Structural design and Kinematics Analysis of Multi-Degree-of-Freedom (MDOF) Cable-Driven Minimally Invasive Surgical Instrument

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Abstract. In the minimally invasive surgical robot system, the traditional single-degree-of-freedom cable-driven surgical instruments have an undesirable phenomenon of motion coupling between the joints and the rotating joints of the grippers, which will affect the accuracy of the surgery. To address this issue, a new type of multi-degree-of-freedom cable-driven surgical instrument is proposed, whose joints adopt a planetary gear structure to achieve motion decoupling. First, the problem of joint motion coupling in single-degree-of-freedom cable-driven surgical instruments and its causes are analyzed. Then, a joint with planetary gear rotation is designed, and it is proved by the geometric method that it has extremely low joint coupling, and the deformation and wear of the steel wire rope during movement are extremely small. At the same time, the kinematic model of this surgical instrument is established, and the simulation model built in UGNX is used to correct the kinematic model of the surgical instrument. The operation results show that the structural design of the proposed surgical instrument is reliable, the motion coupling between joints is low, and its work can meet the requirements of minimally invasive surgery. The research results can serve as a reference for the structural design and kinematic analysis of cable-driven surgical instruments.

Keywords: Minimally Invasive Surgical Robot; Kinematics; Kinematic Decoupling; Surgical Instrument; Cable-Driven.

1. Introduction

Minimally invasive surgery (MIS), which emerged in the 1980s, has become a core development direction in the field of surgical medicine due to its advantages of small incisions and fast recovery. The performance of the end instruments of surgical robots directly determines the surgical accuracy and safety. Classified by driving method, minimally invasive surgical instruments mainly fall into three categories: rigid link type, flexible continuum type, and flexible cable-driven type. Among them, the rigid link type has a complex structure and occupies a large effective space, which is contrary to the operational concept of MIS; the flexible continuum type has shortcomings such as insufficient load capacity and difficulty in kinematic modeling. However, flexible cable-driven instruments have become the mainstream technical path due to their characteristics of light weight, high flexibility, and strong tensile strength [1].

Studies have shown that although flexible cable-driven instruments are widely used, they still face the problem of motion coupling—driving a single joint easily causes uncontrollable displacement of other joints, which seriously affects surgical accuracy. This problem is particularly prominent in surgeries that go deep into the human body, such as neurosurgery and abdominal surgery [2]. Current decoupling solutions are divided into two categories: software decoupling and mechanical decoupling. Software decoupling compensates for coupled motion through the design of control algorithms. For example, the Da Vinci system uses the Jacobian matrix to achieve master-slave mapping decoupling, but its disadvantage is that it needs to customize algorithms for different instruments, and errors are prone to occur due to the interference of electronic components [3]; mechanical decoupling eliminates coupling through structural optimization, which can realize independent control of software and hardware, avoid algorithm errors caused by electronic component interference, and has better safety [2].

Based on this, this study focuses on the innovation of mechanical structure and uses UGNX to design a 4-degree-of-freedom (4-DOF) cable-driven surgical instrument, aiming to optimize the decoupling performance of the yaw joint. The yaw joint of the instrument draws on the motion principle of planetary gears and adopts a planetary gear structure. Through the optimization of gear meshing transmission and steel wire rope routing path, the yaw motion and the action of the end gripper form motion isolation. Geometric theoretical analysis shows that this structure can significantly reduce the forced deformation of the steel wire rope and cut off the motion transmission path between joints from the mechanical level [4].

To verify the effectiveness of the design, a forward kinematic model was established using the MATLAB Robotics Toolbox, the closed solution of inverse kinematics was solved by the analytical method, and Simulink was used to analyze characteristics such as gravity load, inertia matrix, and dynamic manipulability, as well as aspects including load capacity, inertial motion, and workspace [5]. The results show that the joint coupling degree of the new instrument is lower than that of the traditional structure, the workspace can basically cover the operation demand range of minimally invasive surgery, and the positioning accuracy is not affected by electronic interference.

Therefore, the planetary gear-type yaw joint design proposed in this study provides a reliable mechanical decoupling solution for the motion coupling problem of cable-driven instruments. This structure can realize high-precision motion control without complex control algorithms, reduce the manufacturing cost of instruments and clinical application risks, and provide a reference for the structural innovation of flexible cable-driven surgical instruments [1, 6].

2. Advanced Design in the Cable-Driven Structure

2.1. Structure Designing Introduction

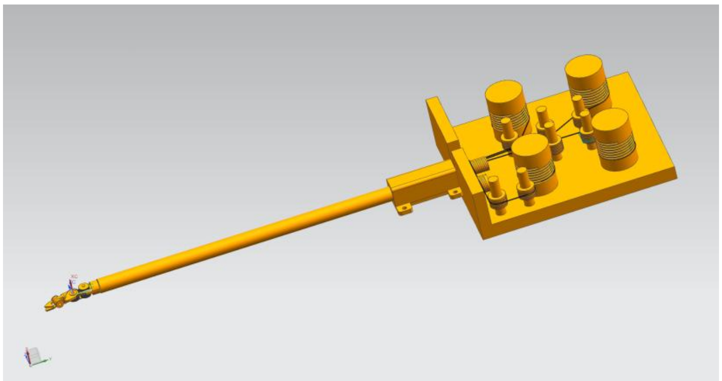


Fig. 1 The structure of the whole instrument (Picture credit: Original).

In the design (shown in Fig. 1), the components related to surgical operations are the connecting rods and the end clamping device. Among them, the yellow-marked clamping jaw and the red-marked clamping jaw serve as pitch joints, and each forms a 3-degree-of-freedom (3-DOF) serial mechanism together with the yaw joint and the connecting rod. In other words, the entire surgical instrument can be regarded as being composed of two identical 3-DOF serial mechanisms. As

shown in Fig. 2, the 4 degrees of freedom of the designed surgical instrument include the pitching and opening-closing degrees of freedom of the clamp, the rotation degree of freedom of the connecting rod, and the yawing degree of freedom of the yaw joint.

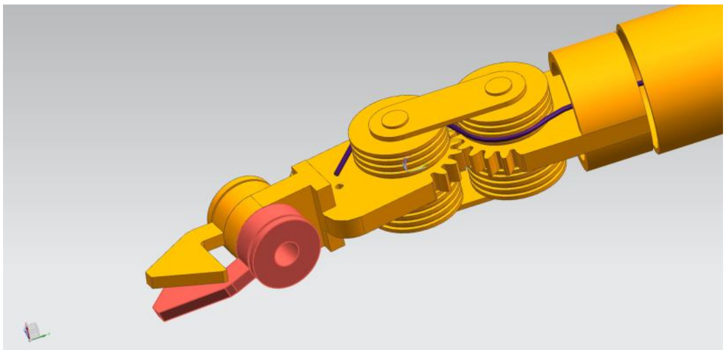
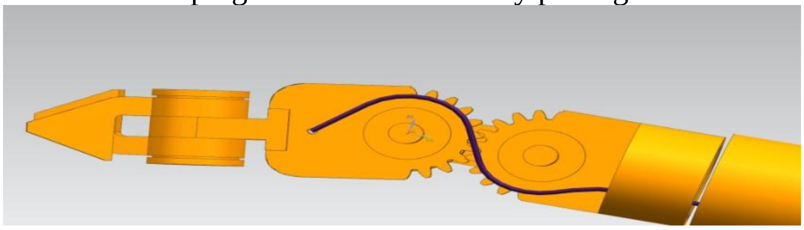
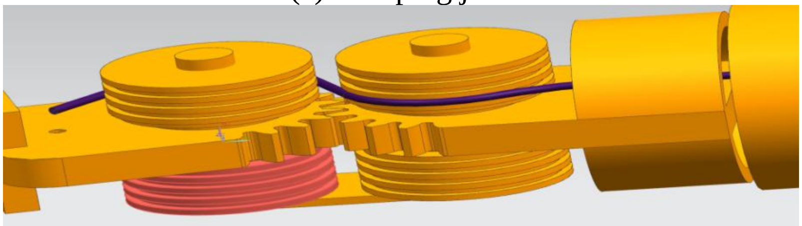


Fig. 2 The structure of the clamping device (Picture credit: Original).

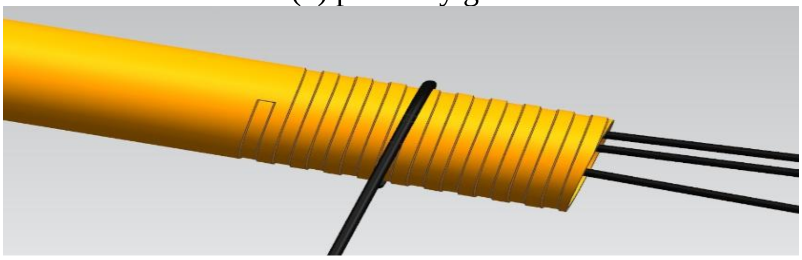
The arrangement of the driving cables for the gripper, yaw joint, and connecting rod in the new surgical instrument is shown in Fig. 3. The steel cables are fixed to various parts of the surgical instrument via cable knots, and each moves independently within its respective guide rail without mutual interference. In Fig. 3-a, the two clamping jaws of the gripper are each equipped with one steel cable and a corresponding drive motor, enabling independent driving of each clamping jaw; the guide pulley sets for the two steel cables are designed in a vertically symmetrical double-layer layout, where the upper and lower layers of guide pulleys direct the two steel cables to the two grippers respectively; the arrangement trajectory directions of the steel cables driving the same clamping jaw on the upper and lower layers of guide pulleys are symmetrical. In Fig. 3-b, a single steel cable drives the planetary gear independently to realize the yaw motion of the gripper. Additionally, as shown in Fig. 3-c, the steel cable is wound around the pipe fixed at the rear end of the connecting rod, and the rotational motion of the end clamping device is achieved by pulling the steel cable.



(a) clamping jaws



(b) planetary gear



(c) pipe

Fig. 3 The detailed structure of the driving cables (Picture credit: Original).

The driving device of this surgical instrument is located in the front-end driving unit, whose structure is shown in Fig. 4. It mainly includes a base, drive spindles for the two clamping jaws, a drive spindle for connecting rod rotation, a drive spindle for the yaw joint, and several guide pulley sets. Among them, by controlling the forward and reverse rotation of the drive spindles, the twodirectional movement of each joint of the surgical instrument can be realized. (The motor model has not been modeled.)

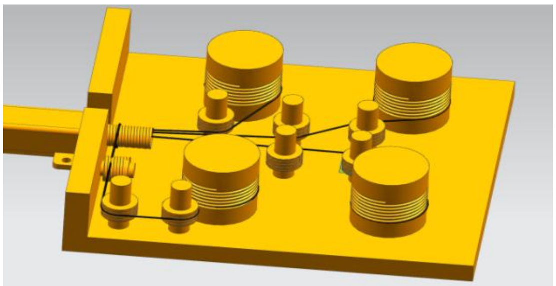


Fig. 4 The structure of the driving device (Picture credit: Original).

Upon completion of the modeling, it will proceed to establish and analyze the forward and inverse kinematic models. These models will be constructed using the MATLAB toolbox suite and validated within the Simulink environment. Concurrently, a series of characteristics, including gravitational load, inertia matrix, and dynamic manipulability, will be verified synchronously to ensure the feasibility of this design.

3. Kinematic Analysis of Cable-Driven Surgical Instruments

3.1. Establishment of the Forward Kinematic Model

The Denavit-Hartenberg (D-H) parameter method, proposed in 1955, is a classic robot kinematic modeling approach. It establishes a coordinate system for each joint and defines four core parameters (link length a, twist angle α, link offset d, joint angle θ) to map joint space to Cartesian space and determine end-effector pose. Widely used in surgical robotics, it has supported kinematic modeling for cable-driven surgical instruments (providing a structural decoupling design basis [7]) and forward/inverse kinematic analysis for lumbar surgical robot end instruments.

For this study's symmetric surgical instrument, a 3-DOF serial mechanism (single clamping jaw, planetary gear yaw joint, and connecting rod, which are simplified to be shown in Fig. 5) was analyzed, referencing multi-DOF surgical instrument modeling simplification [8]. Flexible components (steel cables, guide wheels) were removed, and the remaining rigid structure was equivalent to an open-chain mechanism (reducing coupling complexity). In the D-H coordinate system, joint angles are defined as: θ1(connecting rod rotation), $\theta_2 = \theta_3$ (planetary gear yaw, transmission ratio z=1θ4 θ_4(clamping jaw pitch). This parameter definition aligns with the da Vinci surgical robot's D-H specification, laying a foundation for subsequent simulation (Table 1) [9].

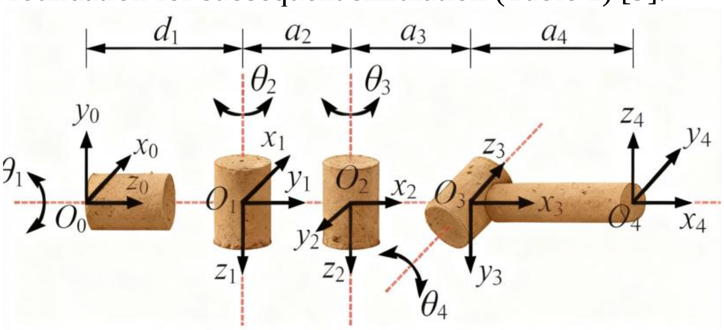


Fig. 5 The establishment of forward kinematic models (Picture credit: Original)

Table 1. D-H parameters of new cable-driven surgical instrument

i	a /°	a /mm	d /mm	θ /°
1	45	0	d1	θ_1
2	0	a_1	0	θ_2+45°
3	45	a_2	0	θ_3
4	45	a_3	0	θ_4

3.2. Inverse Kinematics Analysis

When the end pose matrix of a robot is known, an inverse kinematics solution can be achieved by calculating the joint angles θ_i of the robot. Studies have shown that the closed-form solution of inverse kinematics can be obtained if the robot meets any of the following conditions [9]:

1. The axes of three adjacent joints intersect at a single point
2. The axes of three adjacent joints are parallel to each other.

The surgical instrument designed in this paper satisfies the first condition. Therefore, based on the pose matrix of the clamping jaw 1 mentioned earlier, the algebraic inverse method is used to solve its kinematic inverse solution, and the results are as follows

$$\theta_1 = -arctan\frac{P_y - a_4 n_y}{a_4 n_x - p_x}$$

$$\theta_2 = \theta_3 = 0.5arctan\frac{o_z c\theta_1}{o_z + s\theta_1 o_y}$$

$$\theta_4 = arctan\frac{s\theta_1 n_z - c\theta_1 n_y}{c\theta_1 a_y - s\theta_1 a_x}$$

Wherein, the value ranges of each joint angle are: θ1∈[−180°,180°], θ2=θ3∈[−45°,45°], θ4∈[−90°,90°]

4. Kinematic Simulation Analysis under UG Model

4.1. Forward Kinematics Model Verification

The forward kinematics model of the cable-driven surgical instrument was verified using MATLAB's Robotics Toolbox. First, the instrument's D-H parameters were input: d1=300 mm, a2 =10 mm, a3=10 mm, a4=15 mm; a random set of joint angles was defined: θ1=45◦, θ2=θ3=−60◦, θ4 =−30◦. As shown in Fig. 6, the Robotics Toolbox simulated the single clamping jaw's position coordinates. Comparing these with the position/pose results calculated from the established forward kinematics model (using the same joint angles) revealed consistency, verifying the model's accuracy.

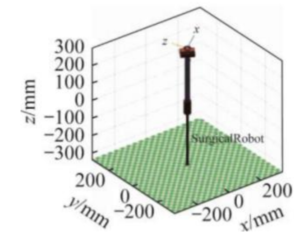


Fig. 6 The verification of forward kinematic models (Picture credit: Original)

4.2. Verification of Characteristics like Gravity Load, Inertia Matrix, and Dynamic Manipulability

(a)Verification of Gravity Load Characteristics

Gravity load is a core term in the dynamic modeling of surgical instruments, and its accurate quantification is crucial for improving the control precision of the end-effector [10]. In the cable-driven instrument of this study, the gravity of rigid components increases cable tension, affecting positioning accuracy.

Verification: Theoretical gravity load was calculated using structural parameters (Fig. 7). Referring to the gravity compensation algorithm in [10], a simulation model was built in MATLAB. The validity of the gravity term was verified by comparing end-effector pose deviations with and without gravity consideration. Results are shown in the Fig. 7 (pose error curve under specific gravity conditions).

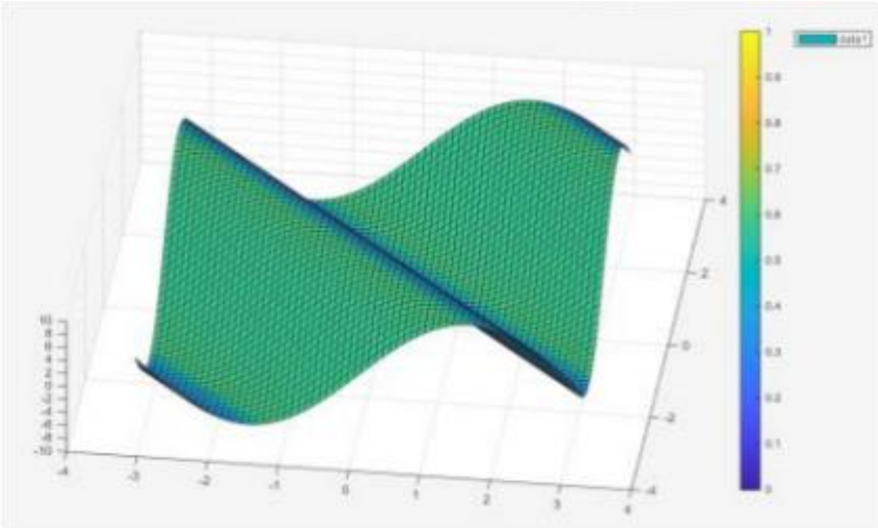


Fig. 7 The verification of Gravity Load Characteristics (Picture credit: Original)

(b)Verification of Inertia Matrix Characteristics

The inertia matrix reflects the mass distribution of components and their resistance to rotation, serving as the basis for accurately predicting the dynamic response of the instrument [11]. For the multi-degree-of-freedom mechanism in this study, the inertia matrix is related to the mass and centroid of each link, directly influencing the calculation of driving torque.

Verification: Inertial parameters of components were extracted in MATLAB to construct a theoretical matrix (Fig. 8). Referring to the "CAD-experiment" method in [8], actual parameters were obtained via a dynamic test platform, and consistency was evaluated using root mean square error (RMSE). Results are shown in the Fig. 8 (RMSE comparison between theoretical and experimental matrices), with small errors indicating matrix accuracy.

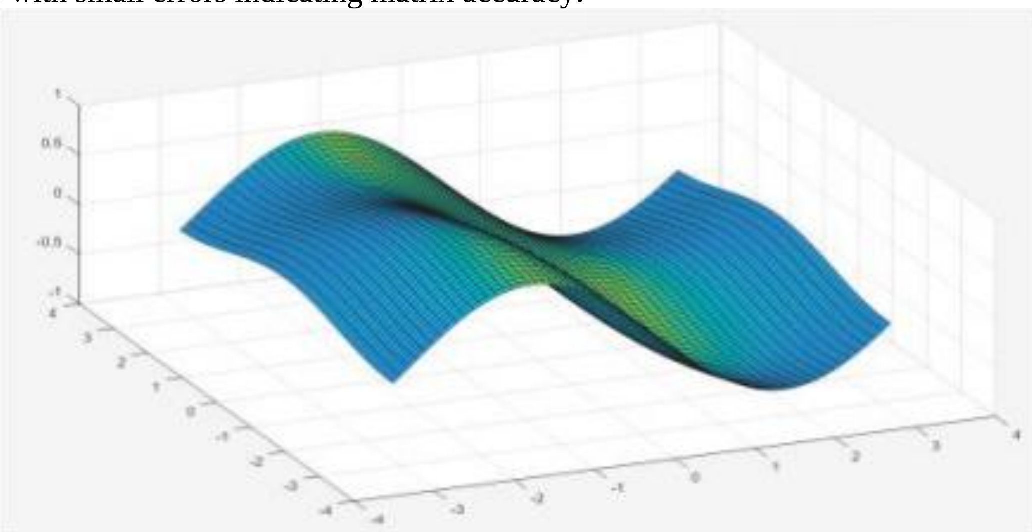


Fig. 8 The verification of Inertia Matrix Characteristics (Picture credit: Original)

(c)Verification of Dynamic Manipulability Characteristics

Dynamic manipulability measures the end-effector's motion capability under force and velocity constraints, being a key index for evaluating the operational flexibility of surgical instruments [12]. For the instrument in this study, dynamic manipulability is related to joint stiffness and cable tension, providing a basis for structural optimization.

Verification: Based on the dynamic equation and Jacobian matrix, a dynamic manipulability ellipsoid was constructed with reference to [12]. The dynamic manipulability index (DMI) under typical postures was calculated, and its variation with joint angles was analyzed. Results are shown in Figs. 9 and 10 (manipulability ellipsoid and DMI curve), indicating sufficient dynamic manipulability within the working space.

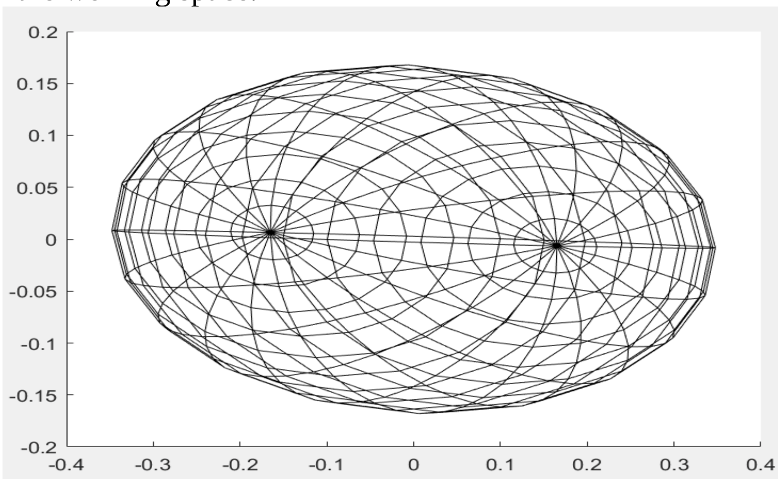


Fig. 9 The manipulability ellipsoid (Picture credit: Original)

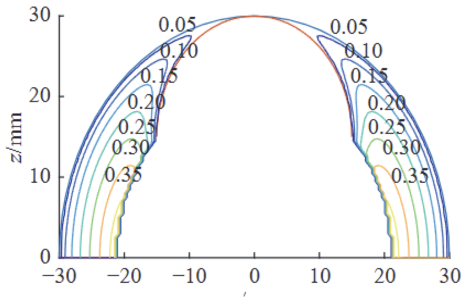


Fig. 10 The Manipulability in workspace of a surgical instrument (Picture credit: Original)

5. Conclusion

To address the issue of joint motion coupling in traditional cable-driven minimally invasive surgical instruments, this study designed a new multi-degree-of-freedom cable-driven instrument with a planetary gear structure to achieve motion decoupling. A forward kinematic model was established based on the Denavit-Hartenberg (D-H) parameter method. Through UGNX simulation and MATLAB verification, the model calculation results were consistent with the simulation results, validating the correctness of the forward and inverse kinematic analyses. Additionally, verification of characteristics such as gravity load confirmed the reliability of the instrument, indicating that its performance meets the requirements of minimally invasive surgery. These results can provide references for the design and kinematic analysis of related instruments.

However, the study has limitations: no physical prototype trial production or clinical scenario testing was conducted. In the future, prototypes can be manufactured and combined with simulation experiments to verify operational performance. Further optimizations can be made in areas such as multi-joint coordinated control, steel cable wear protection, and force feedback accuracy to enhance the clinical applicability of the instrument.

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