Virtual cutter path display for dental milling machine

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Virtual Cutter Path Display for Dental Milling Machine

Teruaki Ito[1], Takashi Niwa[2], and Alexander H. Slocum[3], *Member, IEEE*

[1]The Institute of Technolgy and Science, University of Tokushima,
Tokushima 770-8506, Japan
[2]Graduate School of Engineering, The University of Tokushima
Tokushima 770-8506, Japan
[3]Department of Mechanical Engineering, Massachusetts Institute of Technology,
Cambridge MA 02142, USA
Email ito@me.tokushima-u.ac.jp

Abstract— **This paper presents the prototype of a mixed reality system using the computer controlled dental milling machine, which is called MRD Mill. First, overview of the core dental milling machine developed in this study is presented, showing its kinematics and mechanisms to achieve the objective of the dental treatment. Then the paper covers its basic functions, including joystick-based control, NC code-based control, manipulation recording, and replay operation for the manual manipulation. MRD Mill system was installed with a mixed reality technology using the dental milling machine as the core unit. MRD Mill system is designed to support the operation of the dental mill using the mixed reality technology. This paper shows superimpose of trajectory of cutting tool path and virtual objects over the physical model. Then discussion and future direction will be followed.**

I. Introduction

Thanks to the recent technical advancement in medical and science fields, the benefits of computer-assisted robotic surgery are expected to achieve the patient-centered medical treatment goal of reducing pain, quicker recovery, or consistent and higher quality results. One of the famous robotic surgery systems is called Da Vinci, which provides surgeons with an alternative to both traditional open surgery and conventional laparoscopy, putting a surgeon's hands at the controls of a state-of-the-art robotic platform. As a result, it enables surgeons to perform even the most complex and delicate procedures through very small incisions with unmatched precision. Even though the robot surgery is still in the initial stage in terms of its technology and social aspects, there is a trend to shift towards partially automating various medical procedures using the stage-of-the-art in computer-assisted technology. Dental treatment operation is no exception, ranging from the basic crown preparation to the advanced technology in implant preparation. Dental application seems to have the potential of computer-assisted technology. However, it is quite common to use a manual-based technology. For example, as for the crown preparation, the dentist prepares the tooth using a hand-piece device with a dental drill and a miller. Due to the manual operation, quality of the treatment is highly dependent on the skill of the dentist as well as the location of the tooth within the mouth. Therefore, there is a need of computer-assisted surgical approach in dental operation even though conventional manual approach is still very popular. In fact, some dental CAD/CAM systems are available from the market to meet the needs of design and manufacturing method to reduce costs and improve quality and productivity.

Our research project aims at the design and development of a teleoperated dental milling machine for tooth crown preparation to meet the needs of computer-assisted surgical dental treatment. The machine is designed to allow the dentist to work on the crown preparation task using a remote control operation, and its prototype system has been built for evaluation. The basic controlling device is a joystick type but a force-feedback type of controller is also under study to provide additional real time feedback information to the operator. Another critical approach of user interaction for this machine is mixed reality-based information feedback. The idea is to provide some virtual objects superimposed over the real object during the machine operation. The superimposed objects can vary from basic dental pieces of devices to internal bone of the patient, which are under study using the dental milling machine. Especially, this paper focuses on a cutter path of the dental machine tool which is manipulated by the dentist or dental technician. As for the example of mixed reality-based information feedback, the study result is presented in this paper. First, overview of the dental milling machine developed in the project is presented, showing its kinematics and mechanisms to achieve the objective of the dental treatment purposes. Then the paper covers its basic functions, including joystick-based remote control of the machine, NC code control, manipulation recording, and replication operation for the original manipulation. Mixed reality technology enables several options to support machine manipulation for the dentist. The system is installed with a mixed reality environment to provide operation support using trajectory display. Discussion and future work will follow.

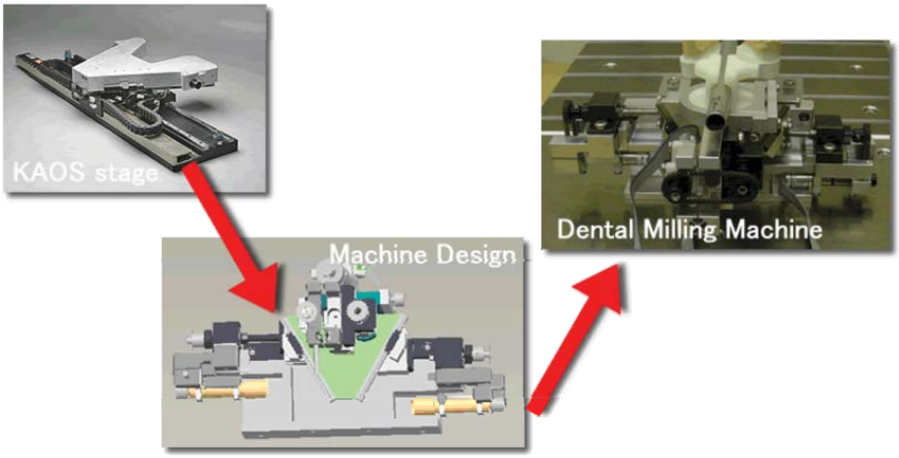

Figure 1: Dental Milling Machine based on KAOS stage

II. Dental Milling Machine Overview

The dental milling machine was designed and developed under the joint research project between the University of Tokushima and Massachusetts Institute of Technology under the cooperation of CIMIT (Center for Integration of Medicine and Innovative Technology) program. Entire mechanism has been built based on the design of the project using various processes from CNC milling to stereo-lithography. All of the completed pieces have been assembled and the milling machine has been built. The critical kinematics of the three active axes of the dental milling machine was designed based on the KAOS stage of Bell-Everman as shown in Figure 1. Figure 2 shows the detailed picture of the machine.

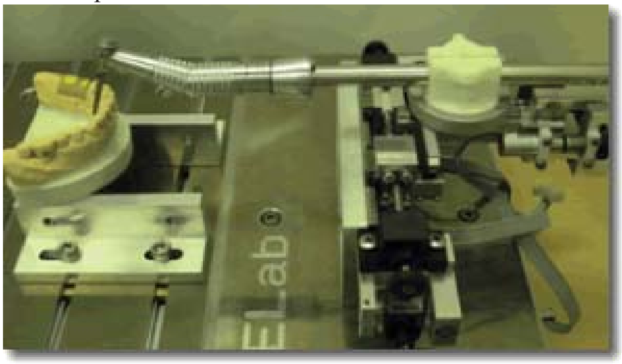

Figure 2: Dental Milling Machine

The stage adopts two actuators along the same line and uses a wedge to turn the parallel linear motion of these two actuators into motion in two perpendicular directions. This stage allows the x and z axis carriages to ride on the same bearing rail, while a traditional linear motion setup consisting of a ballscrew and linear bearing was chosen for the y axis. The x, y, and z motions of the machine are shown in Figure 3, 4 and 5.

The machine adopts three 0816S coreless DC motores (Faulhaber) with 08/1K 64:1 gear box and HEM 0816 magnetic encoder. Each of these motors drove a THK precision ball screw BNK 0401. The motors were coupled to the ballscrew using 20-tooth pulleys and 2mm wide timing belts from W.M.Berg.

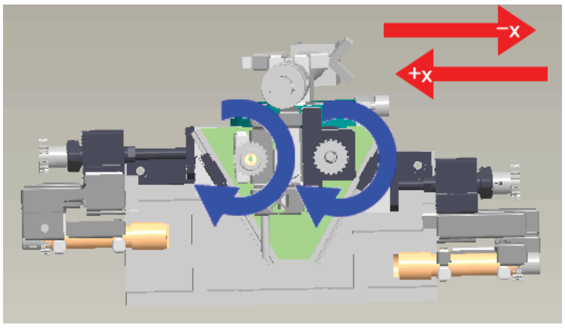

Figure 3: X axis motion of Dental Milling Machine

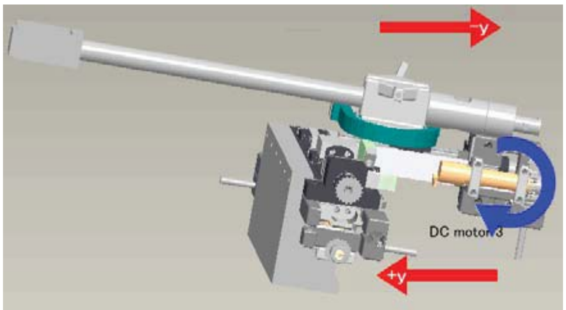

Figure 4: Y axis motion Dental Milling Machine

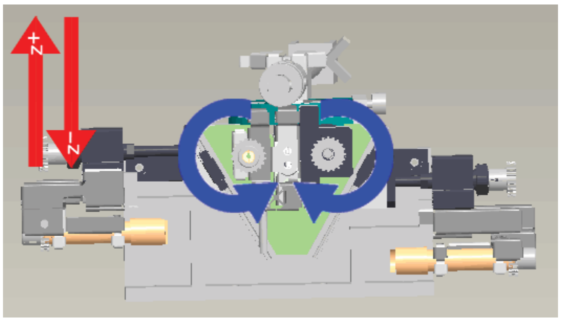

Figure 5: Z axis motion Dental Milling Machine

The control of the motors were developed using the standard MCDC2805 motion controller from Faulhaber. The interface with the computer consisted of a separate RS-232C connection to each of the axes using RS232C to USB converters. A control box was designed to include these motion controllers. The machine is controlled by two joysticks which are connected to the control box using an LCD display and/or direct observation over the machine.

Experimentation using a dental drill on extracted teeth leads to the determination of some of the quantitative goals of the machine. For example, cutting forces on the order of 1N are sufficient to cut teeth, the maximum permissible cutting speed is 1mm/s, and 20 cubic mm of work piece is sufficient to real all area of the single tooth. The design parameters of the machine were determined based on these experimental observations and comments from the dentists regarding this project.

As for the working area of the drill, the active area of the burr should be limited within the 20 cubic mm to avoid any mechanical damage on the machine due to the careless control. Considering the extension of the limit according to the usage, software limit was designed and implemented to the machine.

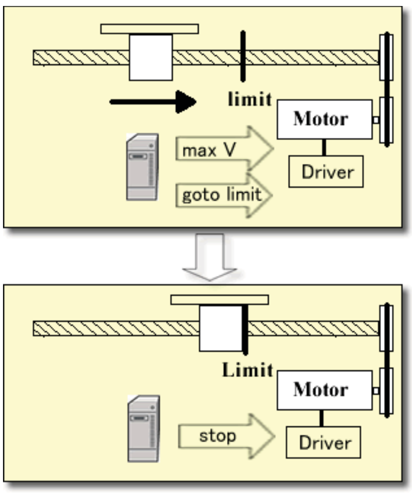

Figure 6: Soft limit for Dental Milling Machine

Position report function of the motor driver enables the motor to stop at the specified spot. However, time delay of the motor occurs and the stage exceeds the limited position before it completely stops the movement. In order to control the movement more precisely and limit the working motion within the limited area, software limit process was implemented using the rotation speed of motor and the burrs coordinate position calculated from the encoder's data as shown in schematic figure in Figure 6. This idea of software limit procedure was applied to all of the three axes.

III. Manipulation, recording, editing, regeneration

A. Manipulation

The machine is controlled by the two joysticks or a keyboard using the three axes motion as mentioned before. The operating person manipulates the machine using direct visual information from the working site or indirect visual information from an LCD monitor as shown in Figure 7. As opposed to the conventional manual operation of a hand-piece, the machine manipulation allows the operator to perform the task under various conditions with different feed speed, movement in a precise manner.

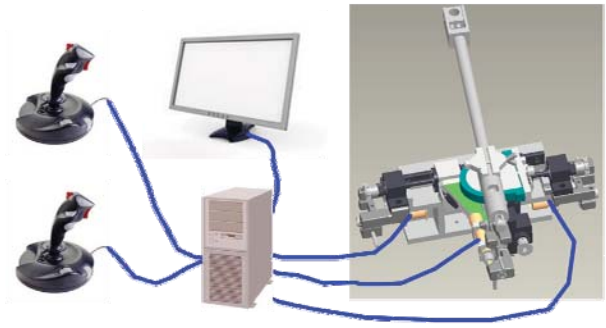

Figure 7: Dental Milling Machine configuration

B. Recording and replay of the operation

Another critical function of the machine is manipulation recording which enables the regeneration of machine manipulation. This module covers the trajectory of the tool, transfer distance with speed / acceleration data obtained from the encoders. As a result, the same manipulation can be replayed on the work piece. The recorded data is stored as a text file, which can be edited to make any correction on the manipulation. The GUI editor is under development for better performance. Therefore, manipulation editing is in the area of future work.

Figure 8 shows the original movement of the tool which results an NC code data. The machine can be operated by the NC code to perform the same manipulation.

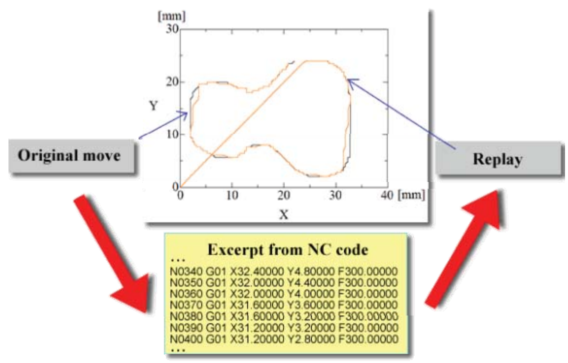

Figure 8: Regeneration of manipulation

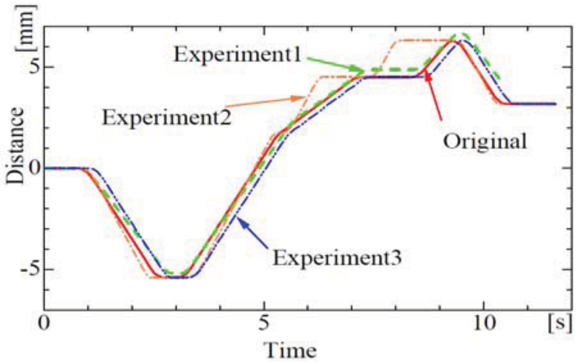

Figure 9: Different moves of the same trajectory in x-z surface

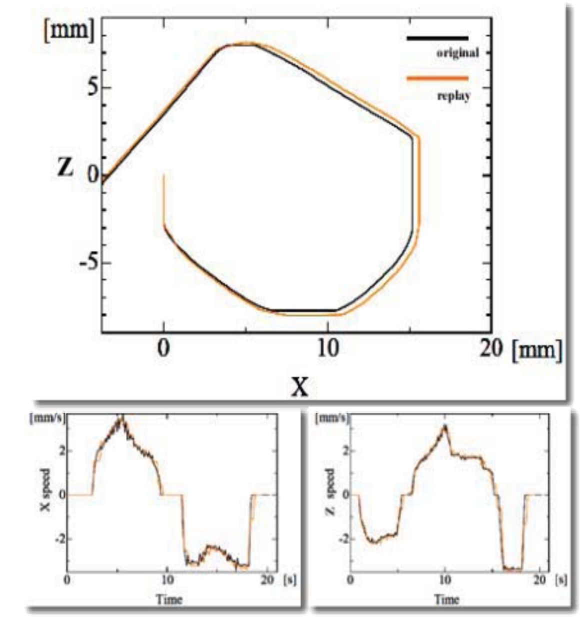

Figure 10: Replicated movement in x-z surface

Experimental machine manipulation was conducted to trace the original tool path movement. The three experiment moves in Figure 9 are based on the same trajectory of the original path. However, the tool movements are different each other because of the manual operation. Since the NC code does not represent these differences, it is not possible to exactly replay the original move. Velocity data was collected in this recording and added to the NC code for adjustment. Figure 10 shows the result of this adjustment. It shows not only that the replayed tool path is similar to the original tool path, but also shows that the movement speed is similar in both directions of x and z axes. As a result, the original move was replayed in x-z surface.

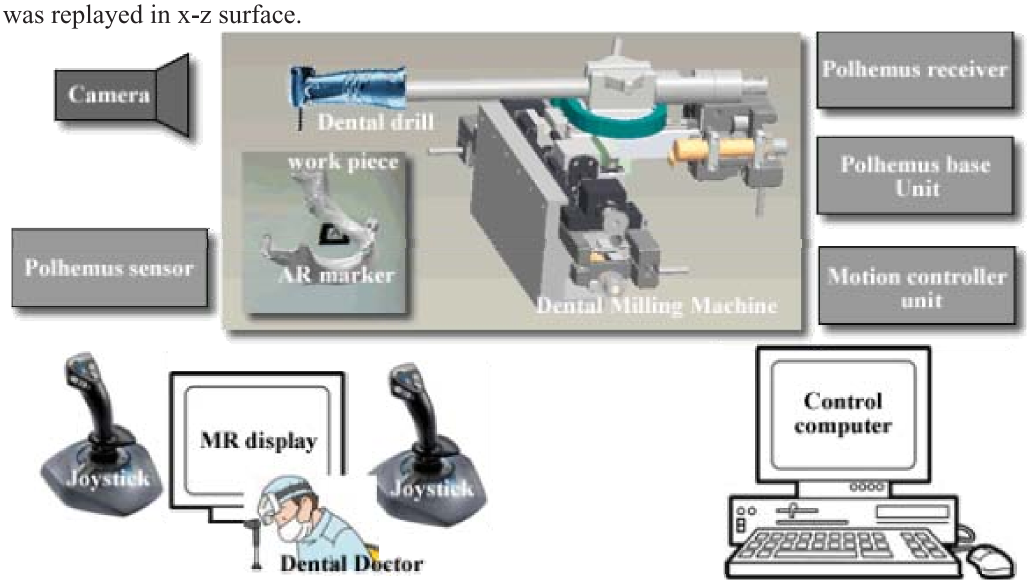

Figure 11: MRD Mill: Mixed reality dental milling machine

IV. Superimpose of Virtual Objects

Mixed reality technology enables several options to support machine manipulation by superimposed virtual object information. In order to implement the mixed reality environment for the dental milling machine, Figure 11 shows the configuration of the MR system based on the dental milling machine, which is called MRD Mill. MR environment is provided to the operator through MR display connected to the CCD camera and the control computer, which shows both the real-world object and virtual-world object using some AR Toolkit markers. MRD Mill also adopts magnetic sensors so that the real-time coordinate data of the real object such as work piece.

As mentioned in the previous section, the manipulation can be recorded in the MRD Mill system, which can tell how the machine tool moves around the work piece. Using the recorded data during the manipulation, the trajectory of the tool can be displayed as shown in Figure 12 under the mixed reality environment. A trajectory of the tool path is superimposed on the AR marker. Using this virtual tool path, the dentist who worked on this operation can review the tool path.

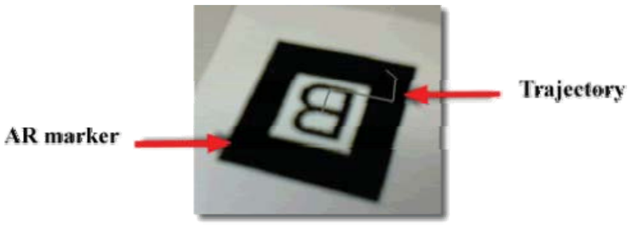

Figure 12: Trajectory over the AR marker

Since the coordinate origin is located at the AR marker's position, an offset procedure on the trajectory is required to show it as the tool path. Therefore, coordinate adjustment is processed using some system functions such as glTranslatef or glRotatef in AR Toolkit. The trajectory can be super-imposed in the real world using the MR display as shown in Figure 13, which can also be viewed using an HMD for a user's choice. In this way, the dentist can review the tool path for evaluation.

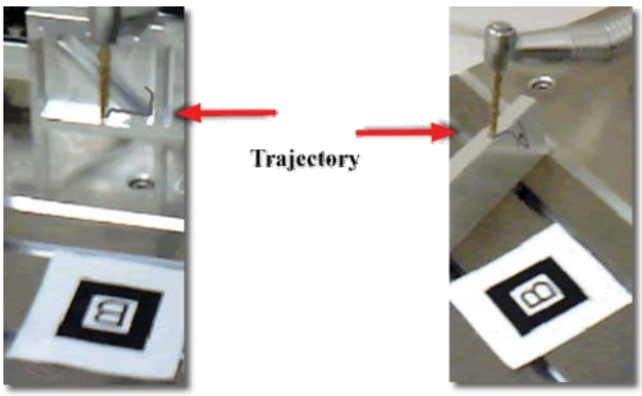

Figure 13: Trajectory on Dental Milling Machine

As mentioned in the introductory section, MR technology provides an environment which can present virtual object information as well as the machine tool path described above. Figure 14 shows that MR display which shows a virtual drill as well as the real drill over the virtual jaw model as well as the physical jaw model. This application is under study for dental implant preparation, designed for informed consent to the patient before taking the surgical operation for implant. The digital bone data for regeneration of the bone shape was prepared from the CT scan data of the patient. The physical bone model was created by the stereo-lithography process. The virtual hand piece and the drill were designed by solid modeling software based on the reverse engineering approach of the dental hand piece. The real drill is controlled by the two joysticks of the system, while the virtual drill is controlled by the assigned key of the keyboard. The virtual drill and jawbone can be shown or hidden according to the application.

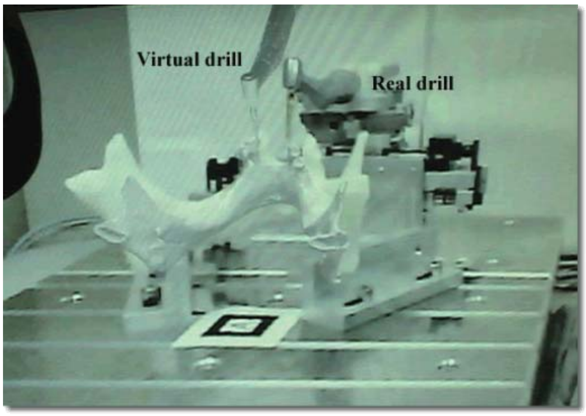

Figure 14: Mixed reality environment in MDR Mill

Electromagnetic sensor enables more flexibility in movement of the physical object. In this example, an AR marker attached on the receiver is used to local the origin of coordinate. Figure 15 shows the superimposed image of jaw bone model treated with a dental implant fixture over the physical jaw bone model held by the operator. As opposed to the image processing approach of AR Toolkit to obtain positioning information, occlusion is not an issue when the magnetic sensor is used for position detection. The operator can freely review the physical jaw model with the superimposed image of implant fixture, which can be used as a demonstration to the patient who is taking the implant operation.

Figure 15: Mixed reality with jaw bone

V. Discussion of results and future work

Several lessons have been learned from the observation and evaluation of the implemented prototype based on the dental milling machine project. The dental milling machine is still in the development stage at this time, taking the comments from the dentists into account for implementation. One of the biggest issue is to design a better human interface to support the dentists, one of which solutions is presented in this paper.

The trajectory display on the MR monitor is based on the recorded data, which means that viewing of the trajectory is available only after the manipulation. Real-time feedback may be one of the options to study for future direction, which means that the trajectory is given in real time during the machine operation so that the operator can review what is going on in real time. However, the trajectory may be obstructive information if it is given as it is. Therefore, the future study should also cover how to feedback the trajectory information during the operation.

Another benefit of mixed reality technology is to provide additional information which cannot be seen in the real world. Figure 14 shows the virtual dental drill and virtual jaw bone model are superimposed over the physical real models. Figure 15 shows the example of implant placement computer graphics image superimposed on the jaw bone model held by the operator. These functions are also implemented in MRD Mill system. The usability studies with dentists are on the schedule. Therefore, the comments and feedbacks from the dentists will be studied for the future works.

VI. Concluding remarks

The mixed reality technology applications for dental milling machine were proposed in this paper. The overview of the dental milling machine was presented to show the basic kinematics and mechanism to implement the critical functions presented in this paper. This paper also shows how the mixed reality environment was implemented based on the dental milling machine. The idea and implementation of superimpose of virtual objects over the real object were presented to show the feasibility of the study using the example of tool path trajectory. Other applications of the mixed reality technique were also presented.

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