Abstract

We propose a special structure for an active catheter: a spiral structure. It consists of flexible belt on which actuators, sensors, and/or control units are built. The belt is spiraled or put spirally around flexible tube to work as a catheter. The actuators on one roll of the spiral move the next roll to realize the bending, twisting, and/or expanding motion of catheter. With this method, minute and complicated actuators, sensors, and circuits can be precisely machined with very high density, fabricated and wired together in one continuous plane with silicon processes. The advantage of this method will be simple and high-density fabrication. In this paper, the overview and kinematic analysis of the spiral-structure active catheter are discussed and some types of active catheters are proposed.

1 Introduction

These days, the surface micro-machining like silicon process has been developed to reduce the size of circuits, sensors and actuators. Many researchers have proposed ideas of micro-machine. One possible applications of micro-machines is minimally invasive diagnosis and treatment, because such a small surgical device would minimize the surgical trauma.

An active catheter is one of the strongest candidates for micro-machine application. Fukuda and Guo [1] proposed a wire-driven active catheter. Their catheter has advantages of easy control and simple structure, but has the disadvantage that the number of its DOFs (Degrees Of Freedom) are limited to around 2 or 3 because the wires occupy a large space and they conflict with each other. Lim’s [2] and Kaneko’s [3] prototypes are advanced with respect to multi-DOF because control units are built-in close to the actuators and they control the actuators independently. A multi-DOF catheter, which moves like snake, will extend the applications of the active catheter not only to blood vessels of the brain and heart, but also to paranasal sinuses and nasotracheal brain treatments.

However, one of the most significant problems for active catheters with built-in control units is that of assembling and wiring. Lim made each link separately and assembled them with laser CVD. Kaneko proposed a MIF (Multi-function Integrated Film), which is flexible film on which control units and SMA (Shape Memory Alloy) are mounted monolithically but each MIF is not connected.

The assembly and wiring problem is caused by the fact that almost micro-machinings, e.g. deposition, etching, sputtering, and masking, are plane processes, so it is difficult to manufacture 3-dimensional objects. This means that a plane structure that can be easily transformed into a solid is advantageous for a micro-machine active catheter. In next section, we propose a SS (Spiral Structure) for and active catheter because it can be easily transformed from a plane to a tube.

2 Outline of Spiral Structure

Basic and common ideas of Spiral Structures (SS) are explained here. Fig. 1 shows one of SS (a 4-DOF type), and the other types will be discussed later.

The SS consists of a flexible belt. The space between the upper and lower sides of the belt is empty or elastic enough for both sides to move separately. The belt is spiraled or put spirally around flexible tube so that the upper side of the belt and the lower side of the next belt are united and move together.

Both sides are connected by some actuators and these actuators generate the relative motion between both sides. For a 4 DOF type, 4 linear actuators are arranged for one roll of the belt. Combinations of
expanding and contracting motions of the 4 linear-actuator generate 4-DOF motion: — 2 bending, twisting and expanding. For example, the catheter expands when all actuators expand.

In the following, we modeled the spiral structure as cylinder hollow.

1. How many DOFs a catheter has.
To decide the number of actuators, it has to be known how many DOFs the mechanism has. The catheter has infinite DOF because it is so elastic and flexible that any motion are possible if sufficient loads are applied or any deformation can be detected however small it is. So we analyzed which motion may occur with less force.

2. How many DOFs are necessary.
It is discussed what kinds of motion are necessary for conventional and new treatments. The catheter should be designed to meet it.

3. Verify how actuators work.
The actuators, which are designed according to possible and requested motion don’t always move as intended. The former two items are necessary condition but not sufficient condition.

4 Possible DOF of Catheter
Eq. 1 formulates the relationship between external forces and displacement of tip of a tube. The matrix $K$ is a compliance matrix, meaning the flexibility of object. As shown in Eq. 2, the $K$ can be diagonalised with orthogonal matrix $T$ because it is symmetric. The reason why with orthogonal matrix is that the magnitude of power remains constant ($F_x^2 + F_y^2 + F_z^2 + M_x^2 + M_y^2 + M_z^2 = const$) and each vector is independent. In practice, some coefficients need be applied because force and moment have different units. For simplicity, the values of $T$ are not shown here, but only plus or minus are shown.

$$\delta X = T^{-1} \begin{pmatrix} \lambda_1 & 0 \\ 0 & \ddots & \lambda_6 \end{pmatrix} T \cdot F$$

$$\lambda_{1,2} = \frac{a+b+\sqrt{(a-d)^2+4b^2}}{2}$$

$$\lambda_3 = \frac{c}{e}$$

$$\lambda_{4,5} = \frac{a+b-\sqrt{(a-d)^2+4b^2}}{2}$$

$$\lambda_6 = \frac{e}{c}$$

$$T = \begin{pmatrix} t_1 \\ \vdots \\ t_6 \end{pmatrix} = \begin{pmatrix} +0000+0 \\ +000−00 \\ 0+0000 \\ 0+0+00 \\ −000+0 \\ 00000+ \end{pmatrix}$$
\[ \delta X = \begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ \delta p \\ \delta q \\ \delta r \end{pmatrix} = K \begin{pmatrix} a & 0 & 0 & 0 & b & 0 \\ 0 & a & 0 & -b & 0 & 0 \\ 0 & 0 & c & 0 & 0 & 0 \\ 0 & -b & 0 & d & 0 & 0 \\ b & 0 & 0 & 0 & d & 0 \\ 0 & 0 & 0 & 0 & 0 & e \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{pmatrix} \]

(1)

\[ \begin{align*}
\delta x, \delta y, \delta z &: \text{Translation in x,y,z axis,} \\
\delta p, \delta q, \delta r &: \text{Rotation around x,y,z axis,} \\
F_i &: \text{External forces in } i \text{ axis,} \\
M_i &: \text{External moments around } i \text{ axis,} \\
E &: \text{Young's modulus,} \\
G &: \text{modulus of rigidity,} \\
r_1 &: \text{Inside radius,} \\
r_2 &: \text{Outside radius,} \\
l &: \text{length} 
\end{align*} \]

\[ \lambda_i \text{ means flexibility in } t_i \text{ direction (combination of forces and moments). Noting the difference between } \lambda_{1,2} \text{ and } \lambda_{4,5}, \lambda_{1,2} \text{ are always larger than } \lambda_{4,5}. \text{ In addition, according to numerical inspection, } \lambda_{1,2} \gg \lambda_{4,5}. \text{ This fact explains that motion (a) in Fig. 2 occurs more easily than motion (b).} \]

2 DOFs of \( \delta x, \delta y, \delta p \) and \( \delta q \) are negligible in comparison to 2 others (Notation of \( \delta x, \) et al., are shown in Eq. 1). There is another reason why \( \delta x \) and \( \delta y \) are negligible. The rotational motion causes more displacement at a distant point.

As for \( \delta z \) and \( \delta r \), the flexibility depends on size and shape, e.g. corrugated tube has more flexibility to \( \delta z \).

This analysis concludes that catheter has 2-4 DOFs.

5 Required DOF of Catheter

A micro active catheter has been demanded for the navigation of instruments in cerebral and cardiac vessel. The vessel guides the catheter, so active bending motion is needed at sharp corner and divergence. So 2 DOFs of bending motions are indispensable for active catheter.

In tubular organ, like vessel, colon and urinary duct, the catheter is free from axial torque. If it were applied to non-tubular organ like paranasal sinuses ventricle of the heart, 1 DOF or stiffness of twisting motion is necessary to resist axial torque.

Today’s active catheter advances being pushed from the back. It is dangerous when the catheter might break through the wall of vessel. Self-propelling, like snake-like or inching motion might facilitate the insertion. So 1 DOF of expanding motion along the axis is useful.

In this section, we conclude that 2-4 DOFs of movement are necessary according to its application.

6 Types of Spiral Structures

The discussions in the former sections lead that catheter has 2-4 DOFs and 2-4 of them must be actuated according to application and the rest of them must be constrained. We would propose 5 types of SS, 1 for 4-DOF, 2 for 3-DOF and 2 for 2-DOF as shown in Fig. 3.

Figure 3: Types of Spiral Structures

The actuators proposed here are bending and linear ones. SMA is widely used as bending actuator. SMA is also used as linear actuator but fluid actuator and ultrasonic motor would be able to be used in future.
(a) 4-DOF(δz, δp, δq, δr): This is a kind of parallel mechanism with linear actuators. One roll of spiral has 4 linear actuators. The combinations of expansions and contractions of actuators realize bending, expanding and twisting motions.

(b) 3-DOF(δz, δp, δq): One roll of spiral has 3 linear actuators. When all of them contract, the catheter contracts. When one of them contracts, the catheter bends to the actuator.

(c) 3-DOF(δp, δq, δr): One roll of spiral has 8 bending actuators. 4 of them bend outside and the rests bend so that the upper side slides along spiral. The former is bending motion and the latter is twisting motion.

(d) 2-DOF(δp, δq): This type bends in the same way as (c) but doesn’t twist.

(e) 2-DOF(δp, δr): This type bends in the same way as (b) but doesn’t expand. For symmetry, this type shown in Fig. 3 has 4 linear actuators. So actuator moves contrary to opposite one.

7 Evaluation of Motions

In this section, it is tested with FEM (Finite Element Method) how the catheter moves and what is the best configuration of catheter. The reason why the verification is necessary is that any arrangement cannot always generate required motion. For example, if all actuators of (a) 4-DOF stay in parallel, the catheter doesn’t twist. The conditions of FEM are shown in Table 1.

<table>
<thead>
<tr>
<th>FEM Program</th>
<th>Free Z88 developed by Dr. F. Rieg, Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem Type</td>
<td>Normal (Not Hyper-elasticity)</td>
</tr>
<tr>
<td>Element Type</td>
<td>Hexahedron with 8 nodes</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>2.0e-6 (that of rubber)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.46 (that of rubber)</td>
</tr>
</tbody>
</table>

Table 1: Conditions of FEM

The Young’s modulus and Poisson’s Ratio are specified but the purpose of this analysis is not absolute evaluation of catheter motion but relative evaluation among different configurations. So these values are not important. For the same reason, the values have no unit (usually FEM program has no unit) and the outside radius \( r_1 \) is fixed to 0.5 (diameter=1.0). The inside radius \( r_2 \) and pitch of spiral \( t \) vary from 0.05 to 0.45, from 0.1 to 2.0 respectively (see Fig. 4).

7.1 4-DOF(δz, δp, δq, δr)

Fig. 5, 6, and 7 show the displacement of the tip of one roll in z-axis, around x- and z-axis respectively when one of 4 actuators exerts normalized force 1.0. So 4 values of displacements are plotted for every radius and pitch. The results of displacement around y-axis are not exactly the same as that of x-axis but have the same tendency, so they are omitted here.

The displacements are divided by the pitch of spiral because the ratio of change is important. Each actuator is coordinated as shown in Fig. 4 (a). The normalized forces are applied oppositely at both sides of actuator.

It can be said as a whole that the value of displacement tends to follow \( \frac{1}{(r_1^2-r_2^2)} \) (n=2 or 4) (See the lower graphs of figures).

As the pitch gets longer, the actuators becomes perpendicular and the vertical force increases but the horizontal decreases (See the upper graphs of figures). So there is a trade-off between \( \delta r \) and the others.

7.2 3-DOF(δz, δp, δq)

Fig. 8, 9, and 10 show the displacements in z-axis, around x- and y-axis respectively when one of 3 actuators exerts normalized force 1.0. So 3 values of
displacements are plotted for every radius and pitch. Each actuator is coordinated as shown in Fig. 4 (b). The normalized forces 1.0 are applied oppositely at both side of actuator. The displacements are also divided by the pitch of spiral.

The value of displacement tends to follow $\frac{1}{(r^2 - r_1^2)}$ (n=2 or 4) too (See the lower graphs of figures). As for pitch, the displacements convergent to constant value (See the upper graphs of figures).

### 7.3 3-DOF($\delta p$, $\delta q$, $\delta r$)

The SMA, which memorizes bending motion exerts moment on the wall of catheter, so it is modelled as $fs$ are applied on both side of SMA and $-2f$ on middle of SMA as shown in Fig 4 (c) and (d). The moment $m = f \times l$ is kept to 1.0 to normalize the load.

Fig. 11 show the displacements around y-axis when the bending moment is applied. This type has 4 actuators for bending motion. The same results are obtained as for the others so they are omitted.

The FEM indicates no twisting motion. As shown in Fig. 12, the counter moment cancel the bending motion because stiffness of catheter is uniform.

So the lower side has to be reinforced to resist against the counter moment while keeping flexibility of the upper side. In practice, the flexible belt should be stiffer than the tube which the belt is spiraled to. This analysis is one of future works.

### 7.4 2-DOF($\delta p$, $\delta r$)

The results are the same as those of 3-DOF($\delta z$, $\delta p$, $\delta q$), Fig. 9 and 10. So they are omitted here.

### 7.5 2-DOF($\delta p$, $\delta r$)

The results are the same as those of 3-DOF($\delta p$, $\delta q$, $\delta r$), Fig. 11. So they are omitted here.
8 Summary and Conclusions
In this paper, we proposed the Spiral Structure for active catheter. We discussed its three kinematic problems: how many DOFs one roll of spiral has and should have and verified how it works.

According to this discussion, we concluded that it should have 2-4 DOF of 2 bending, expanding and twisting motions. So we proposed 5 types of Spiral Structure.

We tested with the FEM how it works and what the best configuration is. Then we also found that it is necessary to increase the stiffness of the lower side while keeping the flexibility of the upper side.

9 Future Works
As mentioned in the introduction, our concept is that a plane structure, which can be easily transformed into 3-D object, is suitable for micro-machine. It is not main subject of our research to develop integrated circuits, sensors, or actuators.

However, a simulation work is not sufficient to prove whether our structure is useful or not. Now we are developing the prototype of Spiral Structure.

References