Design of Intestinal Modular Robot and Dynamics Analysis of Its Docking Mechanism

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Abstract: This paper presents a modular design scheme of intestinal capsule robot, and establishes the analysis model of multi-module docking mechanisms. Firstly, the overall structure design of the intestinal module robot and the method of rod-cone docking in the intestinal tract are given. Then, by dividing the modules into installation module and docking module, the coordinate transformation method and virtual simulation analysis model for the two modules to realize docking in the intestine are constructed. Finally, the docking process of adjacent modules is simulated using dynamic analysis software, and the experimental results verify the effectiveness of the design.

1 INTRODUCTION

In order to overcome the limitations of capsule endoscopy, many research institutions have carried out a lot of improvement works in the past 20 years, and have successively developed two kinds of capsule endoscopes: magnetic control capsule and magnetic rotary capsule (Madani et al., 2016; Phan et al., 2021; Qian et al., 2018; Zhang et al., 2020; Zhang et al., 2017). The magnetic control capsule endoscope can realize three-dimensional movement, which is suitable for diagnosing the expanded gastric cavity, but its disadvantage is that the positioning of the capsule in the body is not accurate, and because of the small magnetic traction, it is difficult to achieve effective movement in the intestine. The magnetic rotary capsule endoscope also has some limitations: for example, when the capsule moves, it needs to fill the intestine with transparent liquid medium, but when the liquid is not full, the rotary capsule is easy to twist the intestine, causing intestinal damage.

Micro gastrointestinal robot is one of the most potential alternatives to traditional gastrointestinal endoscopy, and has been a research hotspot in the field of medical devices in recent years. At the beginning of gastrointestinal robot research, in view of the limitations of capsule endoscope, prototypes of gastrointestinal robots based on many bionic principles have been designed one after another, providing them with the function of imitating the active movement of Inchworm, beetle, cockroach, fish, etc. (Kosa et al., 2006; Li et al., 2007; Menciassi et al., 2004; Moglia et al., 2007; Park et al., 2006). The motion mechanism is the key and difficult point in the development of gastrointestinal robot. The ideal motion mechanism should have the ability of bidirectional movement, expansion and residence in the intestinal tract, and its principle is simple, easy to realize and its size is miniaturized (Buselli et al., 2009; Gao et al., 2016; Gao et al., 2019; Lu et al., 2018; Wang et al.,2013; Zhang et al., 2020).

The method of adding a motion mechanism to the capsule increases the number of various parts that need to be integrated into the capsule, which inevitably increases the overall size of the robot, so that it cannot be orally swallowed by the person to be examined. Therefore, researchers put forward the design idea of building a modular robot system based on magnetic self-assembly. The main idea is to swallow one capsule module each time, and multiple

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modules are swallowed in turn, and finally assembled in the gastrointestinal tract (Li et al., 2018; Nagy et al., 2010; Zygomalas et al., 2014). At present, the method of realizing the docking of multiple capsule modules based on the principle of magnetic adsorption in the gastric cavity is usually used. However, the magnetic interaction between modules is essentially a passive effect, therefore, the docking process between modules simply relying on it is uncontrollable. Meanwhile, after multiple modules are swallowed into the human gastric cavity, their initial mutual positions and their respective postures in the three-dimensional space have many possibilities, thus, it objectively leads to a certain degree of contingency in achieving successful assembly.

In this paper, a design of capsule modular robot based on conical rod docking mechanism is proposed, and the effectiveness of its docking method is verified by dynamic analysis.

2 DESIGN OF INTESTINAL MODULAR ROBOT

2.1 Overall Structure of Intestinal Modular Robot

The intestinal modular robot mechanism designed in this paper is shown in Figure 1, which is composed of three modules, namely module-I, module-II and module-III. Among them, module-I and module-III are of the same structure (Figure 2a, 2b), which is called installation module, and module-II is of abnormal structure (Figure 2c), which is called docking module. The installation module mainly consists of: a radial expansion mechanism, a radial expansion transmission device and a docking cone with double symmetrical configuration. The docking module includes a bidirectional telescopic driving device and a bidirectional telescopic docking rod. The mechanism transmits power to the radial expansion mechanism to expand the intestinal tract through the radial expansion drive device of the installation module, and then drives the telescopic movement of the docking rod through the telescopic driving device of the docking module, and completes the connection between the installation module and the docking module by using the guidance of the docking cone of the installation module. Here, the dimension of installation module is radial diameter Φ14.9mm, axial length 29mm, and that of docking module is radial diameter Φ13mm, axial length 24mm.

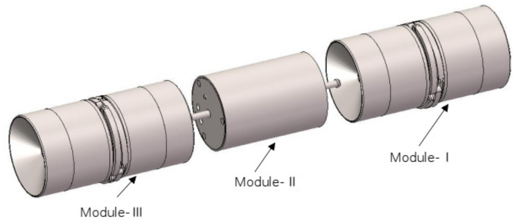

Figure 1: Overall structure of intestinal modular robot.

2.2 Assembly Process of Modular Robot

Figure 3 shows the docking process of three capsule modules in the intestine. When the first installation module (module-I) enters the intestinal tract, its radial expansion mechanism is opened so that module-I resides here; Then, when the second capsule module (module-II) approaches the first capsule module, the front-end docking mechanism of module-II is controlled to realize docking with module-I. Similarly, when the third capsule module (module-III) enters the intestinal tract and is close to the second capsule module, its radial expansion mechanism is opened to make module-III stay, and then the action of the rear docking mechanism of module-II can be

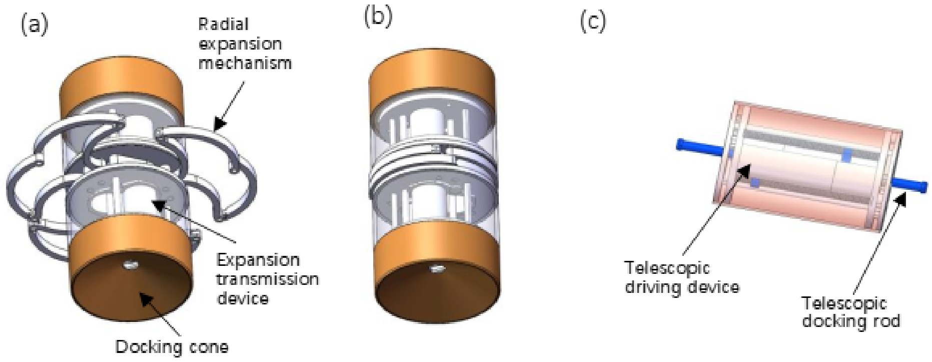

Figure 2: Main structure diagram of individual module. (a)Installation module (closed-state), (b) Installation module (open-state), (c) Docking module.

controlled to realize the docking of module-II and module-III.

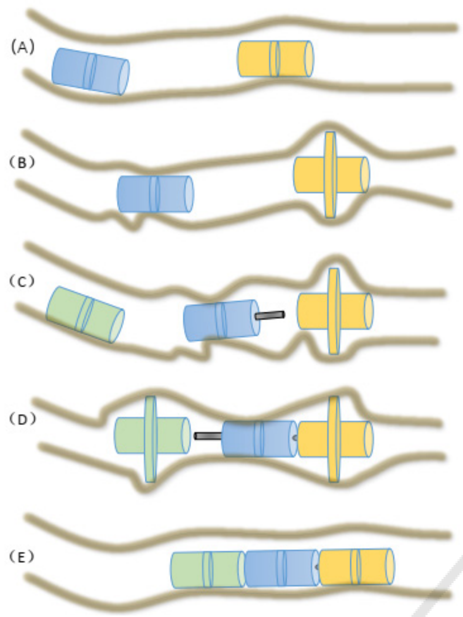

Figure 3: Schematic diagram of capsule module assembly process.

3 CONE-ROD DOCKING MECHANISM

Due to the radial deformation of the intestinal tract, when designing the docking mechanism for module robot, it is necessary to fully consider that the docking mechanism has a good deviation correction ability in the radial position of the intestinal tract. Therefore, this paper studies and designs a cone-rod docking mechanism with a certain envelope space in the radial circumferential direction to ensure that the capsule module can achieve reliable docking in the flexible intestinal tract. The premise for the reliable docking of adjacent capsule modules is that the deviation of their radial relative posture is maintained in the envelope space of the docking cone at one end of the installation module. However, the relative posture of the capsule module in the intestine shows a certain range of randomness because of the viscoelastic deformation of the intestinal wall.

In order to analyze the kinematic characteristics of the module docking mechanism, the simplified model shown in Figure 4 is established. Since the installation module will reside in the intestinal tract due to the expansion tension during the docking process, its relative position with the intestinal wall is fixed during this period. Here, the origin of the global coordinate system O_1-$X_1Y_1Z_1$ is located at the geometric centre of the installation module, in which the Y_1-axis coincides with its central axis, and the X_1-Y_1 plane is taken as the tangent plane of the installation module passing through the central circle point and perpendicular to the Y-axis. While the origin of the local coordinate system O_2-$X_2Y_2Z_2$ is placed at the center of the docking surface at one end of the docking module.

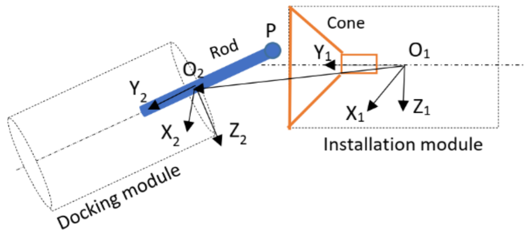

Figure 4: Analysis model of docking mechanism.

Euler angle (φ, θ, ψ) is used to define the attitude of docking module by axis $Z_2Y_2X_2$. Assume that the coordinate of point O_2 in coordinate system O_1-$X_1Y_1Z_1$ is (d_x, d_y, d_z). The formulas of coordinate rotation and translation compound transformation are as follows.

$$ {}_2^1T = Trans(d_x, d_y, d_z)Rot(x_{O2}, \psi)Rot(y_{O2}, \theta) Rot(z_{O2}, \varphi), \tag{1} $$

where,

$$ Trans(d_x, d_y, d_z) = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

$$ Rot(x_{O2}, \psi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\psi & -s\psi & 0 \\ 0 & s\psi & c\psi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3} $$

$$ Rot(y_{O2}, \theta) = \begin{bmatrix} c\theta & 0 & s\theta & 0 \\ 0 & 1 & 0 & 0 \\ -s\theta & 0 & c\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{4} $$

$$ Rot(z_{O2}, \varphi) = \begin{bmatrix} c\varphi & -s\varphi & 0 & 0 \\ s\varphi & c\varphi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{5} $$

Here, $ci, si, (i = \varphi, \theta, \psi)$ are the abbreviations of $\cos(i), \sin(i), (i = \varphi, \theta, \psi)$.

4 DYNAMIC SIMULATION OF DOCKING MECHANISM

Adams solver is used to simulate the dynamics of the docking mechanism of the module. Consider that the expansion mechanism of the installation module expands and resides in the intestinal tract.

The installation module can be regarded as relatively fixed with the intestinal pipe-1, and the docking module in the intestinal pipe-2 can be regarded as relatively fixed in the docking process due to the effect of friction as shown in Figure 5.

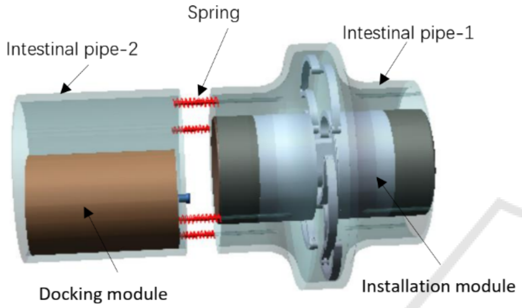

Figure 5: Virtual prototype analysis model.

In addition, four springs are arranged between intestinal pipe-1 and pipe-2 at a circumferential interval of 90° to simulate the flexible deformation of the intestinal wall. The stiffness and damping coefficient of each spring are set as 5.8E-006(N/mm) and 1.5E-006(N·s/mm), respectively.

In order to verify the effectiveness of docking module in different positions and postures, three different cases shown in Table 1 are selected to simulate and analyze the movement of docking rod. The movement speed of the docking rod along the axial expansion of the docking module is set to 2mm/s.

Table 1: Simulation parameters.

Case	Parameters	
	(φ, θ, ψ) [degree]	(dx, dy, dz) [mm]
Case 1	(-1.736,0.20,0)	(-0.44, 20.47, 4.19)
Case 2	(-1.736, -5.192, 0)	(-2.44, 20.59, 4.34)
Case 3	(3.265, 1.803, 0.114)	(3.70, 20.53, 4.14)

The results of simulation analysis are shown in Figure 6, in which motion screenshots at different time points after the start of simulation are taken respectively. It can be seen from Figure 6 that in Case-1 (Figure 6a), the docking rod-head smoothly entered the central circular hole at the top of the installation module after about 4s under the guidance

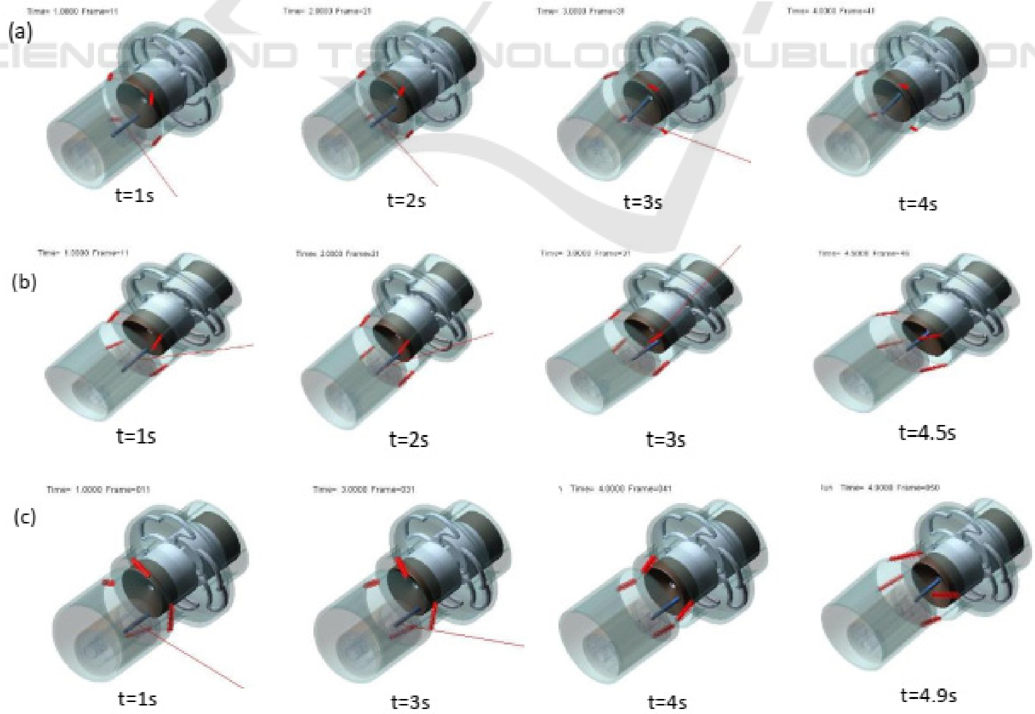

Figure 6: Snapshot of docking process in three cases. (a) Case 1, (b) Case 2, (c) Case 3.

of the docking cone, while in Case-2 (Figure 6b) and Case-3 (Figure 6c), the time required for docking completion is nearly 4.5s and 4.9s, respectively.

Figure 7 shows the trajectory of the docking rod-head in three-dimensional space during the docking movement in the above three cases. In Figure 7, the green square point represents the starting point coordinate of the docking rod-head, while the red dot stands for the end point coordinate after docking process is completed.

Table 2: Coordinates of starting point and ending point of docking rod-head.

Case	Coordinate	
	Start point	End point
Case 1	(-0.894, 25.086, 4.437)	(-0.173, 16.410, 0.265)
Case 2	(-2.808, 25.088, 4.435)	(-0.525, 15.095, 0.0587)
Case 3	(3.014, 25.168, 4.409)	(-0.986, 17.439, 0.622)

The three-dimensional coordinates of the start point and end point of the docking rod-head in the three cases are shown in Table 2. It can be seen from Figure 6 and Figure 7 that in the process of module docking, even if the position and posture of the docking module are different from the installation module within a certain range, the docking rod can successfully complete the docking of two adjacent modules under the guidance of the docking cone.

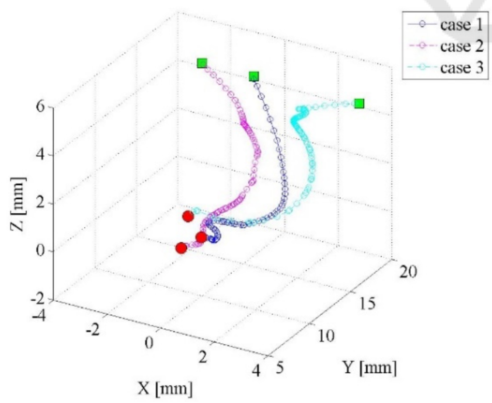

Figure 7: Trajectory diagrams of endpoint in docking rod with three cases.

5 CONCLUSIONS

This paper presented a design scheme of an intestinal modular robot based on docking cone and established the coordinate transformation method and virtual simulation model for the two modules to realize docking in the intestine. The dynamics and docking simulation process of modular docking mechanism are analyzed emphatically. The simulation results showed that the modular design of the intestinal robot proposed in this paper is feasible.

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