs, the compliance variation range can be enlarged up to 300% for the given angular range. Several works exist on the design of such non linear springs (see [9] and references therein). The next step will now concern the design of efficient compliant elements for further implementation, and afterwards the design of an insertion DOF.

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