Simulation of a 6-PUS jaw robot and a new mechanism inspired by masticatory system

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Abstract: A jaw robot based on the 6-PUS parallel mechanism was introduced according to the biomechanical properties of mandibular muscles. For a given mandibular trajectory to be tracked, the inverse kinematics solution is derived and Jacobian matrix formulated from differential kinematics is found. Kinematics performances, such as constant orientation workspace and manipulability are simulated via numerical method. These indices show that the parallel mechanism has enough flexible workspace without singularity, and has a good motion transmission performance for human chewing movement. In order to reproduce jaw motions and mechanics that match the human jaw function truthfully with the conception of bionics, the temporomandibular joints (TMJs) are taken into account. Another novel actuation redundant mechanism for the jaw robot is proposed based on mechanical biomimetic principles, which has four degrees of freedom, but is driven by six actuators.

Keywords: jaw robot; biomechanical properties; mastication system; parallel mechanism; kinematics analysis; workspace; manipulability; actuation redundancy.


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1 Introduction

Jaw robot has found many applications in dentistry, chewing food, speech and facial expression control. The research of the jaw robot has begun in the 1990s, and this kind of robot can simulate human mandible movement and reproduce human mandible force (Cong et al., 2010). One of the application fields of the jaw robot is dentistry area. Alemzadeh and Raabe (2007) developed a dental test simulator based on Stewart platform and used it for experiment on dental component material. Callegari and Marzetti (2004) put forward a 3-PUU parallel mechanism that can assist dentist to perform dental disease pathology research during the mandible motion. But the biological characteristics of human mandible system have not been considered sufficiently in these two robots, so they could not reproduce function and environment of the mandible entirely. In food science area, studies (Gibbs and Lundeen, 1981; Takanobu et al., 1998; Xu et al., 2005; Xu and Bronlund, 2010) have contributed much to the mastication robot. The mechanism which Xu et al. (2005) put forward existed the problems of singularity so it could not achieve the required mandible movement and bite force during the process of food chewing; In biomechanics area, there are Mark III mastication mechanism (Bowey and Burgess, 2005), JSN chin simulator (Hayashi et al., 1996, 2000), and mandible motion simulator (Galer et al., 2007), etc. They are mainly for studying the movement characteristics of the mandible system. In addition, Takanobu et al. (2002) developed a rehabilitate robot aiming at training mandible movement. Flores and Fels (2005) proposed a language physical therapy robot for the research of perception and comprehension function in the process of talking face to face.

Human mastication system is a complex system, making it difficult to be copied by simulating devices. It mainly consists of lower jaw, muscle and temporal mandibular joint. Lower jaw is alternately driven by several opening and closing muscles, performing complex periodic opening and closing movement relative to the upper jaw in three-dimensional (3D) space (Rohrle and Pullan, 2007). The main jaw muscles are masseter, temporalis, and pterygiod muscle, which are symmetric distribution (Hannam, 1997). The mastication system undertakes responsibility of several essential physiological functions, such as chewing food, language speaking and facial expression control.

Considering the biological characteristics of the mandible muscles, including muscle distribution, different muscle line of action, and non-coplanar connecting points between muscles and mandible bones, a jaw movement robot based on the mechanical bionics is introduced firstly. In accordance with the characteristics of the jaw robot, this paper gives out the inverse kinematics which is essential for the kinematics performance analysis of the parallel robot. The constant orientation workspace was analysed under different constraints. The simulation about the manipulability and singularity of the robot is obtained. For a better bionic design of the jaw robot, a novel actuation redundant mechanism is proposed with two higher kinematic pair joints after reviewing the physical structure and function of the temporomandibular joint (TMJ).

2 Masticatory system

The human masticatory system mainly consists of two rigid bodies-a lower jaw (mandible) and an upper jaw (maxilla). The mandible is pivoted onto the maxilla by two TMJs and driven to perform chewing motion by the contraction of the muscles of mastication under the central nervous system. The masticatory muscles, consists of several bundles of muscle groups, is attached to different area of skull and jaw. The lower jaw movement in the 3D space is mainly affected by the TMJ, structure of muscles and dimension parameters.

2.1 Muscles of mastication system

Human mastication is an interaction of several muscle groups that is controlled by the brain. More than twenty muscles are responsible for the motion profile, which is considered to be an aggregate of both clenching and grinding motions (Daumas et al., 2005). The main muscles of mastication system masseter, temporalis, upper lateral pterygoid and lower lateral pterygoid muscles are shown in Figure 1.

Figure 1  Muscle groups of mastication

Source: Koolstra and van Eijden (2001)

2.2 The TMJ

The TMJ is the joint between the temporal bone of the skull and the condyle of the mandible. Different from other joints of human body, its movements are floating in a 3D space instead of rotating around a fixed joint axis. The structure of TMJ is shown in Figure 2. A particular disk and soft tissue separate the condyle and the temporal bone. When rotation and translation take place simultaneously, the condyle and disk move forward on the eminence, and at the same time the condyle revolves on the disk. Therefore, the special
structure of TMJ absorbs the shocks from chewing and other movements.

Figure 2  The temporomandiular joint

Source: Katzberg (1990)

3 Structure of jaw robot

The CAD model of the jaw robot built in SolidWorks is shown in Figure 3. The robot consists of an end-effector (mandible platform) and six driving linkages. In the CAD model, the upper jaw of the robot is not shown. The driving force is transferred from motor to mandible platform through universal joint (U), prismatic joint (P), rod and spherical joint (S). The direction of the rod is the muscle line of action. In this structure, the spherical joint and the translational joint stand for the muscle connecting point and the driving muscle, respectively. The jaw robot can reproduce the mandible movement through the changing position of the six sliders driven by six motors.

Figure 3  Schematic diagram of the jaw robot

The connecting points between the rods and mandibular structure are accurately located in the insertion points between low jaw and driving muscles. A lot of effects have been done to model the masticatory system including the connecting points. Koolstra and van Eijden (1997) measured the parameters of the muscles, including position, length, and cross sectional area, etc. Positions of a set of reasonable connecting points which connect each rods and upper and lower jaw platform, and length of each rod have been estimated (Xu et al., 2008; Cong et al., 2011). The parameters of the jaw robot in this paper are listed in Table 1.

Table 1  mandible attaching points and single chain length of the resultant force

<table>
<thead>
<tr>
<th>Drive muscle</th>
<th>Pterygium</th>
<th>Masseter</th>
<th>Temporalis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandible attaching points $M_i$ (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>0</td>
<td>20.3</td>
<td>28.3</td>
</tr>
<tr>
<td>y</td>
<td>-42.2</td>
<td>-45.2</td>
<td>43.3</td>
</tr>
<tr>
<td>z</td>
<td>0</td>
<td>-45.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Maxilla attaching points $C_i$ (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>-96.1</td>
<td>60.3</td>
<td>-30.7</td>
</tr>
<tr>
<td>y</td>
<td>60.5</td>
<td>100.5</td>
<td>130.0</td>
</tr>
<tr>
<td>z</td>
<td>0.3</td>
<td>5.2</td>
<td>55.2</td>
</tr>
<tr>
<td>Chain length $L_i$ (mm)</td>
<td>127.0</td>
<td>121.0</td>
<td>183.9</td>
</tr>
</tbody>
</table>

3.1 Inverse kinematics

In order to describe the robotic mechanism, frame $O_b$-XYZ (static frame) and frame $O_m$-XYZ (mandible frame) are established on the robot base and mandible structure, respectively, as shown in Figure 4.

The mandible frame is located at the symmetrical centre of the two mandibular condyles when the mandible is at its home position and has a sagittal plane (X-Z plane), a frontal plane (Y-Z plane), and a horizontal plane (X-Y plane). The position of the mandible frame relative to the static frame can be determined by way of transfer matrix $^b_R^m$ as follows:

$$^b_R^m = \begin{bmatrix}
cyβ & -syα + cyβsa & syα + cyβsa & b_{Omx} \\
syβ & cyα + syβsa & -cyα + syβsa & b_{Omy} \\
-sβ & cβsa & cβsa & b_{Omc} \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(1)

in which, $c$ indicates cos and $s$ indicates sin.

$(^b_{Omx} ^b_{Omy} ^b_{Omc})^T$ is the origin of frame $O_m$-XYZ with respect to $O_b$-xyz, and $α$, $β$, $γ$ are roll-pitch-yaw rotational angles about $x$, $y$ and $z$ axis in the static frame, respectively. When the robot is in the initial position, the parameters are as follows:

$$(^b_{Omx} ^b_{Omy} ^b_{Omc})^T = (0 0 0)^T, \ (α, β, γ) = (0,0,0)$$

(2)

Vector $B_iM_i$ as shown in Figure 4 can be written as follows:

$$B_iM_i = B_iO_b + O_bO_m + O_mM_i$$

(3)

$$B_iM_i = -B_iM + ^b_{Omx} + ^b_{Omy} + ^b_{Omc}$$

(4)
where $B_iO_b$ is determined by the coordinates of $B_i$ in static frame $O_s$-xyz; $O_sO_w$ is determined by the initial position of the mandible; and $O_wM_i$ is the coordinates of $M_i$ in frame $O_w$-XYZ.

On the other hand, vector $B_iM_i$ can also be expressed by

$$B_iM_i = B_iC_i + C_iM_i$$  \hspace{1cm} (5)

(5) can be rewritten as

$$C_iM_i = B_iM_i - B_iC_i$$  \hspace{1cm} (6)

The squares of (6) is:

$$\|C_iM_i\|^2 = \|B_iM_i\|^2 - 2B_iM_i \cdot B_iC_i + \|B_iC_i\|^2$$  \hspace{1cm} (7)

in which $\|C_iM_i\| = L(i = 1, 2, \ldots, 6)$ is the length of each linkage, and $B_iM_i$ can be calculated by (4). Defining

$$\|B_iM_i\|^2 = r_i^2$$  \hspace{1cm} (8)

The direction vector of vector $B_iC_i$ is $e = [0, 0, 1]^T$, so

$$B_iM_i \cdot B_iC_i = B_iM_i \cdot e \cdot q_i$$  \hspace{1cm} (9)

Finally, each displacement of the slider is found:

$$q_i = c_i \pm \sqrt{c_i^2 - r_i^2 + L_i^2}$$  \hspace{1cm} (12)

**Figure 4** Illustration of one linkage of the robot

The relation between input $\theta$ of each linkage and output $X$ of mandible can be expressed as:

$$f = (q, X)$$  \hspace{1cm} (13)

Jacobian matrix can be used to describe the relationship between the velocity of each slider and the mandible platform (the end-effector). (13) can be written as:

$$f = (\dot{q}, \dot{X})$$  \hspace{1cm} (14)

According to the Jacabian matrix established by the (13), the velocities in rod direction of point $M_i$ and point $C_i$ along each linkage are the same:

$$\left( v_m + \omega_m \cdot O_wM_i \right) \cdot C_iM_i = v_i \cdot e \cdot C_iM_i$$  \hspace{1cm} (15)

in which $v_m$ and $\omega_m$ represent the translational velocity vector and angular velocity vector, respectively; $v_i$ is the velocity of the slider; $e = [0, 0, 1]^T$ is the unit vector with direction of Z axis. Then we can get:

$$J_s \cdot \dot{X} = J_q \cdot \dot{q}$$  \hspace{1cm} (16)

in which $\dot{X} = [v_m, \omega_m]^T$.

### 4 Simulation of the robot

#### 4.1 Workspace analysis

It is very important to find the size and shape of workspace of the parallel robot and it is an essential index for evaluating the jaw robot’s kinematic performance that determines whether the jaw robot can be competent to reproduce human jaw motion. The constant orientation workspace (translation workspace) which is defined as the volume that can be reached by a reference point on the mandible platform is analysed when the orientation of mandible platform is kept constant.

The major factors that limit the workspace of the jaw robot are as follows:

1. **Length limitation of slider**

$$X_{\text{min}} \leq X_i \leq X_{\text{max}}$$  \hspace{1cm} (17)

in which $X_{\text{min}}$ and $X_{\text{max}}$ are the displacement limitation of each slider.

2. **Rotational angle of spherical joint**

$$\theta_s = \alpha \cos \left( \frac{LKs}{|L|} \right) \leq \theta_{\text{max}}$$  \hspace{1cm} (18)

in which $\theta_s$ represents the angle between driving rod and the plane perpendicular to the shank axis of spherical joint on the mandible platform. $K_s$ is the projection of vector $L$ on the plane perpendicular to the shank axis and $R$ is the transformation matrix between the two coordinate frames.

3. **Interference between linkages**

$$\gamma \geq \gamma_{\text{min}}$$  \hspace{1cm} (19)

in which $\gamma_{\text{min}}$ is the minimum distance that can avoid interference.
Figure 5  Constant orientation workspace when $\alpha = 0^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ with accuracy 2 mm, (a) constant orientation workspace in plane XOY when $\alpha = 0^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ (b) constant orientation workspace in plane XOZ when $\alpha = 0^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ (c) constant orientation workspace in plane YOZ when $\alpha = 0^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$

Base on the constraints listed above, the constant orientation workspace is obtained by using numerical searching method in MATLAB. The constant orientation workspace of the robot when the jaw is closing ($\alpha = 0^\circ$, $\beta = 0^\circ$ and $\gamma = 0^\circ$) is shown in Figure 5. The workspace is described as $X \in [-62, 28]$, $Y \in [-56, 56]$, $Z \in [50, 146]$, which is symmetrical with respect to Y axis. The constant orientation workspace when the jaw is opening in an orientation of $\alpha = 5^\circ$, $\beta = 30^\circ$ and $\gamma = 10^\circ$ is shown in Figure 6. Intervals on X, Y and Z axis are $[-36, 24]$, $[-52, 30]$ and $[66, 158]$, respectively.

For the second orientation, the jaw is opening with a rolling and lateral yawing motion. Consequently the translation workspace is becoming smaller and is not symmetrical any more. But as we can see from the picture that the mandible still has enough space to achieve the require movement.

4.2 Manipulability analysis

The jaw robot is designed based on the mechanical bionics. The connecting points between driving rods and the mandible are in accordance with the insertion points that the muscle groups connect the mandible. As a result, the connecting points on both sliders and mandible platform are non-coplanar, different from traditional mechanism. The manipulability and singularity analysis of parallel robots should be concerned in order to avoid possible dangerous design parameters.

The manipulability can reflect the operability of the end effector when the robot is in different positions and orientations and is also an important index for measuring singularity. The manipulability is defined as the absolute value of the determinant of the Jacobian matrix.

$$\omega = |\det(J_x)|$$

where $\omega$ denotes the manipulability of the robot and $J$ denotes Jacobian matrix. It reflects the extent of homogeneity of the matrix. When $\omega = 0$, the robot is in a singular position and when $\omega > 0$, the robot position is non-singular. The manipulability of the jaw robot in different planes when $\alpha = 0^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ was given in Figure 7. The degree of ill-conditioning of the Jacobian becomes worse when the value of $\omega$ is smaller. Most of them exist around the border of the workspace that the robot trajectory may not pass. Note that the manipulability index will have different values for the different used units. From the analysis, we learned that there is no singularity within the constant orientation workspace of jaw robot. The manipulability graphs for the other orientations are similar.
**Figure 6** Constant orientation workspace when $\alpha = 5^\circ$, $\beta = 30^\circ$, $\gamma = 10^\circ$ with accuracy 2 mm. (a) constant orientation workspace in plane XOY when $\alpha = 5^\circ$, $\beta = 30^\circ$, $\gamma = 10^\circ$ (b) constant orientation workspace in plane XOZ when $\alpha = 5^\circ$, $\beta = 30^\circ$, $\gamma = 10^\circ$ (c) constant orientation workspace in plane YOZ when $\alpha = 5^\circ$, $\beta = 30^\circ$, $\gamma = 10^\circ$

**Figure 7** Manipulability of jaw robot when $\alpha = 0^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$. (a) manipulability in XY plane (b) manipulability in YZ plane (c) manipulability in XZ plane (see online version for colours)
5 A new inspiration

TMJ is the most sophisticated joint in human body. Its compound movements were usually ignored or simplified as a hinge articulation by most of the researchers when a jaw robot was designed so far. Many robots are not able to reproduce human jaw motion and mechanics faithfully. The great challenge in developing a jaw robot is that designing the robotic mechanism considering both the TMJ and the mandible movements. The TMJ is very unique because it does not rotate about a fixed joint axis. The paths of most points on the condyle are infinite and the condyle motion associated to mandibular movements involves both rotation and translation (Takanobu et al., 1993). The simplified condyle movement is shown in Figure 8. A new structure on the robot needs to be designed to achieve similar movement.

Figure 8 Diagram of condyle trajectory (see online version for colours)

From the physiology point of view, the degrees of freedom of the mandible are smaller than the number of muscles of mastication so the mastication system is redundant itself. We are going to establish an actuation redundant mechanism according to the physiology of the masticatory system. Two point contact higher kinematic pairs are introduced into the new jaw robot. As shown in Figure 9, the fossa structure with curved surface which simulates trajectory of point C is fixed on the robot base. The condyle structure with a ball end contacts with the curved surface.

Figure 9 TMJ structure of the actuation redundant robot

Combining TMJ structure with the 6-PUS parallel mechanism for muscle groups of mastication, the redundant mechanism is modelled in SolidWorks, as shown in Figures 10 and 11. It consists of a movable plate and a static plate that is connected by two point contact higher kinematic pairs and six linkages. Each linkage is made up of one spherical joint, one universal joint and a linear guide. The movable plate represents the mandible (or lower jaw), and the static plate represents the skull (or upper jaw). Three muscle groups (temporalis, masseter, and lateral pterygoid) are replaced by six rods. The two point contact higher kinematic pairs are served as the two TMJs.

Figure 10 Robot model in SolidWorks

Because of the existence of the two higher kinematic pairs, the degree of freedom of the jaw movement robot will change. It was essential to verify that the jaw robot can achieve the human-like chewing movements in terms of kinematics. The degree of freedom of the mechanism can be evaluated using the Kutzbach criterion (Uicker et al., 2003).

\[
m = 6(n - 1) - 5j_1 - 4j_2 - 3j_3 - 2j_4 - j_5
\]

where \( m \) is the number of independent DOF required for the robot, \( n \) ( = 14) is the number of links, \( j_i \) is the number of \( i \) DOF pairs, which is \( j_1 = 6, j_2 = 6, j_3 = 6, j_4 = 0, j_5 = 2 \), respectively.

The number of calculated independent DOFs is

\[
m = 6 \times 13 - 5 \times 6 - 4 \times 6 - 3 \times 6 - 2 = 4.
\]

The degree of freedom is smaller than the number of active joints (six actuators). That means the end-effector is
over-constrained by the actuators. The new jaw movement robot proposed in this paper is a redundant parallel robotic mechanism with point contact higher kinematic pair and has four degrees of freedom, but is driven by six actuators.

When a human being bites with maximum strength, the bite force can be up to human’s own weight 50–60 kgf. While the size of the condyle is about 20 × 10 × 10 mm, which is very small to burden such a heavy weight compared with the knee joint of human body (Takanobu, 1993). Redundancy in the robotics might be an effective approach to reveal the physiological phenomenon as redundancy can reduce or eliminate singularity and improve stiffness and controllability.

6 Conclusions

In this paper, two kinds of jaw robot are introduced. The first one is a 6-PUS parallel mechanism and the second one is an actuation redundant parallel mechanism. They are all modelled by reviewing the mechanical bionics of the mastication system, and considering biomechanical characteristics of human mandible system, such as the jaw size parameters and jaw muscle line of action. In order to design a robot that can reproduce jaw motions and mechanics and match the human jaw function truthfully, the actuation redundant jaw robot is proposed. The main difference is the actuation redundant jaw robot contains a higher kinematic joint that can simulate the TMJ of the mastication system.

The inverse kinematics and the Jacobian matrix of the first jaw robot are discussed. In order to ensure the robot achieve adequate kinematic performance, the workspace and manipulability of this jaw robot are analysed. When \( \alpha = 0^\circ, \beta = 0^\circ \) and \( \gamma = 0^\circ \), the constant orientation workspace is described as \( X \in [-62, 28], Y \in [-56, 56], Z \in [50, 146] \). When \( \alpha = 5^\circ, \beta = 30^\circ \) and \( \gamma = 10^\circ \), it becomes \( [-36, 24], [-52, 30] \) and \( [66, 158] \). The analysis shows that the manipulability of the jaw robot in different planes are all in the positive zone, indicating that there’s no singular position within the robot’s workspace and the model has a good motion performance. The 6-PUS parallel jaw robot proposed in this study provided good and feasible performance to achieve the human chewing movement.

Most of the redundantly actuated parallel mechanisms use lower pairs. For the second jaw robot, point contact higher kinematic pairs are introduced in the spatial mechanism, which are inspired by the TMJs of the human mastication system. The kinematics, dynamics and control issues of this jaw robot are great change for an actuation redundant robot. Future work will mainly focus on these issues.

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