Intuitive control algorithm of a novel minimally invasive surgical robot

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ABSTRACT

Background: Minimally invasive surgery (MIS) based on computer and robot-assisted technology is becoming more and more popular.

Methods: Intuitive motion control implemented by kinematic algorithm of the slave manipulator based on the 3D Display (DD) is proposed to eliminate absonant hand-eye coordination, kinematic dissimilarity and workspace mismatch of the master-slave manipulator and is applied in the novel minimally invasive surgical (MIS) robot developed in our lab. Forward and inverse kinematics of MIS robot are analyzed based on the screw theory. The kinematic algorithm of MIS robot based on the DD is achieved.

Results: The trajectory tracking results that the movement trends between the master and slave manipulators consistently validate the effectiveness of forward and inverse kinematics. The simulation results of the kinematic algorithm by virtue of Simulink and SimMechanics sub-modules of the MATLAB and intuitive control experiment that the root mean square error of cumulative position increments is less than 0.5 mm validate effectiveness of intuitive control algorithm.

Conclusion: Successful animal experiments furthermore validate the effectiveness of intuitive control algorithm.

KEYWORDS

Forward kinematic; intuitive control; inverse kinematic; MIS

Introduction

With the advantages of less trauma, few postoperative disease, quick rehabilitation and so on, at the same time, with the development of the computer and robot-assist technology, minimally invasive surgery (MIS) has made rapid progress and is becoming more and more popular. There are two successful compute and robot-assisted MIS systems, Da Vinci system and Zeus system.[1,2] The Raven system is a compact and lightweight robot and designed for military use in the University of Washington.[3,4] The DLR MIRO system is designed to achieve a high degree of versatility and allows for bimanual endoscopic tele-surgery with force feedback.[5] Bogue [6] designed the “Surgeon’s Operating Force-feedback Interface Eindhoven” robot called Sofie integrating force feedback. Berkelman and Ma [7] designed a smaller, simpler, modular and tele-operated robotic systems for MIS.

The improvement of computer and robot-assist technology is not only to improve the robotic structure and function but also design better kinematic control algorithm for the slave manipulator to accomplish surgical operation with preferably comfortable operation posture for surgeon. Stefanie Speidel et al. [8] proposed a method to tracking the instrument trajectory in the operation by virtue of endoscopic image sequences, these image information can be applied for surgical gesture interpretation. Weede et al. [9,10] presented an endoscopic navigation for MIS, which predicted instruments for autonomous guidance of the endoscopic camera based on the knowledge extracted by trajectory clustering, maximum likelihood classification and a Markov model. Reiley et al. [11] have used statistical modeling for capturing variability. Wei et al. [12] proposed a visual tracking method for stereo endoscopy with robustness, simplicity and working frequency being 7Hz. Staub et al. [13] proposed a method based on kinematic pose prediction and image analysis to track surgical instruments. A filtering method proposed by Stephen is utilized to estimate the shape and end effector pose of snake robot.[14]

Intuitive control realized by kinematic algorithm of the slave manipulator based on DD is proposed for the endoscopic and instrument manipulator to be suitable for doctor’s habits; it can eliminate absonant hand-eye coordination, kinematic dissimilarity and workspace mismatch of master-slave manipulator.
Methods

The overview of MIS robotic system

The robotic system designed for holding surgical instrument and endoscopy for surgical operation in abdominal MIS is shown in Figure 1. The robotic system comprises three parts: the master console, the slave device and the surgical instrument. The master console is composed of two 7-degrees-of-freedom master manipulators produced in force dimension that are applied to control three slave manipulators to accomplish surgical operation, four pedals used to switch between various functions, control box, 3D monitor, auxiliary lights and auxiliary buttons. The slave device contains three manipulators, each slave manipulator comprises of macro and micro positioning mechanisms. Macro positioning mechanism adopts SCARA configuration with one translational degree of freedom (DoF) and two rotational DoFs. Micro mechanism is applied to realize remote center motion (RCM). The two slave robotic manipulators are used to hold clamps, forceps, scissors, needle holders and so on. The other robotic arm is utilized to grip endoscopy to collect image of the surgical area and send to the monitor for 3D display.

Forward kinematics of the slave manipulator

Each manipulator for holding the surgical instrument consists of the passive part with three DoFs \((q_1, q_2, q_3)\) and the active part with six DOFs \((q_4, q_5, q_6, q_7, q_8, q_9)\). The base coordinate \(S\) is mounted on the bottom of the table to calculate the position and posture (PAP) of manipulator for holding endoscopy or surgical instrument. The initial configuration of the slave manipulator is depicted in Figure 2.

To construct the twists for the revolute and prismatic joints relative to the base frame \(S\) for the manipulator holding surgical instrument, we have

\[
\begin{align*}
\omega_1 &= \omega_2 = \omega_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T, \\
\omega_4 &= \begin{bmatrix} c_1 & 0 & -s_1 \end{bmatrix}^T, \\
\omega_5 &= \begin{bmatrix} c_1 c_2 & -s_2 & -c_2 s_2 \end{bmatrix}^T, \\
\omega_6 &= \begin{bmatrix} -s_1 s_3 + c_1 c_2 c_3 & -s_2 c_3 & -s_1 c_2 c_3 - c_1 s_3 \end{bmatrix}^T, \\
\omega_7 &= \begin{bmatrix} -s_1 s_3 + c_1 c_2 c_3 & -s_2 c_3 & -s_1 c_2 c_3 - c_1 s_3 \end{bmatrix}^T, \\
\omega_8 &= \begin{bmatrix} -s_1 c_3 - c_1 c_2 s_3 & s_2 s_3 & s_1 c_2 s_3 - c_1 c_3 \end{bmatrix}^T, \\
\omega_9 &= \begin{bmatrix} -c_1 s_2 & c_2 & -s_1 s_2 \end{bmatrix}^T
\end{align*}
\]

where \(s_1 = \sin(\beta_1), c_1 = \cos(\beta_1), s_2 = \sin(\beta_2), c_2 = \cos(\beta_2), s_3 = \sin(\beta_3), c_3 = \cos(\beta_3)\).

To construct the twists for the revolute joints and prismatic joints relative to the base frame \(S\) for the manipulator holding endoscopy, consider

\[
\begin{align*}
\omega_1 &= \omega_2 = \omega_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T, \\
\omega_4 &= \begin{bmatrix} c_{11} & 0 & -s_{11} \end{bmatrix}^T, \\
\omega_5 &= \begin{bmatrix} c_{11} c_2 & -s_2 & -c_2 s_2 \end{bmatrix}^T, \\
\omega_6 &= \begin{bmatrix} -s_{11} s_3 + c_{11} c_2 c_3 & -s_2 c_3 & -s_{11} c_2 c_3 - c_{11} s_3 \end{bmatrix}^T
\end{align*}
\]
Inverse kinematics of the manipulator holding surgical instrument

The active part of the manipulator comprises of one prismatic joint and five revolute joints. The RCM mechanism with first three joints \(q_4, q_5, q_6\) is used to achieve the position control of the end-effector depicted in Figure 2(a). The surgical instrument with three joints \(q_7, q_8, q_9\) is applied to accomplish the posture control of the forceps shown in Figure 2(a).

Based on Equation (8), Equation (9) can be obtained as follows:

\[
\begin{align*}
g_{st}(\theta_9)g_{st}(0)^{-1}(e^3_9)^{-1} &= g_{st}e^{\frac{q_9}{9}} \\
q_9 &\text{ can be obtained.}
\end{align*}
\]

Since \(q_9\) is known, Equation (9) becomes

\[
e^3_8 e^5_8 e^6_8 e^7_8 e^8_8 = g_{st}e^{\frac{q_9}{9}}e^{\frac{q_8}{8}}
\]

First, a point \(p_{B}\), which is the intersection point of the axes of the \(q_6, q_7, q_8\) joints is applied to both sides of Equation (11); second, \(p_4\), which is the intersection point of the axes of the \(q_4\) and \(q_5\) joints is subtracted from both sides, lastly, taking the modulus of both sides of the equation yields

\[
||p_{8} - p_{4}|| = g_{st}(e^3_8 p_{B} + p_{4})
\]

\(q_8\) can be solved by applying sub-problem 3.[15]

Since \(q_8\) and \(q_9\) are known, Equation (9) becomes

\[
e^3_8 e^5_8 e^6_8 e^7_8 e^8_8 = g_{st}e^{\frac{q_9}{9}}e^{\frac{q_8}{8}}
\]

A point \(p_{B}\), which is the intersection point of the axes of the \(q_6\) and \(q_7\) joints is applied to both sides of Equation (13), this yields

\[
e^3_8 e^5_8 e^6_8 e^7_8 e^8_8 = e^3_8 \frac{q_9}{9} \frac{q_8}{8} \frac{q_7}{7} \frac{q_6}{6} p_{B} = g_{st}e^{\frac{q_9}{9}}e^{\frac{q_8}{8}} e^{\frac{q_7}{7}} e^{\frac{q_6}{6}} p_{B}
\]

\(q_4\) and \(q_5\) can be calculated using sub-problem 2.[15]

Since \(q_4, q_5, q_8\) and \(q_9\) are known, Equation (9) becomes

\[
e^3_8 e^5_8 e^6_8 e^7_8 e^8_8 = g_{st} e^{\frac{q_8}{8}} e^{\frac{q_9}{9}} e^{\frac{q_6}{6}} e^{\frac{q_7}{7}}
\]
A point \( \mathbf{p}_9 \) is applied to both sides of Equation (15), which yields:

\[
\begin{bmatrix}
\mathbf{e}_1^q \\
\mathbf{e}_2^q \\
\mathbf{e}_3^q
\end{bmatrix}
\begin{bmatrix}
q_6 \\
q_7
\end{bmatrix} =
\begin{bmatrix}
\mathbf{e}_1^s \\
\mathbf{e}_2^s \\
\mathbf{e}_3^s
\end{bmatrix}
\begin{bmatrix}
\mathbf{g}_1 \mathbf{e}_1^s \\
\mathbf{g}_2 \mathbf{e}_2^s \\
\mathbf{g}_3 \mathbf{e}_3^s
\end{bmatrix}
\begin{bmatrix}
\mathbf{p}_9
\end{bmatrix}
\]  

(16)

\( q_6 \) and \( q_7 \) can be obtained by applying sub-problem 2.[15]

**Inverse kinematics of the manipulator holding endoscopy**

Based on Equation (9), Equation (17) can be obtained as follows:

\[
\begin{bmatrix}
\mathbf{e}_1^q \\
\mathbf{e}_2^q \\
\mathbf{e}_3^q
\end{bmatrix}
\begin{bmatrix}
q_4 \\
q_5 \\
q_6
\end{bmatrix} =
\begin{bmatrix}
\mathbf{e}_1^s \\
\mathbf{e}_2^s \\
\mathbf{e}_3^s
\end{bmatrix}
\begin{bmatrix}
\mathbf{g}_1 \mathbf{e}_1^s \\
\mathbf{g}_2 \mathbf{e}_2^s \\
\mathbf{g}_3 \mathbf{e}_3^s
\end{bmatrix}
\begin{bmatrix}
\mathbf{p}_r
\end{bmatrix} =
\begin{bmatrix}
\mathbf{e}_1^s \\
\mathbf{e}_2^s \\
\mathbf{e}_3^s
\end{bmatrix}
\begin{bmatrix}
\mathbf{p}_r
\end{bmatrix}
\]  

(17)

A point \( \mathbf{p} \), which only locates on the axis of the \( q_6 \) joint is applied to both sides of Equation (17), which gives:

\[
\begin{bmatrix}
\mathbf{e}_1^q \\
\mathbf{e}_2^q \\
\mathbf{e}_3^q
\end{bmatrix}
\begin{bmatrix}
q_4 \\
q_5 \\
q_6
\end{bmatrix} =
\begin{bmatrix}
\mathbf{e}_1^s \\
\mathbf{e}_2^s \\
\mathbf{e}_3^s
\end{bmatrix}
\begin{bmatrix}
\mathbf{p}_r
\end{bmatrix} =
\begin{bmatrix}
\mathbf{e}_1^s \\
\mathbf{e}_2^s \\
\mathbf{e}_3^s
\end{bmatrix}
\begin{bmatrix}
\mathbf{p}_r
\end{bmatrix}
\]  

(18)

\( q_4 \) and \( q_5 \) can be calculated using sub-problem 2.[15]

Since \( q_4 \) and \( q_5 \) are known, based on Equation (18), \( q_6 \) can be solved.

**Intuitive control algorithm of the manipulator**

In surgery, all surgical operations are achieved based on the DD. In order to make all surgical operations to be fit for the doctors' habits, intuitive control algorithm realized by the kinematic algorithm based on DD actually is indispensable.

**The kinematic algorithm based on DD for the manipulator holding endoscopy**

During the operation, if the current display (CD) does not meet the requirement of the surgical operation, the surgeon should move the endoscopy up/down, left/right and forward/backward based on the tool coordinate (TC) of the endoscopic manipulator, then the objective display (OB) can be obtained. The absolute PAP of the endoscopy relative to the based coordinate (BC) can be calculated by the forward kinematics and is given by

\[
\mathbf{T}_{06} = \begin{bmatrix} n_{x1}, o_{x1}, a_{x1}, p_{x1}; n_{y1}, o_{y1}, a_{y1}, p_{y1}; n_{z1}, o_{z1}, a_{z1}, p_{z1}; 0, 0, 0, 1 \end{bmatrix}
\]  

(19)

\( \Delta \mathbf{p} = [0,0,0; \Delta x; 0,1,0; \Delta y; 0,0,1] \) is a transformation matrix from CD to OD based on the CD coordinate. The absolute PAP of the OB based on BC can be calculated as

\[
\mathbf{T}_{BCS} = \mathbf{T}_{06} \Delta \mathbf{p}
\]  

(20)

The PAP of the TC relative to BC can be calculated by forward kinematics and given by

\[
\mathbf{T}_{TCS} = \begin{bmatrix} n_{x2}, o_{x2}, a_{x2}, p_{x2}; n_{y2}, o_{y2}, a_{y2}, p_{y2}; n_{z2}, o_{z2}, a_{z2}, p_{z2}; 0, 0, 0, 1 \end{bmatrix}
\]  

(21)

The PAP of the OD relative to the TC can be obtained as

\[
\mathbf{T}_{TCS} = \mathbf{T}_{TCS}^{-1} \mathbf{T}_{BCS}
\]  

(22)

Then the solution of the endoscopic manipulator kinematic algorithm based on the DD can be obtained based on the inverse kinematics mentioned before. After \( q_6 \), \( q_5 \), \( q_6 \) are known, the position vector \( \mathbf{T}_{06} \) of OD relative to BC can be obtained. Then position variation of OD relative to CD based on BC can be given by

\[
(\Delta \mathbf{p}_x, \Delta \mathbf{p}_y, \Delta \mathbf{p}_z) = (\mathbf{T}_{06} - \mathbf{T}_{06}) \mathbf{T}_r, \mathbf{T}_r = [0, 0, 0, 1]^{T}
\]  

(23)

**The kinematic algorithm based on DD for the manipulator holding surgical instrument**

During surgical process, alignment between the end-effector motion of the surgical instrument on the display and the hand motion of the surgeon is very important to accomplish a variety of surgical operation. The PAP of surgical instrument based on the currently DD will be changed according to surgeon’s demand.

The BC of the endoscopic manipulator is regarded as the normalization BC. The absolute PAP of the endoscopic and surgical instrument manipulator can be calculated by the forward kinematic and are defined as \( \mathbf{T}_{B06} \) and \( \mathbf{T}_{B09} \). The PAP of the surgical instrument relative to the CD can be calculated as

\[
\mathbf{T}_{B06} = \mathbf{T}_{B06}^{-1} \mathbf{T}_{B09}
\]  

(24)

\( (x, y, z, \Delta x, \Delta y, \Delta z) \) are the expected input of surgical instrument motion relative to the CD on the basis of surgeon’s demand. The absolute PAP of the desired surgical instrument relative to the normalization BC can be calculated as

\[
\mathbf{T}_{NB09} = \mathbf{T}_{B06} \mathbf{T}_{B06} \mathbf{T}_{B09}
\]  

(25)

where

\[
\mathbf{T}_{B09} = \begin{bmatrix} \cos(x) \sin(x) \cos(y) \sin(y) \cos(z) \sin(z) \cos(y) \sin(y) \cos(z) \sin(z) \end{bmatrix}
\]

\[
\begin{bmatrix}
c_x = \cos(x), s_x = \sin(x), c_y = \cos(y), s_y = \sin(y), c_z = \cos(z)
\end{bmatrix}
\]

\[
\begin{bmatrix}
s_y = \sin(y), c_y = \cos(y), s_z = \sin(z), c_z = \cos(z)
\end{bmatrix}
\]
The PAP of the TC of surgical instrument manipulator relative to the normalization BC can be calculated by forward kinematics and given by

\[
T_{TCS} = \begin{bmatrix}
    n_{x2}, o_{x2}, a_{x2}, p_{x2};
    n_{y2}, o_{y2}, a_{y2}, p_{y2};
    0, 0, 0, 1
\end{bmatrix}
\] (26)

The PAP of surgical instrument relative to TC can be obtained as

\[
T_{TCS} = T_{TCS}^{-1} T_{NB09}
\]

The solution of surgical instrument manipulator kinematic algorithm based on the DD can be obtained based on the inverse kinematics mentioned before. After the \( q_4, q_5, q_6, q_7, q_8 \) and \( q_9 \) are known, the PAP of the surgical instrument relative to the normalization BC can be obtained. Then PAP variation of the surgical instrument relative to the current based on the normalization BC can be given by

\[
\Delta T = T_{NB09} - T_{NB09}
\]

**Results**

**Simulation analysis**

The simulation tests implemented by two sub-modules of Matlab were achieved to verify the effectiveness of kinematic algorithm based on DD mentioned before.

**Simulation analysis of the endoscopic manipulator’s kinematic**

The simulation models are built by virtue of two sub-modules of the Matlab relative to the kinematic algorithm of the endoscopic manipulator based on DD depicted in Figure 3. The expected D-H values derived by the Simulink toolbox equals the actual values produced from SimMechanics toolbox, which validates the correction of the instrument manipulator kinematic algorithm with respect to DD.

The parameters in Tables 1, 2, 4 and 5 are regarded as the inputs, the corresponding output of the hybrid simulation model are given in Table 6. The expected D-H values of the surgical instrument relative to the CD derived by the Simulink model equals the actual D-H values of motion calculated from Simmechanics model, that proves the correctness of instrument manipulator kinematic algorithm.

**Experiment to test the effective of intuitive control algorithm**

There are three experiments to test the effective of the intuitive control algorithm: the first experiment is trajectory tracking experiment; the second experiment is intuitive control experiment; last is the gall bladder removal experiments.

**Trajectory tracking experiment**

Trajectory tracking experiment is used to test the correction of the forward and inverse kinematics of the endoscopic and instrument manipulators. The master is operated according to the surgeon’s demand, then the surgical instrument or endoscopic manipulators track the motion of the master to achieve the surgical operation. The trajectory tracking is important to accomplish the surgical operation. Four trajectories experiments which are rectangle, triangle, pentagon and circle were finished and the experiment results are shown in Figure 6. The conclusion that the manipulator can achieve a good track following the motion of master can be drawn in Figure 6.

**Intuitive control experiment**

Intuitive control experiment shown in Figure 7 is applied to validate the kinematic algorithm based on DD. Figure 7(a–d) are the cumulative position increments (CPI) between the master and slave in the current vision window following four different trajectories mentioned before. The root mean square error of CPI between the master and slave is shown in Table 7. This experiment validates the effectiveness of the intuitive control algorithm. The reason of errors is the hand tremor and machine processing
Figure 3. The hybrid simulation model of the endoscopic manipulator: (a) Forward kinematic model; (b) The position calculation module of the OD relative to the CD; (c) Absolute position calculation module of the OD relative to BC; (d) Inverse kinematic model; (e) Forward kinematic model; (f) Position variation of the OD relative to the CD based on BC; (g) Forward kinematic model.

Table 1. The parameters of the endoscopic manipulator.

| $q_2$ | $q_3$ | $d_1$ | $d_2$ | $a_1$ | $a_2$ | $d_4$ | $r_1$ | $r_2$ | $r_3$ | $q_4$ | $q_5$ | $d_6$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 45    | 45    | 1800  | 567   | 100   | 400   | 100   | 120   | 74    | 51    | 0     | 0     | 100   |
and assembly errors. However, these errors can be compensated by the visual feedback. It can be seen from Figure 7 and Table 7 that the intuitive control algorithm can achieve excellent performance. The intuitive control algorithm meets the surgical requirement.

**Cholecystectomy removal experiment**

Cholecystectomy removal experiments on pigs were successfully achieved at Harbin Institute of Technology.

**Table 2.** The position vector of the OD relative to the CD.

| No. | Δx (mm) | Δy (mm) | Δz (mm) |
|-----|---------|---------|---------|
| 1   | 27.56   | 35.76   | 43.89   |
| 2   | 20.46   | 16.83   | -20.81  |
| 3   | 28.34   | -36.45  | 28.45   |

**Table 3.** The desire and actual D-H value of motion from the current window to objective window.

| No. | ΔPp_x-desired | ΔPp_y-desired | ΔPp_z-desired | ΔPp_x-actual | ΔPp_y-actual | ΔPp_z-actual |
|-----|---------------|---------------|---------------|--------------|--------------|--------------|
| 1   | -45.9886      | -0.1282       | 32.9038       | -45.9886     | -0.1282      | 32.9038      |
| 2   | -40.9073      | 1.0771        | 38.3521       | -40.9073     | 1.0771       | 38.3521      |
| 3   | 38.0317       | 6.4633        | 12.2104       | 38.0317      | 6.4633       | 12.2104      |
Table 4. The parameters of the surgical instrument manipulator.

| \( q_2 \) | \( q_3 \) | \( d_1 \) | \( d_2 \) | \( d_3 \) | \( d_4 \) | \( d_5 \) | \( d_6 \) | \( d_7 \) | \( d_{10} \) |
|---|---|---|---|---|---|---|---|---|---|
| 45° | 45° | 1800mm | 567mm | 100mm | 400mm | 100mm | 100mm | 100mm | 100mm |
| \( r_1 \) | \( r_2 \) | \( r_3 \) | \( q_4 \) | \( q_5 \) | \( q_6 \) | \( q_7 \) | \( q_8 \) | \( q_9 \) | \( q_{10} \) |
| 116° | 74° | 51° | 0.4712 | 0.3142 | 0.9425 | 80 | 1.571 | 1.6584 |

Table 5. The required parameters for simulation analysis.

| No. | \( a (°) \) | \( \beta (°) \) | \( \gamma (°) \) | \( \Delta x (\text{mm}) \) | \( \Delta y (\text{mm}) \) | \( \Delta z (\text{mm}) \) |
|---|---|---|---|---|---|---|
| 1 | 42 | -30 | 16 | 40 | -83 | 25 |
| 2 | -26 | 60 | 80 | 56 | -76 | 38 |
| 3 | -59 | 52 | 72 | -49 | 48 | -53 |

Table 6. The comparison between desired and practical D-value.

| No. | \( \Delta T_{\text{desired}} \) | \( \Delta T_{\text{actual}} \) |
|---|---|---|
| 1 | \[
\begin{bmatrix}
0.6649 & 0.04183 \\
-0.5107 & -0.1030 \\
0.0994 & 0.8622 \\
0 & 0 \\
0.08167 & -0.4103 \\
-0.8988 & 1.199 \\
0.5354 & 0.9109 \\
0 & 0 \\
-0.9608 & 0.0092 \\
-0.2361 & 1.6632 \\
0.6221 & 0.4475 \\
0 & 0 \\
\end{bmatrix}
\] | \[
\begin{bmatrix}
0.6649 & 0.04183 \\
-0.5107 & -0.1030 \\
0.0994 & 0.8622 \\
0 & 0 \\
0.08167 & -0.4103 \\
-0.8988 & 1.199 \\
0.5354 & 0.9109 \\
0 & 0 \\
-0.9608 & 0.0092 \\
-0.2361 & 1.6632 \\
0.6221 & 0.4475 \\
0 & 0 \\
\end{bmatrix}
\] |
| 2 | \[
\begin{bmatrix}
5.6688 \\
87.2782 \\
37.9371 \\
0 \\
58.24 \\
83.09 \\
7.791 \\
0 \\
69.8687 \\
17.5797 \\
48.2009 \\
0 \\
\end{bmatrix}
\] | \[
\begin{bmatrix}
5.6688 \\
87.2782 \\
37.9371 \\
0 \\
58.24 \\
83.09 \\
7.791 \\
0 \\
69.8687 \\
17.5797 \\
48.2009 \\
0 \\
\end{bmatrix}
\] |

Table 7. The root mean square error of CPI between the master and slave.

| | Rectangle | Triangle | Pentagon | Circle |
|---|---|---|---|---|
| CPI | 0.2687 | 0.2546 | 0.2404 | 0.2970 |

Figure 6. Trajectory tracking experiment: (a) Rectangle; (b) Triangle; (c) Pentagon; (d) Circle.
Technology. The whole process is shown in Figure 8. Three hours after surgery, the pigs wake up and stand up, then pigs start eating, now all pigs were in good health without infection, validating the feasibility of the intuitive control algorithm. The failure rates of the intuitive control algorithm were zero during all experiments, indicating that the intuitive control algorithm is stable and reliable.

**Conclusion**

Forward and inverse kinematics of the MIS robot are achieved based on the screw theory, kinematic algorithm of the MIS robot based on the DD has been set up, then the intuitive control is implemented based on the kinematic algorithm based on the DD. The hybrid simulation experiment based on the MATLAB, test experiments and Cholecystectomy removal
experiments validate the effectiveness of forward, inverse kinematics and intuitive control algorithm.

**Disclosure statement**

The authors report no declarations of interest.

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