Proposal of a Masticatory Robot for Analysis of Jaw Movements
Cong Ming\textsuperscript{1,2,a}, Liu Tongzhan\textsuperscript{1,2,b}, Wen Haiying\textsuperscript{1,2,c}, Chang Zhanbo\textsuperscript{1,2,d}

\textsuperscript{1}School of Mechanical Engineering, Dalian University of Technology, Dalian, 116024, China
\textsuperscript{2}State Key Laboratory of Robotics, Shenyang, 110016, China
\textsuperscript{a}congm@dlut.edu.cn, \textsuperscript{b}liutongzhan0121@163.com
\textsuperscript{c}wenhaiying@gmail.com, \textsuperscript{d}zhanbochang@163.com

Keywords: Masticatory Robot; Human Chewing; Robotic Jaw; Parallel Robot

Abstract. In this paper, a life-sized jaw mechanism is proposed on the basis of biological masticatory structure. Its actual parameters are defined in Solidworks according to human masticatory systems, the trajectory and position error of masticatory robot is performed via ADAMS and Matlab. The simulation results have shown that the robotic jaw is able to reproduce the human behavior. However, because the mechanism is a highly coupled and nonlinear system, the position error cannot be eliminated completely, and more sophisticated control system is required in future study.

Introduction

Masticatory robots which are able to reproduce human chewing behaviour and chewing force [1] have been researched since early 1990s. This kind of mechanism can be applied to the fields of relative services and medical care directly, such as texture analysis, dental training, speech therapy, TMJ research, etc [2]. For example, when making quantitative analysis of new tooth materials, using masticatory robots can avoid time wasting, expense and limitations of clinical experiment. Meanwhile, the objectivity of masticatory robots can compensate the subjectivity in traditional food texture analysis. Therefore, this kind of robot is able to provide scientific measures for the above application fields, and it has extensive development prospects.

A medical mastication robot (WY-6) for training patients whose jaw movements are out of order was developed by Waseda University of Japan [3]. And it is aimed at opening and closing a patient’s mandible as the dentist’s hand motion during mouth opening training session. However, WY-6 robot is primarily responsible for mouth opening and closing. A speech robot for studying the role of the jaw movements play in perceiving and understanding conversation was developed at University of British Columbia in Canada [4]. But this robot uses cantilevered structure instead of biological structure. A 6-DOF dental testing simulator used to test new materials wear performance was developed at University of Bristol in United Kingdom [5]. Although this simulator has sufficient DOF, it did not take the factor of biological structure into consideration and its size is fairly large. A model of a new type of wire driven parallel mastication robot system was developed at Dalian University of Technology [6]. Various types of masticatory robots have been developed so far. However, any of these devices has only one particular function and is not able to simulate complex movements.

To meet the requirement of bionic character of mastication robots, a parallel mechanism model was built up based on the jaw structure and mastication muscles. And a fuzzy-PID controller was designed for the control system. The paper analyzed the kinematics character of the robotic model via ADAMS and the position error via Matlab/Simulink. The results have shown that the masticatory robot is able to reproduce the jaw movements well. However, the jaw movements are highly dynamically coupled, a more bionic control system is required in future study.
The Masticatory System of Human

Mastication is one of the most complex parts whereby food is processed together with saliva into a form suitable for swallowing [7]. It consists mainly of five parts, such as jaw, temporomandibular joint, muscles, teeth and tongue.

The human chewing system mainly consists of an upper jaw, a lower jaw and temporomandibular joint (TMJ), as shown in Fig. 1[8]. The upper jaw is referred to as the maxilla and is attached to other bones that make up the skull. The lower jaw is referred to as the mandible and is attached to the skull by muscle [9]. The TMJ is the joint between the temporal bone of the skull and the condyle of the mandible. In contrast to other joints of human body, its movements are floating in a three-dimensional (3D) space instead of rotating around a fixed joint axis [10]. The mandible moves under control of the central nervous system (CNS), and it makes a periodical 6-DOF movement. During the process of human mastication, the masticatory system completes important physiological functions, such as chewing food, language performance, and facial expression control.

The chewing system is driven by a complex assembly of correlative muscle groups, which includes muscle groups on both sides of the midline. The main muscles of mastication include masseter, temporalis, medial pterygoid and lateral pterygoid muscles, as shown in Fig. 2 [11].

![Fig. 1 Structure of masticatory system](image1.png) ![Fig. 2 Muscles of mastication](image2.png)

Modeling of Mastication Robot

Chewing process is a complicated and self-adaption rhythmic movement, we focus on the mandibular movement at the present stage only. Combine with dynamic characteristics of actual human masticatory system, a 3D jaw model has been built, and analyzed via Matlab and ADAMS.

Modeling of Jaw Mechanism. In order to evaluate the dynamic changes of the jaw movements correctly, a mechanism of human like mandible is required. The trajectory of the mandible is able to be observed through several points such as incisal point (IP), kinematic condylar point (i.e., LCP and RCP), first molar point (i.e., LMP and RMP) and the center of mass (CM), the position of reference points in coordinate, as shown in Table 1 [12]. According to biomechanical information of mandible, the three masticatory muscles are temporalis, masseter and lateral pterygoid. Some research institutions have studied the architecture of masticatory muscle groups and obtained a series of data about it. The coordinates of these actuators are given in Table 2 [12].

<table>
<thead>
<tr>
<th>Reference points</th>
<th>X[mm]</th>
<th>Y[mm]</th>
<th>Z[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incisal point(IP)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Right molar point(RMP)</td>
<td>-25.7</td>
<td>24.3</td>
<td>-0.7</td>
</tr>
<tr>
<td>Left molar point(LMP)</td>
<td>-25.7</td>
<td>-24.3</td>
<td>-0.7</td>
</tr>
<tr>
<td>Right condylar point(RCP)</td>
<td>-101.3</td>
<td>-42.0</td>
<td>34.5</td>
</tr>
<tr>
<td>Left condylar point(LCP)</td>
<td>-101.3</td>
<td>42.0</td>
<td>34.5</td>
</tr>
<tr>
<td>Center of mass(CM)</td>
<td>-41.2</td>
<td>-0.3</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Table 2 Position of reference points for masticatory muscles

<table>
<thead>
<tr>
<th>Masticatory muscles</th>
<th>Skull attaching points[mm]</th>
<th>Mandible attaching points[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Lateral pterygoid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>-158.5</td>
<td>25.4</td>
</tr>
<tr>
<td>Left</td>
<td>-158.5</td>
<td>25.4</td>
</tr>
<tr>
<td>Masseter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>-85.0</td>
<td>85.5</td>
</tr>
<tr>
<td>Left</td>
<td>-85.0</td>
<td>85.5</td>
</tr>
<tr>
<td>Temporalis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>-53.8</td>
<td>82.5</td>
</tr>
<tr>
<td>Left</td>
<td>-53.8</td>
<td>82.5</td>
</tr>
</tbody>
</table>

According to the parameters of joints, a masticatory robot model was built up based on the Stewart platform, as shown in Fig. 3. The movable plate represents the mandible and the ground plate represents the skull. The six actuators divided into three groups represent temporalis, masseter and lateral pterygoid, respectively.

**Fig.3 A robotic model in Solidworks**

**Jaw Mechanism Model in SimMechanics.** The chewing robot structure is a typical parallel mechanism, the precise dynamic model is difficult to establish and the robot control algorithm are mostly built on the basis of approximate model. Virtual reality technology of Matlab/SimMechanics is used to perform the kinematics and dynamic analysis.

Based on the built Chewing robot model, we used SimMechanics to set up the chewing system model. The virtual simulation system with control reference trajectory primarily consisted of three components: mechanism, fuzzy-PID controller actuations and scope, as shown in Fig. 4. To achieve the desired motion, the mechanism was controlled by the fuzzy-PID system. The reference trajectory of the mandible was designed in actuations, and the simulation result was shown in scope.

**Fig.4 Masticatory robot control system in SimMechanics**

**Simulation Result and Analysis**

The purpose of simulation and analysis is checking whether the model can produce the human-like chewing movements, and ADAMS is used to analyze the kinematics character of the chewing mechanism. The kinematics trajectory of the robot is able to be described by a series of reference points on the mandible. As the points of the RMP and RCP are symmetrical distribution with LMP and LCP, the paper uses the points of IP, RMP and RCP to describe the trajectory of the mandible, as shown in the Fig. 5.
In each point the trajectory of the mandible is described by the position and angles around the X-axis, Y-axis and Z-axis in the coordinate system. As shown in Fig. 5, the maximal displacement is about 0.4 inch at incisal point and the minimal displacement is about 2 inches at fist molar point. The simulation has shown that the trajectory of the model is similar to the actual human chewing trajectory, and the jaw mechanism is able to reproduce the human chewing behaviour.

Based on the built chewing mechanism, a fuzzy-PID controller was designed in SimMechanics for the control system (Fig.4). The position error do not fall off over time, due to the mechanism is a highly coupled, nonlinear system, as shown in Fig. 6. The control strategy of Fuzzy-PID only reduces the error to a certain range, and cannot fully solve this problem.
Summary
Based on the structure of human masticatory system, a chewing robot of parallel mechanism was modeled in SolidWorks. It has been validated by extensive simulations in ADAMS and Matlab. The simulation results have shown that the jaw mechanism is able to reproduce jaw trajectory, however, the position error cannot be well eliminated via Fuzzy-PID. So to enable the masticatory robot to perform human chewing behavior, a bionic control system is required.

This project is supported by “State Key Laboratory of Robotics” open topics (Project NO. RLO201008).

References
Proposal of a Masticatory Robot for Analysis of Jaw Movements
10.4028/www.scientific.net/AMM.138-139.15