Parallel Architecture Manipulators for Use in Masticatory Studies

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ABSTRACT

There is considerable scientific and commercial interest in understanding the mechanics of mastication. In this paper, the authors develop quantitative engineering tools to enable this process by: (i) designing a general purpose mastication simulator test-bed based on parallel architecture manipulator; capable of producing the requisite motions and forces; and (ii) validating this simulator with a range of test-foods, undergoing various mastication cycles under controlled and monitored circumstances. Such an implementation provides a test bed to quantitatively characterize the mastication based on “chewability index”. Due to the inherent advantages of locating actuators at the base (ground) in terms of actuator efforts and structural rigidity as well as benefits of using prismatic sliders compared to revolute actuators, the 6-P-U-S system was chosen. A detailed symbolic kinematic analysis was then conducted. For the practical implementation of the test-bed, the analytical Jacobian was examined for singularities and the design was adapted to ensure singularity free operation. A comprehensive parametric study was undertaken to obtain optimal design parameters for desired workspace and end effector forces. Experiments captured jaw motion trajectories using the high speed motion capture system which served as an input to the hardware-in-the-loop simulator platform.

Keywords: Jaw Motion Analysis, Masticatory Simulator, Parallel Manipulator, Posselt Envelope

INTRODUCTION

The goal of this research is to develop an experimental testbed for analyzing the masticatory jaw motions of animals (including humans) and establish the quantitative relationship between relevant geometric parameters (tooth geometries, numbers and types) as well as regimen parameters (joint forces, motions) during the mastication process for further detailed studies. Such an understanding would be of tremendous importance from different perspectives. From

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a biological science perspective, it is critical to understand the physiological variability in mastication across individuals in a species as well as across the entire population. It is also very useful to know how various animals preprocess food while chewing and biting so that the research scientists can hypothesize behavioral analyses of how certain breeds of animals kill their prey with an accurate estimate of biting forces (Signore, Krovi, & Mendel, 2005) and understand the resulting muscles functioning to draw interesting conclusions. From an engineering perspective, such a study on masticatory performance would enable to quantitatively assess the “chewability or performance index” due to variations in food properties as well as facilitate the parametric design of dentitions/prosthetic additions.

To this end our work focused on developing quantitative engineering tools to enable this process (Figure 1). Specifically, we focused on (i) designing a general purpose mastication simulator test-bed based on parallel architecture manipulator, capable of producing the motions and forces encountered; and (ii) validating this simulator with a range of test-foods undergoing varying mastication cycles under controlled and carefully monitored circumstances. Such an implementation could provide a testbed to quantitatively characterize the mastication based on “chewability index” factor for a wide range of applications. Building a generic engineering test-bed that can be used to study mastication for these diverse goals offers significant challenges. The multiple facets of the overall project are shown in Figure 1 – in this paper, we will focus only on the highlighted sections. Specifically, various design variants of parallel manipulators were examined for jaw simulators before finalizing on 6-P-U-S keeping in mind the high force requirements as well as desirable workspace required for various masticatory motions. A detailed workspace analysis based on the Jacobian measures is considered to be significant to ensure desired characteristics for the manipulator that is presented in mathematical background section. We then drive the kinematic model with the jaw motion trajectories obtained from the motion capture (MoCap) analysis system. Finally, the optimal configuration and workspace analysis results of 6-P-U-S parallel manipulators will be presented in results section. This paper also discusses the validation performed on the physical platforms using the recorded MoCap data.

LITERATURE REVIEW

Robotic Mastication Test-Rig

Many research groups have concentrated on accurately simulating the jaw motion by building a physical robotic manipulator and conducting real time studies on biting and food texture properties. However, the first ever device built for tracking the jaw motion was in mid 1950s (Posselt, 1957). The apparatus (known as the Gnatho-thesiometer) permits measurements (at three points) in the three main planes on a freely movable cast of a lower jaw and he presented a simple comparative study on error obtained between mounting various casts manufactured by different techniques. The research group from Waseda-University actually marked the beginning of this new era. The group has developed a “Waseda Jaw” series of masticatory robots (Figure 2a), whose mechanical structures resemble those of the human masticatory system, especially muscle positions, mandibular movements and sensors in muscles and under the teeth. The same group had also succeeded in extending their application of WJ series of robots (Takanobu & Takanishi, 2003) to treating TMJ disorders with their new WY series of robots (Figure 2b).

Even though, their robots are predominantly 3-DOF, the authors mention in one of their works that human masticatory system is similar in configuration to 6-DOF parallel mechanical manipulator driven by linear or rotary actuators (Takanobu, Kuchiki, & Takanishi, 1995). We would like to make use of this insight in our research to model a general purpose robotic masticator. Another research group named BioMouth was actively involved in jaw modeling and dynamic analysis. They imple-
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