Compliant grasping device for robotized medical applications

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Résumé :

Cette communication présente le développement de dispositifs de préhension (NGDs) permettant la manipulation d'objets élancés tels que des aiguilles chirurgicales. Après avoir décrit les principales exigences imposées par les procédures médicales utilisant des aiguilles, un cahier des charges pour un NGD typique est établi. Quelques principes de solution sont alors générés, combinés puis classés pour aboutir à un ensemble de variantes de solutions. L'étude de conception et de modélisation d'un NGD à corps flexibles est ensuite présentée. Le comportement mécanique de ce mécanisme compliant agissant sur le corps d'une aiguille est simulé par une analyse EF incluant un modèle des non-linéarités induites par les grandes déformations et le contact entre l'aiguille et le dispositif de préhension. Des prototypes fonctionnels de deux variétés de NGD, l'un construit à partir de solides rigides, l'autre, avec des pièces compliantes sont expérimentalement évalués et qualifiés.

Abstract :

This paper presents the development of NGDs (needle grasping devices) capable of handling elongated objects such as surgical needles. After describing the main demands of medical needle-based procedures, a requirement list for a typical NGD is presented. Some solution principles for a grasping device are generated, combined and then classified to obtain a set of principle variant solutions. The design study of one device candidate constructed using compliant parts is then presented. The mechanical behavior of this compliant mechanism acting on a needle barrel is simulated with a FEM analysis including the model of non-linearities induced by large deformations and the contact between the needle and the grasping device. Functional prototypes of both rigid and flexible NGDs have been constructed and a first experimental assessments of their service capability are finally exposed.

Mots clefs : **dispositifs de préhension; mécanismes compliants; robotique médicale**

1 Introduction

Grasping and manipulation of surgical needles represent a very common concern in many medical specialties involving image guided needle insertions. This paper presents the development of two grasping devices capable of handling such elongated objects. More specifically, the principal motivation of the proposed work originates from the need to insert needles in the context of interventional radiology. In this medical specialty, minimally invasive procedures are performed to diagnose or treat pathologies under image guidance. The medical interventions targeted by the devices presented in this paper encompass the wide class of procedures that necessitate needle insertion such as biopsies, radiofrequency ablations or cancer local delivery treatments.To ensure a proper safety level in the procedures visual feedback is mandatory to monitor the instrument insertion. Among the various imaging modalities available, computed tomography (CT) and fluoroscopy provide a fast and accurate visual feedback to the radiologist and are now very widely used in medical routine. However, repeated CT and fluoroscopy endanger physicians with potentially harmful ionizing radiations. That is the main motivation for developing teleoperated robotic assistant to remotely insert needles under CT guidance.

A possible layout of teleoperated percutaneous procedures was presented in [4]. It is composed of a master station protected from the radiation source and operated by the physician using an haptic interface. At the remote site, the slave station comprises the CT scanner, the patient and the robotic assistant dedicated to the percutaneous procedure. This layout enables the radioprotection of the medical staff but also provides the practitioner with an haptic feedback on the insertion task which is highly desirable for safety reasons. As a consequence, the development of NGDs is an important subject for the targeted application on which the present paper focuses upon.

2 Requirements stemming from the targeted application

The available space between a CT-scan ring and a patient is a prominent limiting factor. The corresponding volume corresponds typically to a 200 mm radius hemisphere which is just slightly higher than the length of most biopsy needles. Consequently, the grasping device size should be as small as possible. In addition, it would be beneficial to comply with existing surgical needles, in terms of diameter and length, and thus avoid the use of device specific needles. Another important feature for the NGD is the capacity to allow a wide aperture around the needle when opened as well as to get the needle centered during re-grasping of the needle. This demand originates from the fact that the needle insertion is not a one step task. Indeed to avoid internal tissue laceration and improve gesture accuracy, the insertion motion itself is generally done during a short patient's apnea. After that, the non-inserted part of the needle requires to be released to comply with the motion exerted by the internal perforated organs. At this stage the needle should move freely off a central position about the entry point on the patient's skin. To perform the following insertion step the grasping device should be capable to re-center and re-grasp the needle. One optional but very desirable feature of the grasping device corresponds to the possibility of rotating the needle about its axis to facilitate the needle steering. On the side of force transmission, the grasping device should sustain a maximum insertion action of 15N (value determined experimentally) and allow haptic feedback, more precisely, be compatible with real-time insertion force measurement. To avoid needle deterioration the grasping device should ideally incorporate a grip limiting scheme. Concerning the material requirement, the grasping device should not generate artefacts in CT scanner images. And the concluding items in this requirement list are the safety and sterilization properties pertaining to the medical context. Systems dedicated to needle manipulation are very scarce in literature and use mostly opposing rollers to perform simultaneously the needle grasping as well as its insertion motion (e.g. Refs [7, 9]). This working principle makes it very difficult to measure axial insertion force. To add this important functionality, it seems necessary to uncouple the needle displacement from its grasping. This issue has been addressed in the system developed by Badaan *et al.* [1], but the proposed embodiment does not provide a controlled feature for recentering and gripping back the needle during insertion. This functionality was included in the NGD described in [4] as well as in the further developments presented in the following sections.

3 Needle grasping device design

3.1 Problem Statement and Solution Principles

To establish the functional structure of a NGD, mainly four elementary subfunctions are considered, which can be formulated as (1) put obstacles around the needle, (2) move obstacles radially, (3) transmit motion to the obstacles and (4) actuate moving obstacles. This decomposition tends to formulate the essential problems at a higher level of abstraction in order to leave open possible solutions and make a systematic approach easier [3]. Several solution principles fullfiling NGD subfunctions can be derived using this functional decomposition. A descriptive list of such solution principles has been detailed in [5] and can be used to classify existing gripping devices.

The initial two grasping devices developed in prior research [6, 4] were solely composed of rigid bodies. Even if this type of NGDs finally presented the required functionalities this rigid-body approach implies the construction joints between small rigid parts with the inherent issues of manufacturing precision or mechanical slack. As a workaround, we modified the design to include compliant parts which helped to improve the overall NGD functioning.

Following sections detail mainly the modeling and design relative to one NGD based on flexible bodies. Its qualification in terms of grasping capability will be presented and compared to that of the rigid-body NGD in section 4.

3.2 Flexible-Body NGD

The design candidate that is considered here uses thermoplastic flexible parts. In this design variant the number of moving obstacles is increased to three in comparison with the rigid-body NGD described in [4]. As indicated in Figure 1, constituting parts of this NGD include a main body on which, three flexible jaws equipped with high grip neoprene pads, are hinged. Each jaw is then connected to the gear via a pin joint. Simultaneously, the gear is guided in rotation with respect to the main body part. The implementation of this design candidate requires the use of spatial arrangement of the joints at the end of each jaw. The geometry of the jaw has been iterated to provided two interrelated models, namely a pseudo-rigid-body model [2] and the corresponding flexible and monolithic form of the model as described in Figure 1 and 2i.

3.2.1 Flexible-Body Modeling

When considering the jaws as deformable bodies, the closing of the NGD causes a coordinated motion and deflection of the three jaws around the needle. In the case of thermoplastic parts such as those considered in this NGD, the low material stiffness and yield strength could create the conditions for nonlinear behaviors to occur [8]. However, in the proposed NGD design, the dominant source of non-linearities comes from geometry and the occurrence of contact conditions between the jaws and the needle. Thus, it is assumed here that the problem includes mainly geometric and contact nonlinearities and can be consistently solved using linear material behavior. As a result, the large displacement imposed to the jaws generates stresses and strains on the deformable parts which need to be calculated to check both the NGD's functionality and the parts failure. For this purpose, two operating phases for the modeling of the flexible NGD are considered : i) the motion of the jaws in free space during the NGD closing and ii) the interaction with the needle barrel during the grasping itself. This loading scenario requires the modeling of large strains induced by the large displacement of the jaws rotated by the gear. This problem has been solved with a nonlinear FEA code allowing contact analysis.

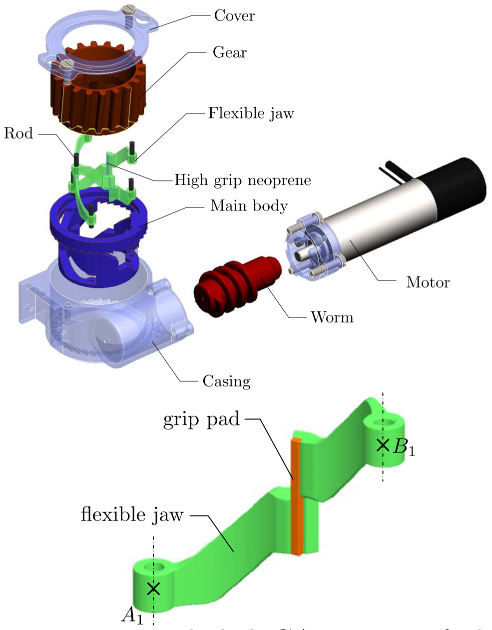
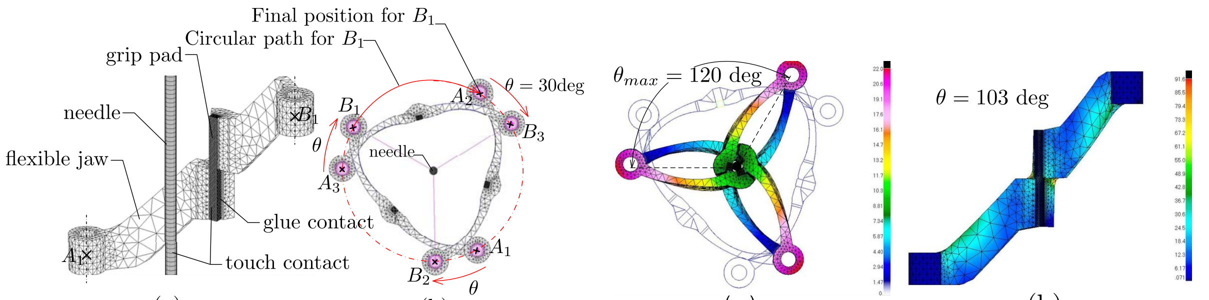


Figure 1: Exploded CAD view of the flexible NGD with the servo actuator, CAD view of one flexible jaw.

Meshing The created mesh shown in Figure 2i-a uses 4-node tetrahedral elements for the jaws and the neoprene pads and 6-node wedge elements for the needle. Each part of the FEA model was assigned with the corresponding material namely polymer resin for the jaws (PX220, Axson Tech. Inc.), neoprene for the pads and stainless steel for the needle. This polymer resin was chosen to be compatible with the fabrication process. Starting from a master part corresponding to the jaw fabricated with a conventional 3D printing machine, a silicon mold was constructed and a small series of parts could then be obtained using vacuum casting.

Boundary and loading conditions The modeling of the pin joints at both ends of each jaw is conducted using rigid body elements. The points A_i and B_i ($i = 1..3$) are respectively attached to the fixed main body part and the rotating gear. Contacts are set between the jaws and the grip pads (indicated as glue contacts in Figure 2i-a) whereas contact areas between the grip pads and the needle barrel are specified in the model and denoted touch contact in Figure 2i-a. Loading conditions on the jaws are applied in the form of imposed displacements of the points B_i along a circular path centered with the needle axis.

Results The resolution of the problem with three moving jaws has been solved. firstly the displacements of the jaws during the closing of the NGD was understood. Figure 2ii-a presents the displacements of the deformed shapes of the NGD with an indication of the starting configuration plotted in wireframe display style. As the first contact between the grip pads and the needle is gained at the configuration $\theta = 88$ deg, the analysis has been continued until $\theta = 120$ deg. At this fully tighten position, the principal maximum strain for the jaw is located in the central area of the part. Its value is in the order of 10 % which corresponds to the elongation at break for the chosen resin. The Von Mises stresses in the configuration $\theta = 103$ deg are displayed in Figures 2ii-b for a single jaw. The maximum VM stresses are also located in the central area of the part. The location of stress concentration coincide with the highest level of strain. After reviewing the Von Mises stress results, one can note that the yield stress is reached for $\theta = 103$ deg. Consequently, a rotation of the gear by an angle in the range 103–120 deg may potentially deforms the jaws irreversibly.



(a) (b) (a) (b)

(i) Meshing and BCs. (ii) Displacements and VM stresses.

Figure 2: Mesh for one of the flexible jaw and a portion of the needle (i-a), Boundary conditions and loads applied on the flexible NGD (i-b). Displacements distribution for the flexible NGD at final position $\theta_{max} = 120$ deg (ii-a), Von Mises stresses calculated for the flexible NGD at the angular position $\theta = 103$ deg (ii-b).

4 Experimental assessment

A comparative experimental study of the two types of NGDs namely the rigid and the flexible-body NGD has been carried out. Objective of the experiments is to characterize the grasping capability of the proposed NGDs. Most important functional characteristics of the proposed NGDs is their ability to maintain the grip on the needle, over the range of forces and range of rate of change of forces applied to it. This can be done by assessing the maximum force sustained by the NGDs, without allowing the needle to slip.

4.1 Experimental Setup

Experimental setup depicted in figure 3 consists of a traction machine from Zwick, GmbH (Z005 THN - Allround Line), capable of applying varying magnitudes of force and rates of change of force to the cross-head. A 18 gauge (1.3 mm), polished, stainless steel needle is held between the jaws which is attached to the cross-head. Both NGDs are actuated by a Harmonic Drive DC servo motor (RH-5A-5502) which is controlled by another computer via I/O cards. Force is applied to the cross-head by the traction machine, which in turn applies the force on the needle grasped

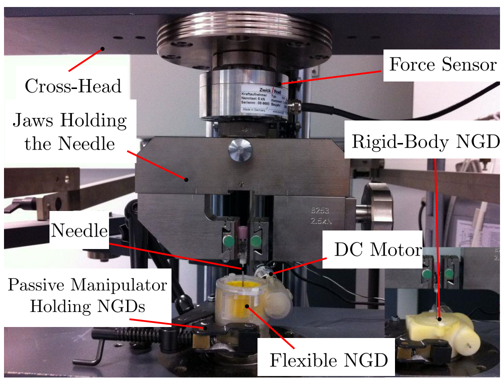


Figure 3: Experimental setup.

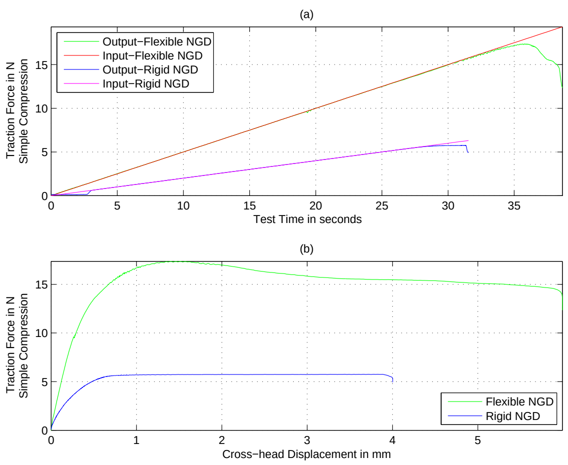
tightly between the NGD. During the experiments there is no slipping between the proximal end of the needle and the chuck jaws of the traction machine, so NGD experiences the same amount of force. Input current to the motor was maintained constant, so as to maintain constant grasping force for each experiment. Also length of the needle, at which the NGDs grasp it, is same for all experiments. This was done to have the same constant set of conditions at the beginning of each experiment.

4.2 Results

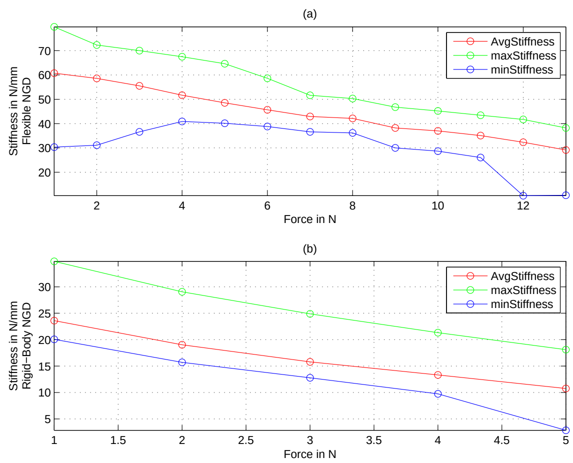
In this section, some results of the traction experiments conducted on the proposed NGDs and a qualitative and quantitative comparison of their respective performances, are presented. A total of the 58 experiments were conducted on the rigid-body NGD and total of the 46 experiments on the flexible NGD. For the rigid-body NGD experiments were stopped after slipping of 4 mm, whereas for flexible NGD experiments were stopped after slipping of 6 mm, as can be seen in Figure 4i-b.

During needle insertion one can observe two distinctive phases in force profile i) a phase of constant rate of change of force when needle is being inserted gradually through tissue of uniform density ii) a phase where force suddenly decreases over very small periods of time, for example during tissue ruptures or sudden changes in tissue density. Therefore, these experiments were designed in two parts: i) In first part, input rate of change of force was kept constant, which is called here simple compression loading. ii)In second part, different segments in input force profile each segment with a varying rate of change of force, which is called here the variable loading, were introduced.

We present here only the results of the first part of experiments devoted to simple compression loading during which the rate of change of force was kept constant, as in Figure 4i. Typical results for simple compression loading for Rigid-NGD and for Flexible-NGD are presented. In Figure 4i-a, it can be seen that both NGDs are capable to comply with input force, as curves for input and output fall on each other, until a certain threshold force, when the slipping occurs. Also it can be observed, that value of the threshold force for flexible NGD is much higher than that for rigid body NGD.



(i) Results of the simple compression loading.



(ii) Stiffness characteristics of the NGDs.

Figure 4: Experimental results for the compression loading (i) and for the stiffness characteristics (ii).

During needle insertion stiffness plays an important role, for needle must not slip when there are sudden and large changes in the force. Stiffness characteristics of the NGDs can be evaluated at given force levels using curves in the Figure 4i-b. Stiffness at force point F can be defined as slope of the tangent line to the curve and passing through the given force point. In Figure 4ii-a and Figure 4ii-b, the quantitative measures of the stiffness at different levels of the input force are presented. These figures also describe the average value of slipping for both NGDs at different force levels, which can be obtained by dividing the force level with average stiffness value. Threshold value of force at which needle starts slipping is not very well defined and ideally it should be defined as the force at which instantaneous slope of the curve shown in Figure 4i(b) is nearing to zero. Here threshold value has been defined as force at which needle has slipped by 0.5 mm. This definition is more conservative than ideal one and required for safety considerations. Magnitude of this threshold value is less than ideal threshold value. In Figure 4ii limit of the 13 N for flexible NGD and limit of the 5 N for rigid-body NGD were chosen, because at these force limits respective NGDs have slipped on an average of less than 0.5 mm. As evident from this figure average stiffness of the sample decreases as force increases. A comparative study of the above figures suggests, that flexible NGD outperforms the rigid-body NGD both in the value of threshold force and stiffness values. This is of course influenced by several factors which might be improved by, for example, using a material of higher coefficient of friction between the NGD and the needle to improve the traction force.

5 Conclusion

The availability of NGD appears to be a limiting factor to the development of robotized needle insertion assistants. In this paper, the current development of our latest NGD based on flexible parts was presented. The first comparative experimental assessments of this new embodiment reveal a much higher performance level than the previously developed NGD based on rigid bodies. The flexible NGD has a wider aperture to allow free motion of the needle when it is required by the medical procedure but remains compatible with needle regrasping. The measured traction force transmitted to the needle is also improved by a three times higher factor. Future work includes additional tests to assess the flexible NGD behavior using other standard needle sizes and the integration of the proposed NGD into one novel needle insertion assistant.

Acknowledgment

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