



Design of Insertion Mechanism for Cannula Flexible Needle Based on TRIZ

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Abstract. Insertion mechanism is one of the basic parts in robot assisted surgery system. In this study, we designed an insertion mechanism for a cannula flexible needle based on TRIZ. According to the degree of freedom (DOF) requirement for the insertion movements, the nesting principle was used to solve the complexity problem of the traditional design. The nested screw nut mechanism effectively reduced the volume and the weight of the insertion mechanism and made the whole structure more compact. The extraction principle and the separation principle were used to solve the supporting problem, and the scheme of separated supporting blocks was proposed. According to the finite element analysis results, the initial supporting position of each supporting block was obtained. Then the substance-field analysis method was utilized to solve the dynamic supporting problem. An elastic connecting band was introduced linking each supporting block to realize a linkage motion of the supporting blocks. This not only improved the supporting effect by adjusting each block to the right position in real time, but it can reset each block to its original position as well. Finally, we used the proposed mechanism to perform the insertion experiments, and the error was within 0.4mm, which confirmed the validity of the proposed insertion mechanism.

Keywords: cannula flexible needle; insertion mechanism; TRIZ; mechanical design

DOI: <https://doi.org/10.14733/cadaps.2021.655-668>

1 INTRODUCTION

In minimally invasive surgery, needle insertion is one of the most commonly used surgical treatments. However, the traditional and widely used rigid interventional needle cannot meet the needs of modern complex surgeries, for it neither steers clear of obstacles (like bones), nor the important and sensitive organs (like blood vessels, nerves, etc.). Also, it is difficult for a traditional needle to achieve a precise positioning control since the bending in the tissue can hardly be rectified. Webster et al. had proposed a bevel tip flexible needle to replace the traditional needle [1]. There is a sufficient flexibility in a flexible needle, and the lateral force acted on the bevel caused by the interaction of the bevel tip and tissue can make the needle bend so as to steer clear

of obstacles and correct the deviated path to achieve the target [2]. The movement principle of the flexible needle is as shown in Figure 1. When the flexible needle inserts into the tissue, the bevel of the tip is subjected to the lateral force of the tissue, causing the tip of the needle to puncture a curved trajectory. By the rotation of the root of the flexible needle with a certain angle, the bending direction of the needle is changed, causing the flexible needle to bend in a three-dimensional (3D) trajectory. In this way, the obstacles can be avoided and the deviated path can be corrected. However, the bevel tip flexible needle also has some big drawbacks: the curvature of the path is difficult to change which hinders the agile of the flexible needle; the precision of rotational control of the bevel is low because of the torsional friction between the needle shaft and tissue. In view of the deficiencies mentioned above, we come up with an idea of a cannula flexible needle. It is composed of two parts: a flexible cannula and a flexible stylet (see Fig. 2a). On the one hand, the cannula separates the stylet from the tissue, reducing the torsional friction effectively and improving the accuracy of the rotation of the bevel tip. On the other hand, the stylet with a bevel tip can move relative to the cannula, and the different length of the stylet extending out of the cannula results in a different radius of the entire insertion path of the cannula flexible needle (see Fig. 2b). Thus, it effectively solves the both problems mentioned above, and makes the needle more agile and precise, because of the variable curvatures and reduction of the torsional friction.

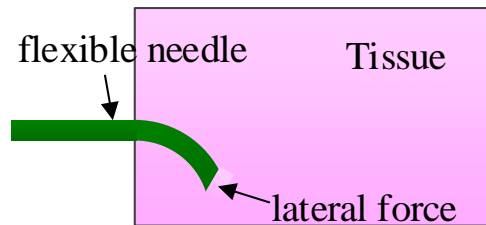


Figure 1: The bending of the flexible needle.

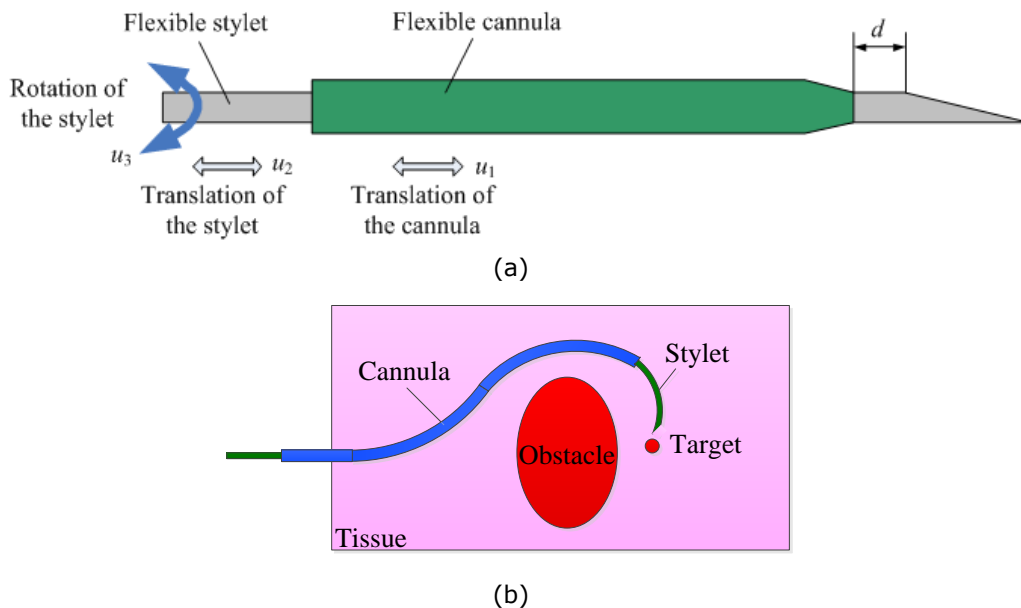


Figure 2: Motion and DOF analysis of the cannula flexible needle.

In robot assisted surgery, the cannula flexible needle requires an insertion mechanism for the robotic system. Webster et al. proposed two sets of insertion mechanism for a bevel tip flexible needle [2]: one is a screw nut mechanism, which uses telescopic tubes to support the needle shaft in order to prevent the buckling when insertion (see Fig. 3a); the other is a friction-wheel mechanism, which omits the supporting mechanism thanks to the friction wheels arranged at the front of the insertion mechanism for inserting the needle (see Fig. 3b). Although the latter mechanism is more compact than the former one, its control accuracy is inferior to the former due to the slippery error of the frictional wheels. And also, the structure of the former mechanism is simple. Thereafter, most insertion mechanism for the bevel tip flexible needle are screw nut mechanisms [3-6]. Moreover, Bebek proposed a parallel robot to insert a rigid needle [7]. Yamada propose a novel flexible mechanism called "Active Sheath" for realizing shape-controllable cannulas by using two flexible elements. This mechanism is mainly composed of two linear drive mechanisms, which enable the needle to penetrate in a two-dimensional plane. Without the driving of the rotating needle tip, it is difficult to achieve bending puncture in 3D space [8]. However, the insertion mechanisms for the bevel tip flexible needle or rigid needle mentioned above are not suitable for the cannula flexible needle, since the cannula flexible needle has more DOFs, requiring a more complex drive mechanism [9]. There is no existing insertion mechanism for the proposed cannula flexible needle. Moreover, the current insertion mechanism mainly uses telescopic tubes to prevent buckling of the needle shaft. Because the telescopic tubes have a multi-layer structure, the outermost layer of the telescopic tubes has a large diameter, so the effect of preventing buckling is not sufficient. Thus, it is necessary to carry out an intensive study on the insertion mechanism for the cannula flexible needle.

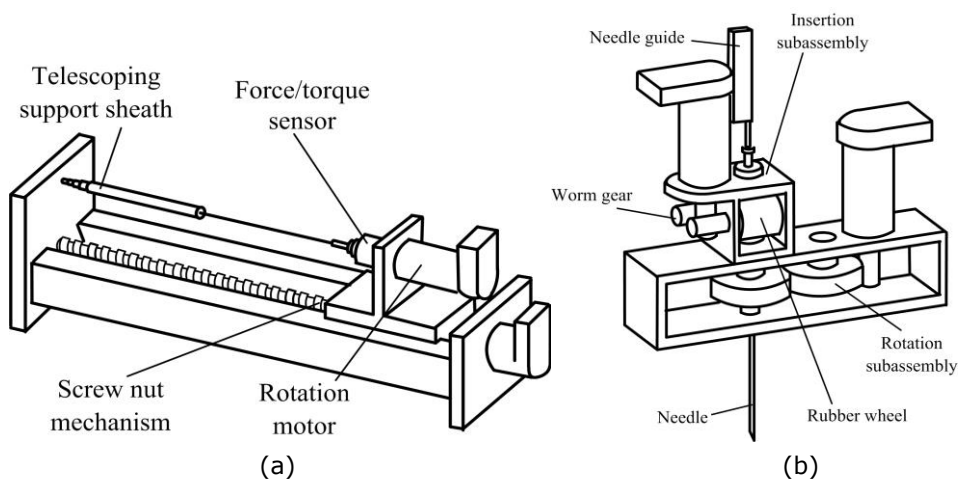


Figure 3: Insertion mechanism proposed by Webster. (a) Insertion mechanism with a telescopic support; (b) Insertion mechanism with friction wheels.

TRIZ (Teoriya Resheniya Izobreatatelskikh Zadatch) is an engineering problem solving toolkit proposed by Genrich Altshuller in Soviet Russia, which summarizes the past solutions and successes of nearly 2.5 million high-level inventions all over the world to show us how to systematically solve the future problems. TRIZ is considered as the most comprehensive and systematic theory for invention, creation and technological innovation [10-12]. The main tools of TRIZ include: system analysis, product evolution theory, substance-field analysis, 40 inventive principles and 76 standard solutions, etc. [13]. TRIZ enhances and speeds up the process by directing engineers to the places full of good solutions to the particular problems, and helps engineers to power forward to useful and practical answers [14]. As opposed to brainstorming, mind mapping, lateral thinking, and morphological analysis, TRIZ is able to identify or discover

problems and their root causes, as well as provide abstract solutions. Compared with other methods, TRIZ theory has a certain structural framework, which avoids searching for problems and solutions repeatedly and wastes a lot of time (see Fig. 4). And TRIZ can produce more effective and novel solutions [15].

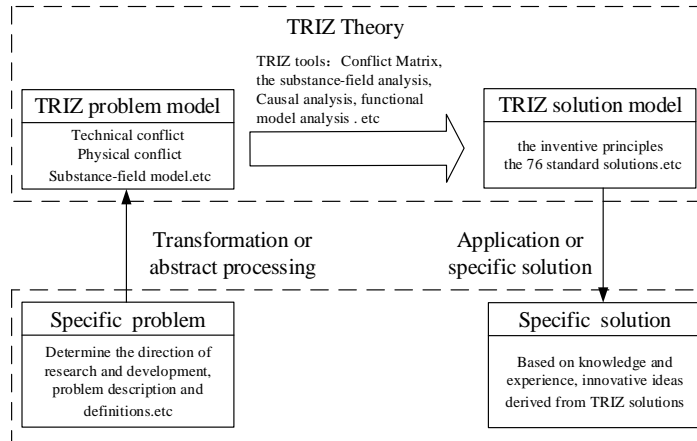


Figure 4: TRIZ systematic approach to problem solving.

In this paper, the inventive principles and the substance-field analysis method are used to design an insertion mechanism for the cannula flexible needle in overall and partial structures. It solves the problem of large volume of cannula flexible needle insertion mechanism, reduces the buckling phenomenon of the needle before puncturing the tissue.

2 DOF AND MOTION ANALYSIS OF CANNULA FLEXIBLE NEEDLE

The cannula flexible needle has two parts (the cannula and the stylet) which are required to have independent feed motions of the cannula and the stylet. And the orientation of the bevel of the stylet is required to be altered in order to change the bending direction. Thus, there should be three DOFs for a cannula flexible needle, two of which are the movement and rotation of the stylet, and the other is the movement of the cannula, as shown in Fig. 2a. The extension length of the stylet out of the cannula is controlled by the relative movement of the cannula and the stylet in order to realize different curvatures of the insertion path. The three DOFs are independent to each other, requiring three separated drive units. Moreover, the three motions can be performed both separately and simultaneously. The insertion modes include:

- 1) To adjust the extension length of the stylet out of the cannula, to drive the cannula and the stylet to insert simultaneously, thus, different curvatures of insertion path can be obtained.
- 2) To adjust the orientation of the bevel tip, to drive the cannula and the stylet to insert simultaneously, thus, an approximate arc path in a certain direction can be obtained.
- 3) To insert the stylet for a certain distance, and control the cannula to insert along the stylet while the stylet remains static, thus, a certain stylet-cannula coupling path can be obtained.
- 4) To dynamically control the relative motion velocity of the cannula and the stylet, thus, variable curvature arcs of path can be obtained.
- 5) To insert and rotate the stylet simultaneously, when the rotation speed is less than 5 times of the insertions speed (the angular speed unit is rad/s, the linear speed unit is mm/s), a helical path is obtained [16].

6) when the rotation speed exceeds 5 times of the insertion speed, the insertion path is a straight line [16].

Thus, Insertion paths such as arcs, helix lines, straight lines, etc. can be obtained if the three DOFs are coordinately controlled. With combination of the insertion modes 1) to 6), a various forms of 3D paths can be obtained [16].

3 DESIGN OF INSERTION MECHANISM FOR CANNULA FLEXIBLE NEEDLE

3.1 Overall Design of Insertion Mechanism

In order to design the insertion mechanism for the cannula flexible needle, we resort to analyze the insertion mechanism for the bevel tip flexible needle first. The insertion mechanism for the bevel tip flexible needle has two DOFs, one is the feed movement, and the other is the rotation of the needle. The rotation motor is mounted on a sliding way, as shown in Fig. 5.

Compared with the bevel tip flexible needle, the cannula flexible needle introduces a new DOF for inserting the cannula, which presents greater flexibility and adaptability. Drawing on the experience of the insertion mechanism of the bevel tip flexible needle, the conventional idea of designing an insertion mechanism for the cannula flexible needle may be: based on the original screw nut mechanism, another screw nut mechanism will be parallel and mounted horizontally [17] or vertically to the former so as to achieve the insertion of the cannula flexible needle (improved), as shown in Fig. 6.

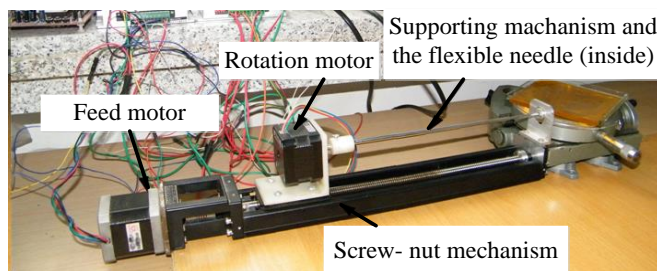


Figure 5: Insertion mechanism for a bevel tip flexible needle.

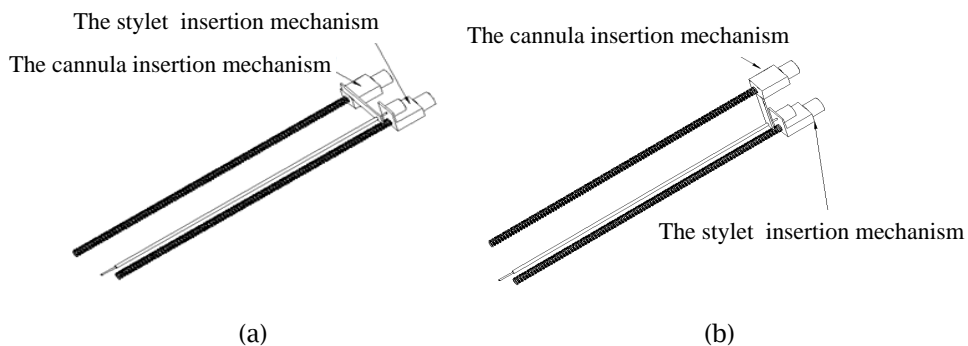


Figure 6: Conventional design ideas. (a) Two horizontally arranged screw nut mechanisms, (b) Two vertically arranged screw nut mechanisms.

However, the parallel-screw solutions will make the whole structure more complex and larger (deteriorated). Meanwhile, the stylet is supposed to be longer than the cannula, so that it can be extended out of the cannula for some distance. Hence, the mechanism that drives the cannula

should be in front of the mechanism that drives the stylet, causing the two parallel screws uneven and the whole structure even longer as a result (deteriorated). However, the operation workspace is often limited, such as transperineal prostate surgery, the space between opened legs is not wide. Converted into the 39 general engineering parameters in TRIZ, there are the conflicts between “35, adaptability” (improved), and “5, the area of static objects” (deteriorated) and “36, device complexity” (deteriorated). Conflict is indicative of inventive problems arising from the apparent incompatibility of desired features within a system. So, we use the conflict matrix and the inventive principles to solve this kind of problem [18]. By searching the matrix table of conflicts (Altshuller’s Classic Conflict Matrix), we can find out the inventive principles available to potentially solve these conflicts, as shown in Tab. 1.

| | | |
|------------------|------------------------------|-----------------------|
| deteriorated | 5, Volume of dynamic objects | 36, device complexity |
| improved | 35, 30, 29, 7 | 15, 29, 37, 28 |
| 35, Adaptability | | |

Table 1: Matrix table of conflicts.

After analysis, principle No. 7 is feasible. The principle and solution are shown in Tab. 2.

| No. | Principles | Explanations of the principles | Solutions |
|-----|-----------------------|--|---|
| 7 | The nesting principle | (1) An object is located within another object, and the latter is within the third object; (2) An object passes through the cavity of another object. | The driving mechanisms of the cannula and the stylet can be nested, making the mechanism smaller in volume, lighter in weight and more compact in shape, which greatly reduces the restrictions of small workspace during insertion and enhances the flexibility of operation. The design sketch is as shown in Fig. 7. |

Table 2: Principle and solution.

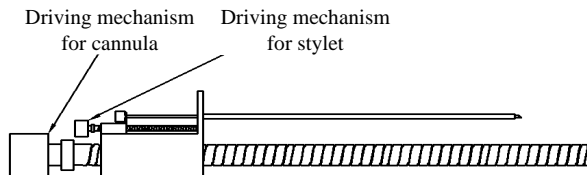


Figure 7: Design sketch using the nesting principle.

3.2 Design of Supporting Mechanism

Different from the rigid needle, the flexible needle would buckle before inserted into the tissue due to its great flexibility. Thus, a supporting mechanism is needed to prevent this from happening. Conventional supporting mechanism of the flexible needle is made of several rigid telescopic supporting tubes, which are sequentially changed diameters, as shown in Fig. 8. However, the effect of this supporting mechanism has a direct relationship with the diameters of the supporting tubes. The diameter of the supporting tubes is related to the number of supporting tubes. When less supporting tubes are nested together, the diameter of the outermost supporting tube decreases. This will make the length of single supporting tube longer, and make the compression length of the multi-layer supporting tubes longer, leading to the unavailable parts of the needle

body and the entire insertion apparatus even longer. On the contrary, if there are more supporting tubes nested together, the length of each single supporting tube could be reduced and the final compression length is smaller, so that the unavailable length of the cannula flexible needle is shortened and the whole insertion mechanism is more compact. However, the larger diameter of the outermost tube brings in the poor supporting effect at the same time. Moreover, the multi-layer support tubes nested together brings the difficulty of manufacturing. This leads to a conflict between "length of the supporting tube" and "supporting effect", "the difficulty of manufacturing". Converted into 39 general engineering parameters, there will be a conflict between "3, the length of moving object" (improved) and "27, reliability" (deteriorated), "32, ease of operation" (deteriorated). By searching the conflict matrix, we can find the inventive principles available to potentially solve these conflicts, as shown in Tab. 3.

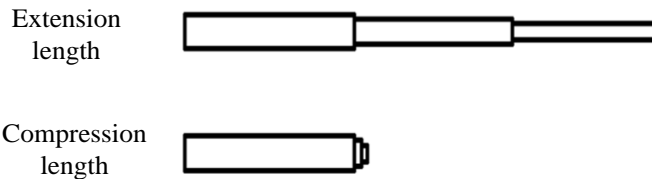


Figure 8: Conventional support of telescopic tubes.

| | | |
|--------------------------------|-----------------|-----------------------|
| deteriorated | 27, Reliability | 32, ease of operation |
| improved | 10, 14, 29, 40 | 1, 29, 17 |
| 3, The length of moving object | | |

Table 3: Conflict Matrix.

After analysis, the principles No. 1 and 10 are feasible. The principles and solutions are shown in Tab. 4.

| No. | Principles | Explanations of the principles | Solutions |
|-----|------------------------------|---|--|
| 1 | The separation principle | (1) To divide the object into separate parts; (2) To make objects detachable; (3) To increase degrees of segmentation of an object. | The original support pipe is transformed into several small scattered support blocks, which are hung on the square rigid beam and distributed along the needle shaft. The distance between these small supporting blocks can be compressed dynamically, and they can finally be next to each other, thus solving the problem of large compression size, shortening the unavailable length of cannula flexible needle within supporting mechanism and reducing the size of the whole insertion mechanism. |
| 10 | The advance action principle | (1) To complete the required role previously; (2) To place tools in advance so that they can function immediately at the most convenient spot. | Combined with the Finite Element Method (FEM) to analyze the characteristics of needle deformation, the supporting blocks are distributed in the locations where the needle shaft is easy to bend. |

Table 4: Principles and solutions.

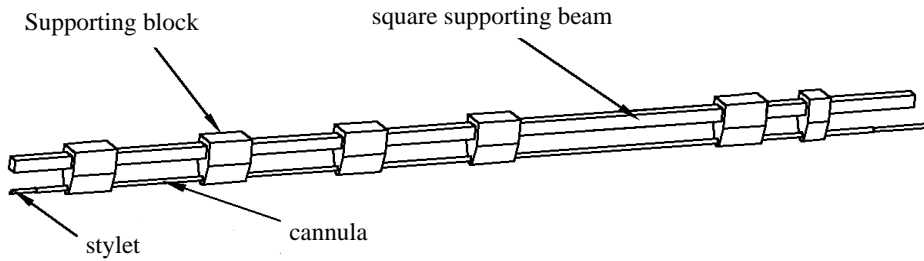


Figure 9: Design sketch of the supporting structure.

The transformation from abstract principles of invention to practical solutions requires the use of specialized knowledge or tools [19]. According to the "advance action principle", the supporting blocks should be placed where the needle body is highly curved. Through finite element analysis of the deformation of the needle body, we can better apply the invention principle No. 10. The cannula flexible needle is subjected to the axial force during insertion, which can be simplified as a stability problem of a pressure bar. The parameters of the needle are as follows: the length is 220 mm, the diameter is 0.38 mm, and the tip angle is 53° , the Young's modulus is 50 Gpa, the Poisson's ratio is 0.33, and the density is $7.8 \times 10^3 \text{ kg/m}^3$. Load and constraints for simulation are as follows: a load of 2N acted on the tip with the axis direction; the freedom of the needle tip is the Z axis, the boundary condition at the needle tip is "ZASYMM ($U_1=U_2=UR_3=0$)", and the boundary condition at the bottom is "completely fixed ($U_1=U_2=U_3=UR_1=UR_2=UR_3=0$)".

According to the finite element analysis result, when the needle shaft loses its stability, the buckled position is about 1/3 the length of the needle shaft away from the needle tip (see Fig. 10). As shown in Fig. 11, the cannula flexible needle is fixed to the insertion mechanism on point A, and point B is the needle end (insertion point). According to the buckling rule as shown in Fig. 10, to ensure the reliability of the support, the supporting block C is added at 1/3 the length of AB away from point B; similarly, the supporting block D is added at 1/3 of the CB away from point B; the supporting block E is added at 1/3 the length of AC away from point C; the supporting block F is added at 1/3 the length of AE away from point E. The support effect is as shown in Fig. 12. We can conclude from the result that the largest buckle after supporting is about 1mm, which has been greatly improved and sufficiently small to meet the needs of operational accuracy.

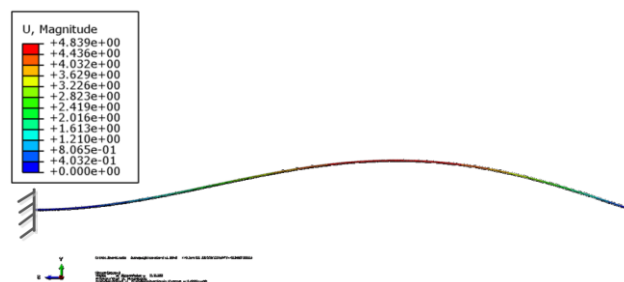


Figure 10: Simulation result of the buckling.

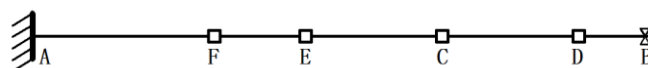


Figure 11: Distribution of the supporting blocks.

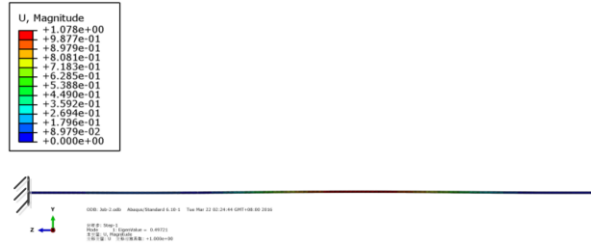


Figure 12: Support effect of the distributed supporting blocks.

However, after a careful analysis of this scheme, we find that although the position of the supporting block in the initial state is reasonable, as the length of needle changes during insertion, the position of supporting blocks will not be 1/3 positions any longer. Thus, in order to achieve a dynamic supporting, we need dynamical supporting blocks. Therefore, thinking of the principle No. 15 “dynamic principle” (Change a stationary object to be movable or adaptive), the supporting block should move in company with the feed mechanism, so that the supporting position would be adjusted in real-time to achieve favorable supporting effect. However, how to achieve linkage is another problem to solve. Since the substance-field analysis can accurately point out the problems of the system without adding unnecessary details to the system, we use it to analyze the current system state, as shown in Fig. 13. In the initial substance-field model, there are only S1 (supporting block 1) and S2 (supporting block 2), and there is no “field” interacting with each other. Thus, this is an incomplete substance-field model. In order to achieve a complete one, a field F (that is the interaction between the supporting blocks) should be added, so that the entire system is complete and is able to work. Thinking of solution No. 1 (To complete an incomplete substance-field model) of the 76 standard solutions, we can introduce a magnetic field, as shown in Fig. 13(a). Magnetizing the supporting blocks, one supporting block would promote the other to move by the repulsion of the same poles. And we can extend this model to all the supporting blocks to achieve linkage between each other.

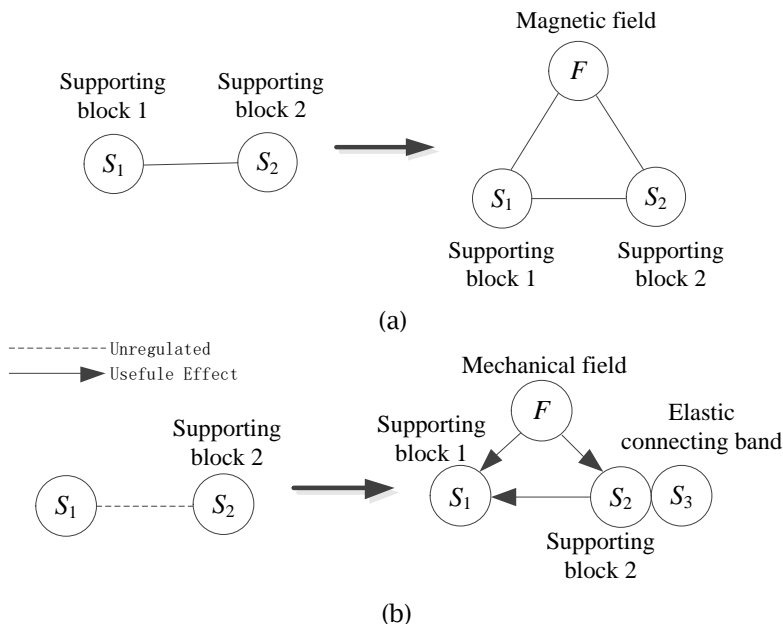


Figure 13: Models of the substance-field analysis. (a) Substance-field model 1, (b) Substance-field model 2.

According to solutions No. 1 and No. 3 (The system cannot be changed, but a permanent or temporary addition is allowed to help the system perform its functions) of the 76 standard solutions, an external substance S3 and a field F can be introduced to change the system, as shown in Fig. 13(b). We can introduce an intermediary substance S3 and a mechanical field F, so that S2, S3 can both act on S1 through the mechanical field F. The principle of introduction of S3 is that on the one hand, it generates a sufficient force on the S1, and on the other hand, it does not bring side-effect to the original function. Therefore, S3 cannot be rigid. According to inventive principle No. 30 (softening method), it is conceivable that an elastic connecting band with bending elasticity should be hinged between the two supporting blocks.

Compared these two schemes, although the structure of scheme one (Fig. 13(a)) is relatively simple, the drawback is that on the one hand, when the supporting blocks are very close to each other, the repulsive force between them will be enormous, which would increase the load of the motor greatly; and on the other hand, it is difficult for the repulsive force to drive each supporting blocks to return to their initial positions during the reset process. Although scheme 2 (Fig. 13(b)) introduces a new substance S3, and makes the structure slightly more complex, the disadvantages of the scheme 1 can be effectively overcome. On the one hand, the elasticity of the elastic connecting band will promote each supporting block to the right position during insertion by the linkage, and when the distance between the supporting blocks is small, the elastic connecting band will be bended and folded together, so that the load will not increase much; on the other hand, the elastic connecting band can also tow the supporting blocks to return to their initial positions during the reset process, as shown in Fig. 14.

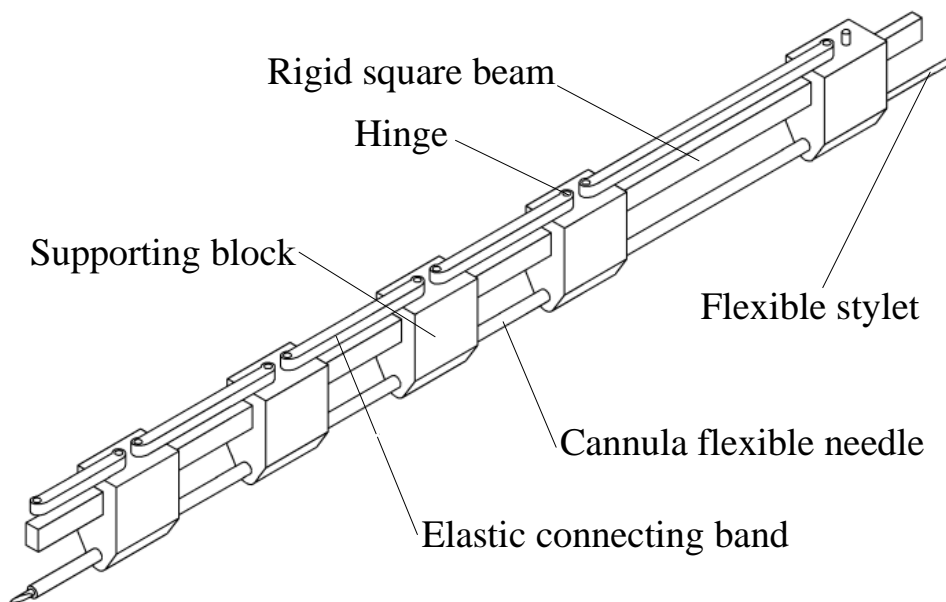


Figure 14: Elastic connecting bands linking each supporting block.

In summary, the final scheme for the insertion mechanism of the cannula flexible needle is as shown in Fig. 15 [20]. The rotational motor for the stylet is to control the stylet rotation in order to adjust the tip angle. The driving mechanism for the stylet is to insert or withdraw the stylet in the cannula in order to control the length of the stylet out of the cannula. The driving mechanism for cannula is to insert or withdraw the whole cannula flexible needle. Moreover, the driving mechanism for the stylet is nested onto the driving mechanism for the cannula. Besides, there is a supporting mechanism for the cannula flexible needle, which is composed of a rigid square beam, the supporting blocks and the elastic connecting bands.

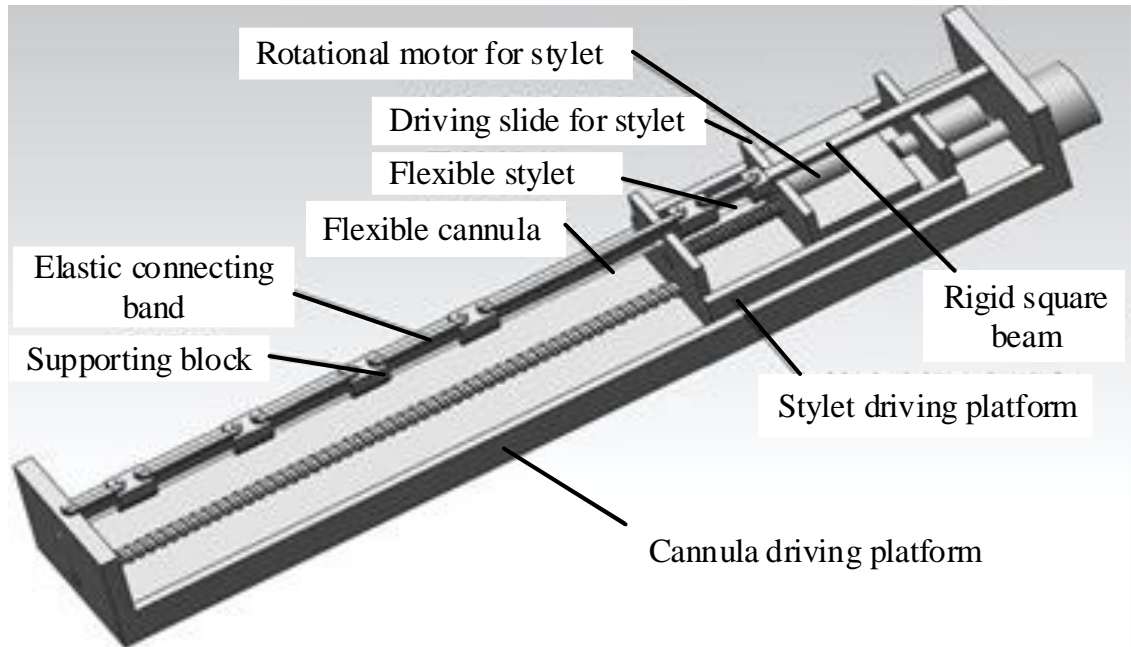


Figure 15: Insertion mechanism of the cannula flexible needle.

4 EXPERIMENTATION

In order to verify the effectiveness of the proposed mechanism, the insertion experiments were carried out. The experimental system of the cannula flexible needle is as shown in Fig. 16.

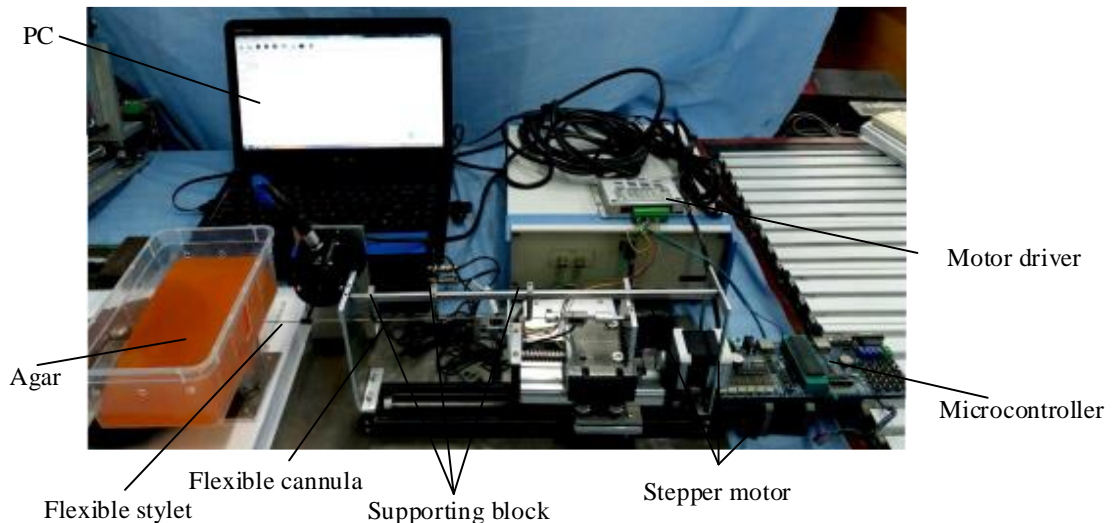


Figure 16: Experimental system of the cannula flexible needle.

We gave the feed length L as 30mm, 40mm, 50mm, 60mm, 70mm, 80mm, 90mm and 100mm, respectively. During the insertion, we can see that on the one hand, there was hardly buckling

when the cannula flexible needle inserted; on the other hand, the errors δ between the theoretical feed lengths and actual insertion lengths are as shown in Figure 17. From the experimental results, we can conclude that, all the actual insertion lengths were less than the theoretical feed lengths. However, the error is $0.246 \pm 0.078\text{mm}$ (mean error \pm standard deviation) and the maximum error was within 0.4mm.

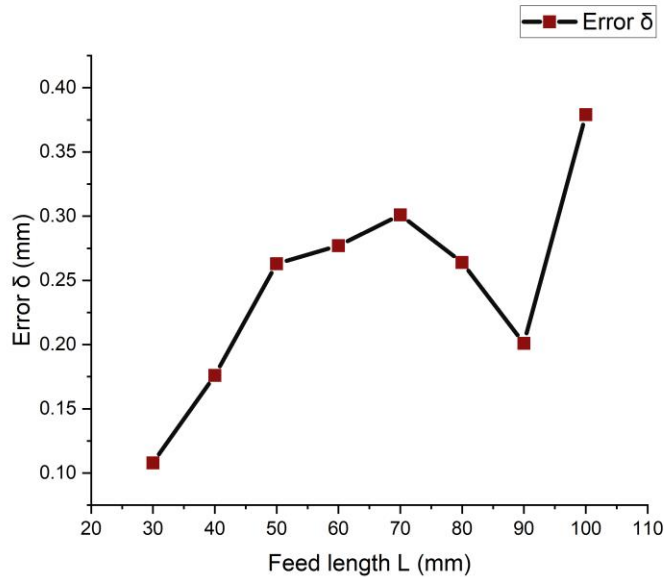


Figure 17: Errors under different feed lengths.

5 DISCUSSION

5.1 Discussion on the Use of TRIZ

When conventional design ideas have conflicts on technical functions or parameters, the conflict matrix in TRIZ theory can efficiently solve the problems. The inventive principles listed in the conflict matrix would guide an engineer to the innovative solutions. TRIZ not only provides several ways that will quickly inspire us to the ideal solution, but also can be combined with CAE tools. TRIZ tools are to give a way of solving problems, and the CAE tools can make the solution concrete.

In this paper, a compact and light weight insertion mechanism was obtained by the nesting principle listed in the conflict matrix. Furthermore, based on the separation principle suggested in the conflict matrix, a separate supporting-blocks structure is inspired. Moreover, through the substance-field analysis, the elastic bands are introduced. However, it is of significance to point out that for a specific problem we can either use the inventive principles or use the substance-field method or even use both to solve the problem. For instance, we used the substance-field method to obtain the elastic bands as a solution to solve the lack of the dynamic supporting problem. However, we can also be inspired by the principle No. 15 Dynamicity and the principle No. 24 Mediator to conceive a solution. Maybe we can also have an elastic band solution.

5.2 Discussion on the Superiorities of the Mechanism

(1) The nested screw structure effectively made the whole insertion mechanism compact compared to the conventional parallel-screw solution.

(2) Compared with the telescopic tubes, the separate supporting blocks not only made the needle well supported, but also shortened the unavailable length of cannula flexible needle within the supporting mechanism, and made the whole insertion mechanism even more compact.

(3) The elastic bands could not only dynamically adjust the supporting blocks in their places during the insertion process, which improved the supporting effect, but also reset the supporting blocks when withdrawing.

5.3 Discussion on Experimental Result

Through the experiments, we can see that the supporting effect of the proposed supporting mechanism is sufficient. And from the experimental results, we can conclude that, the insertion precise was quite satisfied with the accuracy requirement of the invasive surgery. The errors mainly come from the following causes:

- (1) mechanical clearance of the screw mechanism;
- (2) the lost steps of the stepper motor;
- (3) the buckling of the needle shaft.

6 CONCLUSION

Based on the analysis of the motion of the cannula flexible needle and the required DOFs of the insertion mechanism, a novel insertion mechanism with a supporting structure for the cannula flexible needle were designed using TRIZ and CAE. A compact and light weight insertion mechanism was obtained by the nesting principle. Furthermore, based on the separation principles, and substance-field analysis, the supporting mechanism was designed. A solution of the separate supporting blocks with elastic bands was obtained. According to the results in the finite element analysis, the initial supporting position of each supporting block was obtained. And the design of the insertion mechanism for the cannula flexible needle was shown at last. Finally, the insertion experiments were carried out using the proposed mechanism, and the maximum error was within 0.4mm, which confirmed the validity of the proposed insertion mechanism.

ACKNOWLEDGMENTS

This research is supported in part by the National Natural Science Foundation of China (Grants #51305107 and #51675142), by the Natural Science Foundation of Heilongjiang Province of China (Grant#E2015059 and #ZD2018013).

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