35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

On the Use of Discrete Steps in Robot-aided Flexible Needle Insertion

André A. Geraldes, Murilo M. Marinho, Mariana C. Bernardes, Antonio P. L. Bó, Geovany A. Borges

Abstract— **Needle steering devices present great potential for improving the safety and accuracy of medical interventions with percutaneous access. Despite significant advances in the field, needle steerability remains an issue to be solved by the scientific community. In this paper, we propose the use of discrete steps in flexible needle insertion, inspired by the manual procedure performed by physicians. Conceptually, the method relies in alternating between two motions: grasp-push and release-retreat. For experimental evaluation, a modified gripper is used along with a 6DOF robotic manipulator to control needle insertion velocity, rotation and grasping. Preliminary results indicate that the use of discrete steps minimizes some negative effects, such as slippage and needle buckling, observed on alternative methods, while preserving their functional advantages.**

I. INTRODUCTION

Many medical interventions and diagnosis make use of percutaneous access, which already comprise a substantial fraction of minimally invasive procedures. Brachytherapy, biopsy, anesthesia and neurosurgery are examples of procedures which depend on precise positioning of the medical instrument for effectiveness [1]. The final misplacement of the needle tip may be caused by several factors, including errors in the insertion location, deflection of the instrument, and tissue deformation. In order to minimize such effects, excellent 3D spational reasoning and extensive experience from the physician are required, since the trajectory must be corrected manually [2].

Robot-assisted needle insertion has been an area of active research in recent years, in order to overcome some of the shortcomings of manual needle insertion. Furthermore, experiments carried out by different groups have shown that robotic systems are not only able to insert needles with consistent precision, but they also allow complex trajectories inside the body. In order to achieve such performance, different techniques have been proposed to guide needles once they are inserted inside the tissue in order to reach targets inaccessible by a straight-line trajectory, while avoiding obstacles such as vital organs, bones, nerves or vessels.

One of these techniques uses flexible needles with asymmetric tips, which create an imbalance in the interaction forces when inserted in soft tissue, making the needle deflect in a curved path. As a result, these curved trajectories could be used to avoid sensitive or impenetrable areas. Nevertheless, the insertion methods proposed so far in the literature for this type of insertion [3] present undesirable side effects, which may interfere with the needle control.

An alternative device proposed in [4], despite being used for rigid needles, gives light to a different insertion scheme using discrete steps. In this work, we adapt such concept to flexible needles in order to minimize some of the drawbacks observed in other solutions. Hence, in this paper, we first present a literature review and introduce the motivations of the current work. Next, we propose the design of a needle insertion device for robotic insertion of beveled flexible needles using discrete steps. In sequence, we present characterization experiments performed to quantify the device performance. With the obtained results, a preliminary evaluation of the device is made, in comparison to the other methods proposed in the literature. Finally, considerations and perspectives for future works are presented.

II. PROBLEM FORMULATION & RELATED WORK

Due to its asymmetric geometry, the natural behavior of a beveled steerable needle, when inserted into soft tissue, is to bend in the direction of its sharpened tip, following an arc of approximately constant radius of curvature r, as depicted in Fig. 1. The kinematic model for this kind of needle can be approximated by that of a nonholonomic unicycle vehicle [2], with the following nonholonomic constraints: $\omega_y = \nu_y = \nu_z = 0$ and $\omega_z = {}^{\nu_x}/_{r}$. Thus, the system has two control inputs ν_x and ω_x, that are respectively the needle's insertion and rotation velocities along its shaft, and are referred simply as ν and ω. Consequently, the beveled needle trajectory inside the tissue can be seen as a combination of circular arcs.

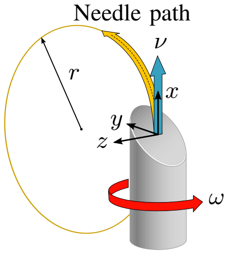

Fig. 1: Flexible beveled needle and its control inputs.

So far, two different mechanisms have been proposed to enable controlling ν and ω concurrently: the *Friction Drive* and *Telescopic Support* devices. These devices are shown in Fig. 2 and discussed as follows.

The *Friction Drive* device, proposed by Webster *et al.* [2], used a friction-based insertion subassembly to drive the needle to its insertion point in the tissue, while an additional structure was used to control needle rotation. The main advantage of this device is its simplicity and compact

---

André Augusto Geraldes, Murilo Marques Marinho, Mariana Costa Bernardes, Antônio Padilha Lanari Bó and Geovany Araújo Borges are with the Laboratory of Robotics and Automation (LARA), University of Brasília, Brasília, Brasil, e-mail: {andregeraldes, murilomarinho, bernardes, antonio.plb}@lara.unb.br; gaborges@unb.br.

978-1-4577-0216-7/13/$26.00 ©2013 IEEE

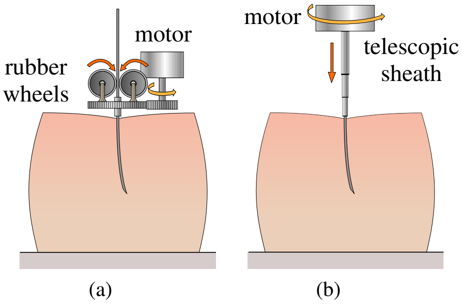

Fig. 2: Existing needle control systems: (a) *Friction Drive* and (b) *Telescopic Support* devices.

design. However, it presents slippage in the insertion degree of freedom and unwanted needle spinning due to imperfect alignment of the friction device.

An alternative solution was presented in [3], where a design based in a *Telescopic Support* device was proposed. In this case, the needle base is directly attached to the motor controlling the spin about the needle shaft, while the rotation subassembly is translated by a linear stage. In this mechanism, the needle is driven from its base instead of being driven from its insertion point and, since the needle is attached to the device, the slippage issue is eliminated. Furthermore, to prevent the needle from buckling, a telescoping support sheath was used. This device has become the standard mechanism for flexible beveled needle steering and has been largely used in studies in the area [5]–[10].

Nevertheless, the actuation in the needle base adds other problems to the design. Despite the use of the telescoping support, small buckling still happens inside the tube, causing uncertainty in the insertion depth and complex unmodeled interaction forces that can disturb the needle insertion controller. Also, the actuation at the needle base worsens the effects of torsional stiffness, inducing a lag between the applied rotation and the one observed at the needle tip. The effects of the torsional dynamics in flexible needles have been modeled by Swensen *et al.* [11], [12]. From his results, the formulation that allows the greatest degree of control over the orientation tip is the one with rotational control at the tissue insertion point, which is referred by Swensen as the ideal control mechanism.

III. PROPOSED SOLUTION

The use of a discrete step needle insertion, as proposed in [4], should allow the rotation mechanism to be arbitrarily close to the point of insertion and could solve inherent issues of the flexible needle insertion devices proposed so far. In this method, the needle is inserted in a manner inspired by the movements normally performed by physicians. Throughout one step, the needle is grasped, inserted into the tissue and then released while the actuation point is reset to allow another step. In contrast with *Friction Drive* devices, grasping the needle during the insertion with enough force should prevent slippage. Furthermore, by actuating the needle from closer to the puncture point, problems related to buckling and torsional stiffness may be reduced when compared to the *Telescopic Support* devices.

A. The conceived discrete step device

To enable the insertion of flexible needles with the previously described discrete step approach, we designed a device to be assembled to a robotic manipulator with an electric gripper as end effector.

The device, shown in Fig. 3, is based on a metallic frame with a 1.0 mm center hole, through which the needle is inserted. A pair of acrylic plates with rubber blocks attached in their end were used to extend the gripper, so that they could be used to grasp or release the needle.

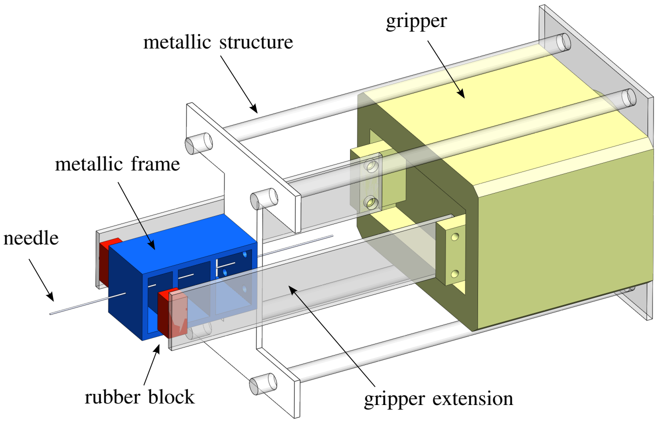

Fig. 3: CAD model of the discrete step insertion device.

Fig. 4 shows an operational sequence describing the discrete step insertion method, using the conceived device. Initially, the device grasps the needle (Fig. 4a) by actuating its gripper. Then, a short insertion is performed by approximating the whole structure to the tissue phantom (Fig. 4b). The needle is then released (Fig. 4c), and the device returns to the initial position (Fig. 4d). This four operations compose a step, which is how the device controls v. Performing steps repeatedly allows reaching deeper targets. In order to control ω, as the gripper and needle rotational axis are aligned, the gripper is rotated. This gives full control of the nonholonomic insertion inputs. For better understanding, this process is also presented in the attached video[1].

IV. EXPERIMENTAL CHARACTERIZATION

In order to evaluate the system performance, experimental data was obtained from *in-vitro* trials using a translucent tissue phantom. In those experiments, two major aspects of the insertion were experimentally analyzed: the buckling of the needle and the repeatability of open loop insertions.

A. The Experimental Setup

For both experiments, we used a Schunk modular manipulator with 6 DOF associated with the discrete step device

---

[1] http://www.youtube.com/watch?v=vod864UYmv4

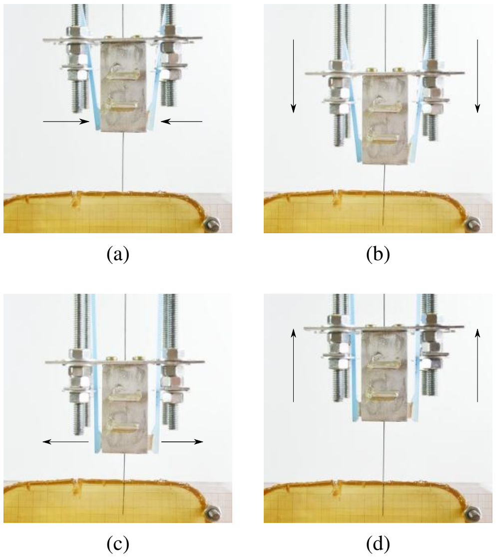
(a) (b)
(c) (d)

Fig. 4: Operational sequence of a discrete step insertion. (a) Grasping the needle; (b) Inserting the needle; (c) Releasing the needle; (d) Moving back to the initial position.

described in Section III-A. The tissue phantom consisted of a ballistic gelatin, stored inside a transparent container and placed bellow the robot end effector so that the needle was inserted vertically. The needle used in our experiments was a prototype built from a 0.61 mm diameter wire made of Nitinol (55.5%Ni - 44.5%Ti), with a hand-machined bevel of approximately 5° at its tip. To improve steerability, a small bent was added to the needle beveled tip. All measurements were obtained using a D7000 Nikon camera pointing to the center of the phantom container. A millimeter paper was fixed to the rear plate of the container in order to assist in perspective transformations. The entire setup is shown in Fig. 5.

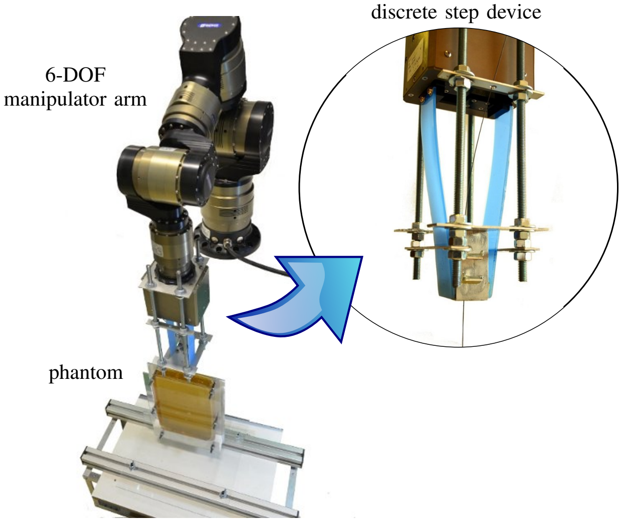

Fig. 5: Complete experimental setup.

B. Needle buckling evaluation

The needle buckling effect should be smaller when the distance between the needle actuation and the puncture points is reduced. In order to verify this relation, we conducted experiments measuring the buckling of needle for different step sizes.

The experiments were conducted in the following way: for each of the 5 selected distances, the needle was recorded with our camera while being inserted 5 times in the tissue phantom, each time at a different entry point. For each of the 25 resulting videos, the maximum buckle was measured as the maximum deviation of the needle from its insertion axis during the insertion. Only the first step of the insertion was analyzed; since, in this situation, the buckling effect is maximum. The results are shown in Table I.

TABLE I: Results of the needle buckling experiment.

Step size (mm)	Maximum buckle (mm)
20	≈ 0
40	≈ 0
60	0.8 ± 0.2
80	1.3 ± 0.8
100	2.4 ± 0.8

C. Open loop repeatability evaluation

Closed loop control techniques aim to compensate modeling errors that may deviate the needle from the desired target during insertion. The bigger these errors, the more complex it is to design the insertion controller. In order to allow a simpler control implementation, it is desired that the open loop needle insertion presents the best precision possible. For this reason, we conducted an open loop repeatability experiment.

In this experiment, the needle was inserted in the tissue phantom with a fixed path chosen beforehand. The needle tip is initially pre-inserted at the tissue puncture point before the experiment started. The chosen step size was 10 mm, as this size was short enough not to induce buckling. After an insertion, a picture was taken for data evaluation and the needle was pulled out of the tissue using steps backwards. After the needle returned, the phantom was laterally repositioned and the insertion was restarted with the same fixed path. This procedure was repeated for 5 insertions sufficiently apart so that the deformation in the tissue caused by one insertion would not affect the following one.

The resulting pictures were adjusted and blended in a single one for better view and comparison in Fig. 6. The final point of the need tip was measured in relation to the puncture point. The repeatability of the needle tip placement was 2.61 mm.

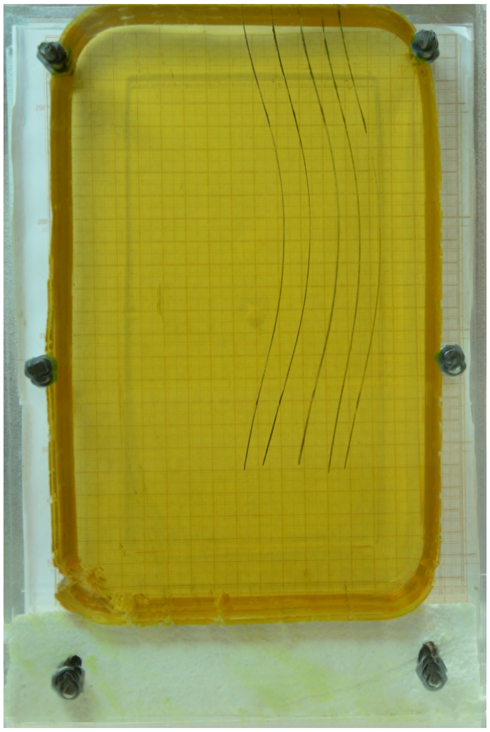

Fig. 6: Image comprised of the blending of pictures taken in all open loop experiments for repeatability evaluations.

V. DISCUSSION

The performance of the needle insertion device, whose design is presented in this paper, has been evaluated using 2 experiments, whose results allow us to preliminary compare our device with the previous ones.

Friction Drive mechanisms present problems related to unreliable insertion and rotation, due to slippage and imperfect alignment of the friction device, respectively. In a discrete step device, the concept of firmly grasping the needle should allow, as it did in our experiments, an insertion without slippage.

Telescopic Support devices present problems related to needle buckling inside the telescopic support and torsional stiffness. Buckling generates complex interaction forces between needle and telescopic sheath, which can disturb the controller in an unmodeled way. In experiments with steps smaller than 40 mm, no buckle was observable with our measuring system. This means that choosing step sizes in that interval would allow us to infer that any buckling is negligible, resulting in a more reliable and easier to control system.

Additionally, with respect to the performance of the device and the feasibility of using it in needle steering interventions, the obtained data indicate satisfactory results. Due to our design choices, the repeatability of the open loop insertions was 2.61 mm. Similar experiments, using ultrasound-guided manual insertions [13], presented a repeatability of 3.19 mm. Even though such evaluation for friction and telescopic devices are not found in the literature, to the best of our knowledge, our results illustrate that the device may be successfully applied in closed loop control schemes.

VI. CONCLUSIONS

In this work we presented two traditional flexible needle steering devices and discussed their advantages and drawbacks. As an alternative, we proposed the use of discrete steps, which intends to solve existing problems like slippage and needle buckling. The results of our experiments suggest that the discrete step device may concurrently solve both problems, while preserving the functional advantages of the previous methods. Moreover, it allows actuation of the needle from close to the puncture point and provides admissible repeatability.

In future works, we intend to evaluate the problem of the angular displacement error, between the needle tip and actuation point. This could be measured by using a posture sensor attached to the needle tip. Finally, we intend to incorporate additional elements to our needle insertion system, such as a needle tracker system based on computer vision and a path planner in order to perform closed-loop experiments. This would also allow us to better compare ours with other existing devices, since we would be able to perform experiments in the same conditions.

REFERENCES

[1] N. Abolhassani, R. Patel, and M. Moallem, “Needle insertion into soft tissue: A survey,” *Med. Eng. & Physics*, vol. 29, pp. 413–431, 2007.

[2] R. Webster III, J. Kim, N. Cowan, G. Chirikjian, and A. Okamura, “Nonholonomic modeling of needle steering,” *The International Journal of Robotics Research*, vol. 25, no. 5-6, pp. 509–525, 2006.

[3] R. J. Webster III, J. Memisevic, and A. M. Okamura, “Design considerations for robotic needle steering,” in *Proc. IEEE International Conference on Robotics and Automation*, 2005, pp. 3588–3594.

[4] O. Piccin, L. Barbé, B. Bayle, M. de Mathelin, and A. Gangi, “A force feedback teleoperated needle insertion device for percutaneous procedures,” *The Internation Journal of Robotics Research*, 2009.

[5] J. Engh, G. Podnar, D. Kondziolka, and C. N. Riviere, “Toward effective needle steering in brain tissue,” in *Conf Proc IEEE Eng Med Biol Soc.*, 2006.

[6] “Teleoperation of Steerable Needles,” in *Proc. IEEE International Conference on Robotics and Automation*, 2007, pp. 934–939.

[7] N. A. Wood, K. Shahrour, M. C. Ost, and C. N. Riviere, “Closed-Loop Control of Needle Steering for Percutaneous Kidney Access,” in *IEEE Int. Conf. on Robotics and Automation*, no. 4, 2010, pp. 48–50.

[8] A. Majewicz, T. R. Wedlick, K. B. Reed, and A. M. Okamura, “Evaluation of Robotic Needle Steering in ex vivo Tissue,” in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2010, pp. 2068–2073.

[9] B. K. B. Reed, A. Majewicz, V. Kallem, R. Alterovitz, K. Goldberg, N. J. Cowan, and A. M. Okamura, “Robot-assisted needle steering,” *IEEE Robotics & Automation Mag.*, vol. 18, no. 4, pp. 35–46, 2011.

[10] M. C. Bernardes, B. V. Adorno, P. Poignet, and G. A. Borges, “Semi-automatic needle steering system with robotic manipulator,” in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2012, pp. 1595–1600.

[11] J. P. Swensen and N. J. Cowan, “Torsional dynamics compensation enhances robotic control of tip-steerable needles,” in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2012, pp. 1601–1606.

[12] J. P. Swensen, “Torsional dynamics and rotational estimation of tip-steerable needles,” Ph.D. dissertation, The Johns Hopkins University, 2011.

[13] E. M. Boctor, M. A. Choti, E. C. Burdette, and R. J. Webster III, “Three-dimensional ultrasound-guided robotic needle placement: an experimental evaluation,” *Int J Med Robotics Comput Assist Surg*, vol. 4, pp. 180–191, 2008.