2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) | 979-8-3503-2447-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMBC40787.2023.10340087

The Future of Dental Care: The Manipulation of Dental Instruments & Preparation Towards Automated Tooth Cleaning

Evie M. Deaker, *Student Member, IEEE*, Prof Hans Zoellner, Dr Ali Haydar Göktoğan,
Emeritus Prof Elizabeth Martin, and Dr Graham Brooker, *Member, IEEE*

Abstract— **Dentistry is an essential practice to maintain the health of the oral cavity. Recent advances in digitization and technology for oral examinations have improved the speed and ease of disease diagnosis and dental treatment. Dental robotics has emerged as a new field of dentistry and offers numerous benefits to dental professionals and society. This paper proposes an innovative design of a dental robot setup with a preliminary study on a head model for the preparation of automated dental exploration in MATLAB and discusses further considerations for automation.**

I. INTRODUCTION

Dentistry focuses on the management of oral health to improve patient wellbeing through diagnosis, prevention, and treatment of teeth. A number of chronic diseases have been linked to poor oral health including increased incidence of stroke, lung conditions, increased cardiovascular disease, low birthweight, poor diabetic control, post-surgical infections and acceleration of cognitive decline [1-4]. A lack of pain until severe symptoms emerge can impede early-stage detection and diagnosis of dental infection. Oral disorders, such as dental caries, periodontal disease, and tooth loss, were the most prevalent health conditions worldwide in 2017 (3.47 billion people) [5]. Furthermore, dental infection is a major cause of preventable hospitalizations, with over 72,000 dental hospitalizations in Australia attributed to this cause between 2017-2018 [6]. Digitization of the oral cavity has opened opportunities to improve detection and diagnosis, and so help minimize the prevalence of dental disease.

In dentistry, the small oral opening, awkward seating positions, repetitive tasks, and challenge of tracking tooth drift, alongside patient pain, fear, and discomfort, afford many opportunities for robotics to benefit both patients and dentists. Disease transmission is also a major concern, particularly at a time of global pandemic, and there is potential to improve safety for the dental workforce, by exploiting robotics to physically separate dental operators from their patients. A study of 2,053 dentists in the UK by Collin *et al.* (2019) found that 54.9% were experiencing high stress in their job, where 43.8% stated that they could not cope [7]. Hence, 17.6% had seriously considered committing suicide with 57.7% of those were in the last 12 months [7]. Interventions to reduce patient discomfort and pain using virtual reality (VR) have been explored [8]. However, dentists have been reluctant to integrate VR technologies into their practices, likely due to the large size of headsets affecting their line of sight and the benefit of reading patient facial expressions [9]. Moreover, to prevent musculoskeletal injury for dentists, they are recommended to divide dental procedures into multiple appointments and perform daily exercise or yoga [10]. Dental robotics offers a solution to help overcome these challenges, and to improve the accuracy of procedures in the oral cavity.

Recent advances in dental digitization are especially facilitative for dental robotics. The invention of non-contact intraoral scanners has allowed for the creation of fast digital impressions and 3D models of full dental arches, improving workflow, and reducing miscommunication with patients and possible legal action. This replaces conventional mold casting impression methods, and has further benefits of reducing: patient discomfort; possible errors from post process modifications; and discrepancies in dental records [11]. Facilitation of dental robotics with digital models may eventually allow for remote tele-dentistry.

In the last decade, robots have had an increasing presence in dentistry. In 2012, a robotic simulator, the dental robotutor, was developed to teach tooth brushing methods using a stepper motor [12]. In 2013-14, the accuracy and repeatability of multi-degree of freedom (DOF) robot arms was exploited for toothbrush design optimization and efficacy testing [13, 14]. More recently in 2017, Yomi by Neocis was approved in the USA as the first robotic assistant for dental implants, using patient tracking using CT scans and haptic cues for localization and feedback, although costs upwards of $150,000 USD which limits its use [15]. Also in 2017, a large robotic arm autonomously performed a pre-programmed dental implant surgery in China for a patient under local anesthesia, implanting two 3D printed teeth in one hour with a 0.2-0.3 mm margin of error [16]. As robot arms are becoming more compact, they are less confrontational and more suitable for small workplaces and direct patient contact. An example of such a robot is the 6 DOF Meca500 by Mecademic (Montreal, QC Canada).

E. M. Deaker and G. Brooker are with the Australian Centre for Field Robotics and the Aeronautical Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia (e-mail: evie.deaker@sydney.edu.au).

H. Zoellner is a Professor and Honorary Associate with Biomedical Engineering, University of Sydney, NSW 2006, Australia, as well as in the Graduate School of Biomedical Engineering at the University of NSW, Kensington, NSW 2052, Australia, and is at Strongarch Pty Ltd, Suite 11, 380 Pennant Hills Rd, Pennant Hills, NSW 2120, Australia.

A. H. Göktoğan was with the Australian Centre for Field Robotics and the Aeronautical Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia.

E. Martin is Emerita Professor in the Sydney Dental School, Faculty of Medicine and Health, The University of Sydney, 2 Chalmers St, Surry Hills NSW 2010, Australia.

The concept of Dentronics was introduced by Grischke *et al.* (2019) for the emergence of lightweight robots in dental applications, from cleaning to assisting procedures [17]. Jayaweera *et al.* (2021) highlighted the importance of introducing more digital devices to dentistry to enhance productivity during a pandemic [18]. To meet the demand of Covid-19 testing, robots from Taiwan and Denmark were designed to automate nasal and throat swabbing, respectively [19, 20]. For these systems, the user supervises the robot and has the freedom to move away from the robots reach if they experience pain or discomfort [19]. In China, Covid-19 tests were performed from a chamber by a large robot arm [21]. The individuals stood and rested their mouth on small window opening for the robot [21]. This paper assesses the automation of dental techniques that can be implemented in a robot system and aims to determine the ideal angles of entry of dental instruments into the oral cavity. We propose a face-down setup using the Meca500 as the most beneficial patient position for a robotics dental system as illustrated in Fig. 1a.

II. DESIGN

The Meca500 weighs 4.5 kg and has a very high repeatability precision of 0.005 mm, which is valuable for more precise dental techniques [22]. In the proposed setup for the dental robot system, the patient lies face-down above an enclosed chamber housing the Meca500 robot (Fig. 1a). The structure of robotic dental check-ups can be broken down into five aspects for preparation and implementation (Fig. 1b). This process begins with an intraoral scan performed on a patient, where a coded mouth prop is fitted in patients requiring procedures with high precision. This design has a number of benefits (Table 1) and can limit the transmission of diseases, including those carried by blood-borne viruses, and can be programmed to assist in infection control procedures or other routine tasks [23, 24]. As with other surgical robots such as the da Vinci surgical system, dental robots may be fitted with sleeves to protect against water damage and aid cleaning.

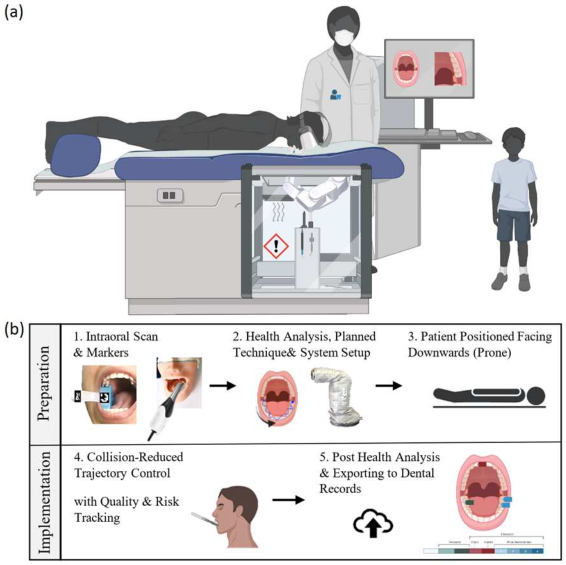

Figure 1. (a) Conceptual design for supervised robotic dentistry. (b) A proposed workflow for robotic dentistry. (Created with BioRender; Sources: Mecademic.com and MobileMedical.com.au).

TABLE I. BENEFITS FROM MAJOR CHANGES TO THE DENTAL SETUP

Prone Position	Enclosed Chamber
• Saliva does not pool in the throat (reduces or eliminates the need for suction). • Reduces risk of inhaling or dropping dental equipment down into the throat. • The patient has control to stop the procedure at any time. • Most collisions with the patient can be transient and the patient can move away upon impact. • In case of an emergency, the patient is in a recovery position.	• Controlled air flow/ventilation limits potential spread of blood by drying out the mouth. • Isolates aerosol/airborne debris and particles from oscillating dental instruments and the patient's mouth (coughing). • Dampens loud sounds and vibrations from instruments. • The headrest reduces head movement. • Bystanders are not at risk of collision with the robot.

III. METHODS

A. Data Point Selection

A silicone local anesthetic head model by OneDental (Castle Hill, NSW Australia) was acquired from the Westmead Centre for Oral Health Clinical Simulation Laboratory. The model was scanned and converted to an STL file from DICOM images using Simpleware ScanIP. Intraoral scans were carried out using the CEREC Primescan by Dentsply Sirona (Charlotte, NC USA) which has high accuracy [25]. The models were imported into MATLAB as 3D triangulation data and converted to point clouds. A PCPNT12 periodontal probe by Novatech (Chicago, IL USA) was used as the instrument for study, on the basis that this instrument is used to evaluate the health of gingival tissues (gums) and measure the extent of periodontal disease. The instrument has a periodontal tip perpendicular to its handle.

The regions of the mouth prone to the buildup of dental plaque are between teeth (interdental), along and below the gumline on teeth (gingival margin), and in crevices or cracks on chewing surfaces of teeth (dental fissures). Locations with the highest changes in surface normal were used as target points from the intraoral scan. These were chosen using moving region of interest with a width of 2 mm in the x, y, and z axes and data points with largest differences in the mean surface normal of that region were included as potential target points. This represented approximately 10% of the data points for the upper and lower dental arches. Hence, to reduce overlap, the total number of target points was simplified to 25 targets points in each quadrant of the dental arch.

B. Point Cloud Registration

To align the intraoral scans with the head model scan, the head model dental arch scans were manually sectioned out in MeshLab. The intraoral point cloud data were then registered to the head model dental arches. Two methods were trialed, the Iterative Closest Point (ICP) and Coherent Point Drift (CPD) algorithms. The MATLAB ICP method translation onto the head model was offset, although it did provide a simplified and correct rotation matrix output to rotate the mean surface normal of each point (Fig. 2a). The MATLAB CPD method had better registration and was used to translate the intraoral scan data (Fig. 2a). CPD algorithms use non-rigid registration, thus making it robust for models scans with varying edges and soft tissue/silicone deformation.

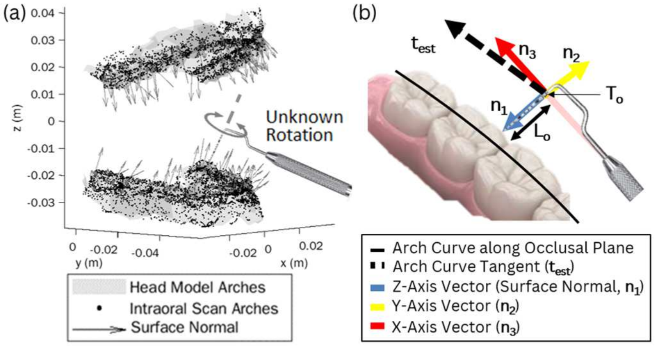

Figure 2. (a) CPD registration showing the point cloud data translation with the target mean surface normal of selected points rotated using the ICP rotation matrix. (b) The normal indicates the PCPNT12 probe orientation with the other axes defined by the occlusal plane curve. The target offset (T_o) is 10 mm in length (L_o) from the probe tip.

C. *Solving the Target Point Axes*

The axes of the instrument at each point were determined by rotating vectors using Euler angles. To estimate the x-axis vector that aligns with the instrument handle along the occlusal plane (Fig. 2b), curved arch profiles with the width (w) and depth (d) of the dental arches were calculated using the equation for an ellipse,

$$x/w \times y/d = 1. \tag{1}$$

The profile tangent vectors ($\mathbf{t_{est}}$) were calculated to point towards the back of the mouth, using either forward or backward difference, and assigned to nearby target points. Using the mean surface normal for the z-axis vector ($\mathbf{n_1}$) and the estimate x-axis vector ($\mathbf{t_{est}}$), the three axes of the instrument could be calculated using right-hand rule cross products to ensure that the axes were orthogonal. If the surface normal was not perpendicular to the occlusal plane (Fig. 2b), the x-axis vector ($\mathbf{n_3}$) was rotated away from the estimated vector ($\mathbf{t_{est}}$) by repeating the cross product,

$$(\mathbf{n_1} \times \mathbf{t_{est}}) \times \mathbf{n_1} = \mathbf{n_3}. \tag{2}$$

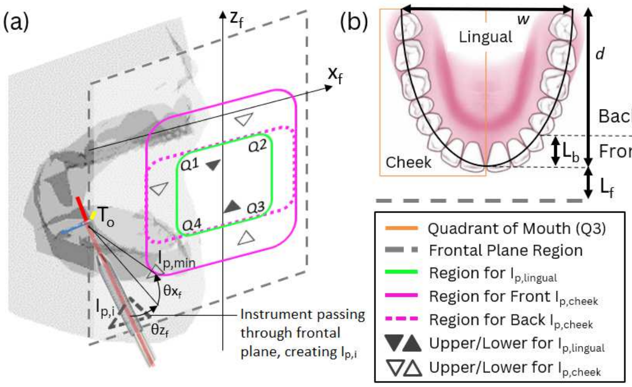

Figure 3. (a) The regions of the frontal plane for plane intersections (I_p) with the x-axis of lingual and cheek targets: back lingual (green, -20 mm $\leq x_f \leq$ 20 mm and -37 mm $\leq z_f \leq$ -7 mm); front cheek (solid magenta, ±10 mm in x_f and z_f); and back cheek (dashed magenta, ±10 mm in x_f). It shows an example intersection point outside its region ($I_{p,i}$) rotating by θ in x_f and z_f axes to minimum intersection point ($I_{p,min}$). The four quadrants of the mouth are denoted by Q1-4. For the tool axes, refer to Fig. 2b. (b) The dental arch defined by its different regions, the depth (d), the width (w), the distance to the back teeth (L_b), the curved arch profile and the distance to the front plane (L_f).

D. *Regions of the Mouth & Accounting for Limited Opening*

To access the mouth, dental instruments require additional rotations to ensure they pass through the frontal opening without colliding with the lips or teeth (Fig. 3a). Instruments operating at the back of the mouth are more at risk of colliding with the cheeks and other teeth, further influencing the angle of entry. The back region was defined as 12.67 mm away from the front of the curved profiles (L_b) and the frontal plane distance, L_f, is offset 10 mm (Fig. 3b). The points of intersection with the frontal plane (I_p) were computed using the *line_plane_intersection* function in 3D space [26]. For x-axis intersections initially outside their appropriate regions ($I_{p,i}$), the target axes were rotated to the closest acceptable intersection point ($I_{p,min}$). These Euler angles were calculated using the angle between two vectors formula for rotations in the in the x and z axes of the frontal plane,

$$\cos^{-1}\left(((I_{p,min}-T_o)\cdot \mathbf{n_3})/(|I_{p,min}-T_o|\times|\mathbf{n_3}|) \right) = \theta \tag{3}$$

IV. RESULTS

A number of the initial x-axis to frontal plane intersections from targets do not pass through the required green and magenta regions on Fig. 4a,b, risking the instrument handle not passing through the oral opening. By rotating the target axes, the points of intersection were improved for most points. This is presented by the number of intersections for solid lingual markers that appear in the green region of Fig. 4c,d, compared to Fig. 4b. Shifting the intersections were more challenging for the front targets that only show a minor improvement, from Fig. 4a to Fig. 4c, which was likely due to the proximity of the targets to the frontal plane. Of 100 target points, 8 were unsuccessfully transformed and did not intersect within their specified region: 2 back lingual targets; 2 front buccal targets; and 4 front lingual targets.

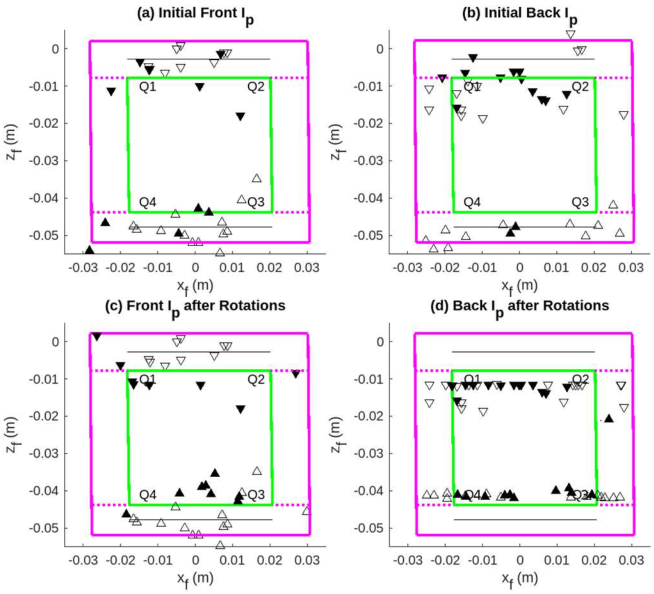

Figure 4. Initial frontal plane intersections ($I_{p,i}$) in the x-z plane for front (a) and back (b) targets, and after Euler rotations for the front (c) and back (d) targets, of the mouth. The upper and lower lingual intersections are ▲ and ▼, while the buccal targets are unfilled. The green and magenta regions are indicated on Fig. 3a, and the four quadrants of the mouth are denoted by Q1-4.

V. DISCUSSION & CONCLUSION

Robotics has appreciably improved precision and accuracy for dental implants. As dental implants are concerned with hard tissues of the body, it is necessary to use radiographic CT scans to identify the location for the implant. Therefore, the CT scan is available for tracking in robotic or assisted surgery. However, frequent radiation exposure is not suitable for frequent robotic check-ups. This paper has proposed the use of an intraoral light scanner to create an accurate 3D model of the mouth with the ability to localize coded markers that are fitted into the mouth. From these scans, the results presented in Fig. 4 present the variations in fulcrum position for dental techniques to be performed in different regions of the oral cavity. Further improvements need to be performed to ensure the instrument handle does not collide with the oral tissues, such as by using an iterative method for target point rotations.

For robots to fully integrate into dentistry, patient-adaptable algorithms need to be developed that vary based on variations in dental arch shape, tooth positions, maximal oral opening, and patient cheek elasticity. These algorithms would be previewed and approved by the operator before the robot carries out the procedure, tracking the patient's movement and assessing the risk and quality of the procedure (Fig. 2). However, the robots must be robust so that clinicians are only responsible for maintaining the system and managing alert/error messages. This suggests that robotic companies might share the medico-legal burden that currently contributes substantial insurance costs and stress for dental professionals [7]. Given the low risk of routine dental cleaning, like brushing and flossing, self-supervised operation could reduce the reliance of individuals with reduced motor skills or dementia on their caregivers for dental care [27].

The proposed design simplifies aspects of dentistry by reducing the need for two robot arms (i.e., for dental suction or mirrors). However, cameras and lighting will need to be fitted on the robot arm and chamber to track the patient and provide visual feedback to the dentist. The main challenges for this design are the lack of visibility of the patient's face to check their emotional state and the difficulty for some patients to lie on their front for extended periods of time, such as patients with severe obesity or facial trauma. Sensors to detect patient stress by measuring heart rate, galvanic skin response and temperature, could help address these difficulties. For dental robots to be successful, the accuracy, affordability and safety of such systems needs to be proven and supportable by regulatory institutions, dental practices, and the public.

ACKNOWLEDGMENT

Thanks to Dr Ken Hooi from CREED CE and Associate Prof Dale Howes from Sydney Dental Hospital for advice and assistance with the intraoral and CT scans, respectively.

REFERENCES

[1] M. Ide *et al.*, "Periodontitis and Cognitive Decline in Alzheimer's Disease," (in English), *PLoS One,* vol. 11, no. 3, 2020-04-30 2016.

[2] J. S. Yasny and A. Herlich, "Perioperative Dental Evaluation," *Mount Sinai Journal of Medicine: A Journal of Translational and Personalized Medicine,* vol. 79, no. 1, pp. 34-45, 2012.

[3] DHSV, "Links between oral health and general health the case for action," Dental Health Services Victoria 2011, Available: https://www.dhsv.org.au/__data/assets/pdf_file/0013/2515/links-between-oral-health-and-general-health-the-case-for-action.pdf.

[4] H. Zoellner, "Dental Infection and Vascular Disease," *Seminars in thrombosis and hemostasis,* vol. 37, no. 3, pp. 181-192, 2011.

[5] S. L. James *et al.*, "Global, regional, and national incidence, prevalence, and years lived with disability for 354 diseases and injuries for 195 countries and territories, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017," *The Lancet,* vol. 392, no. 10159, pp. 1789-1858, 2018.

[6] AIHW, "Oral health and dental care in Australia," Australian Institute of Health and Welfare, Canberra2020, Available: https://www.aihw.gov.au/reports/dental-oral-health/oral-health-and-dental-care-in-australia.

[7] V. Collin, M. Toon, E. O'Selmo, L. Reynolds, and P. Whitehead, "A survey of stress, burnout and well-being in UK dentists," (in English), *British Dental Journal,* vol. 226, no. 1, p. 40, 2019-01-11 2019.

[8] M. D. Wiederhold, K. Gao, and B. K. Wiederhold, "Clinical use of virtual reality distraction system to reduce anxiety and pain in dental procedures," (in eng), *Cyberpsychology, behavior and social networking,* vol. 17, no. 6, pp. 359-365, 2014.

[9] A. Cunningham *et al.*, "A systematic review of the use of virtual reality or dental smartphone applications as interventions for management of paediatric dental anxiety," *BMC Oral Health,* vol. 21, no. 1, p. 244, 2021.

[10] A. Joshi, H. Soni, A. Hedaoo, C. Bande, M. Goel, and A. Mishra, "Prevalence of musculoskeletal disorders affecting general dental practitioners in nagpur and proposal of a new composite classification system," *Journal of Indian Association of Public Health Dentistry,* Original Article vol. 17, no. 3, pp. 241-246, July 1, 2019 2019.

[11] E. Yuzbasioglu, H. Kurt, R. Turunc, and H. Bilir, "Comparison of digital and conventional impression techniques: evaluation of patients' perception, treatment comfort, effectiveness and clinical outcomes," *BMC Oral Health,* vol. 14, no. 1, 2014.

[12] M. Ahire, N. Dani, and R. Muttha, "Dental health education through the brushing ROBOTUTOR: A new learning experience," (in eng), *Journal of Indian Society of Periodontology,* vol. 16, no. 3, pp. 417-420, 2012.

[13] J. Liu, "A novel motion generation strategy for robotic tooth brushing simulator," *Industrial robot,* vol. 40, no. 4, pp. 355-362, 2013.

[14] T. Lang, S. Staufer, B. Jennes, and P. Gaengler, "Clinical validation of robot simulation of toothbrushing - comparative plaque removal efficacy," (in English), *BMC Oral Health,* vol. 14, p. 82, 2014.

[15] A. Parmar, "Florida startup aims to make robot use in dental implants ubiquitous," in *MedCity News* ed. Online: Breaking Media, Inc, 2017.

[16] A. Yan, "Chinese robot dentist is first to fit implants in patient's mouth without any human involvement," ed: South China Morning Post, 2017.

[17] J. Grischke, L. Johannsmeier, L. Eich, and S. Haddadin, "Dentronics: Review, First Concepts and Pilot Study of a New Application Domain for Collaborative Robots in Dental Assistance," in *2019 International Conference on Robotics and Automation (ICRA)*, 2019, pp. 6525-6532.

[18] M. Jayaweera, H. Amarasinghe, and N. W. Johnson, "Reshaping dental practice in the face of the COVID-19 pandemic: leapfrogging to Dentronics," (in English), *Oral Diseases,* 2021.

[19] J. Vincent, "Please remain calm while the robot swabs your nose," ed. Online: The Verge, 2020.

[20] S. Crowe, "Danish startup develops throat swabbing robot for COVID-19 testing," in *The Robot Report*, ed. Online, 2020.

[21] Z. Changyue, "Highly efficient auto throat swab robots introduced for COVID-19 tests," in *Global Times*, ed, 2022.

[22] Mecademic. (2021). *Meca500 Six-Axis Industrial Robot Arm*. Available: https://www.mecademic.com/en/meca500-robot-arm

[23] P. Ahmad *et al.*, "Dental Robotics: A Disruptive Technology," *Sensors,* vol. 21, no. 10, 2021.

[24] J. Grischke, L. Johannsmeier, L. Eich, L. Griga, and S. Haddadin, "Dentronics: Towards robotics and artificial intelligence in dentistry," *Dental Materials,* vol. 36, no. 6, pp. 765-778, 2020.

[25] K. Ryan Jin Young, G. I. Benic, and P. Ji-Man, "Trueness of ten intraoral scanners in determining the positions of simulated implant scan bodies," (in English), *Scientific Reports (Nature Publisher Group),* vol. 11, no. 1, 2021.

[26] N. Douillet. (2021, 2/20/2022). *Line plane intersection (3D) v2.3*. Available: https://github.com/NicolasDouillet/line_plane_intersection/

[27] N. J. Wilson *et al.*, "Countering the poor oral health of people with intellectual and developmental disability: a scoping literature review," *BMC Public Health,* vol. 19, no. 1, p. 1530, 2019/11/15 2019.