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A Kinematic Concept for Robotic Assisted Dental Rehabilitation

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ABSTRACT

The current technique of dental rehabilitation relies largely on the qualitative perception of the dentist in the relocation and reorientation of the teeth. Furthermore, the patient does not have the final visual appearance of the teeth after the procedure. In this project, we plan to address this issue by ultimately developing a concept of robotic assistant dental rehabilitation. The key elements in the concept consist of cone-beam computed tomography machine (CBCT), image processing algorithm and a robot manipulator system, which will function as an integrated unit to aid and guide the dentist in the diagnosis and treatment procedures. The aim of this paper is to show the kinematics concept that relates the dental configuration system with the dental operatory. A homogeneous transformation matrix that relates the key elements of translation and rotation in the robotic work cell concept is developed. From this matrix, the positions and orientations of any tooth can be determined. The relationship between any arbitrary points relative to a tooth frame can also be defined. The formulation of kinematics model for the robotic work cell is discussed. This new model will aid the dentist in the exploration, manipulation and reconfiguration in the dental rehabilitation.

Keywords: *dental occlusal;, rehabilitation; kinematics equations; robotic; dental rehabilitation.*

1. INTRODUCTION

This research will investigate the kinematic model of the dental features of occlusion in three dimensions. This investigation will be carried out by measuring the dental geometrical configuration. This knowledge will furnish the base for the development of a conceptual model of robotic assisted dental rehabilitation. The availability of this concept will aid the dentist in the exploration, manipulation and reconfiguration of the dental rehabilitation.

Theories and concepts of human masticatory system and occlusion are the current guide in restoring occlusion and teeth position whether the treatment involves a single dental implant or the reestablishment of occlusion as in some orthodontic cases which involves multiple teeth movements [1]. The concept of occlusal rehabilitation takes its origins partially from the spherical theory of occlusion [2], [3]. There is a need to develop a more accurate model of dental geometry to improve the current gnathological method of occlusal rehabilitation, which has progressed from the concept of balanced articulation. The balanced articulation can be

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described as bilateral, simultaneous, anterior and posterior occlusal contact of the teeth in centric and eccentric positions [4]. It is believed that gliding teeth contacts in harmony with the anatomical condylar guidance and incisal guidance established to achieve esthetic and phonetic goals [5]. Effort to formulate a scientific basis for clinical observations and the attempt to create a balanced occlusion led to development of geometric schemes and mathematical models of the dental system [6], [7], [8]. Currently those models serve only as a visual reference, which fails to give a precise measure of the discrepancy that need to be corrected. As a result, the dentist assessment is still qualitative [9]. Through this project we aspire to conduct a series of investigations, which can ultimately lead to the development of a quantitative assessment of static and dynamic features of occlusion which can play a critical role in the rehabilitation according to the requirements of the dental system. This assessment tool can aid in the diagnosis and treatment of occlusal rehabilitation cases that involves restoring or realigning the teeth. It can also guide the dentist in denture construction to best satisfy esthetic and phonetic requirements.

The knowledge of accurate three-dimensional models of occlusal geometry would be helpful when providing oral rehabilitation for patients with or without occlusal derangement. In orthodontic treatments, dentists often use qualitative assessment for oral rehabilitation. However, with the advancement of recent scanning and imaging technology, a more accurate model of occlusal geometricalstructure can be formulated, developed and customized according to the needs of an individual patient. The detailed geometry of dental configuration as well as the position and orientation of every tooth is essential for better oral rehabilitation, esthetic and phonetic requirements. This new model will aid the dentist in the exploration, manipulation and reconfiguration in the dental rehabilitation. The overall objectives of this paper are as follows:

1. To propose a robotic assisted concept for dental rehabilitation.
2. To formulate kinematics and inverse kinematics of the dental occlusion.

2. GENERAL CONCEPT ROBOTIC WORK CELL IN DENTAL OPERATING ROOM

The conceptual of robotic work cell for assisted dental rehabilitation is shown in Figure 2. The figure showed the dental operating room with the robotic work cell concept. Each frame is labelled as frame i, j, and o. Frame i is for dental model, frame j is the base frame, while frame o is the vision frame, which is the reference frame for dental model. The cone beam computed tomography (CBCT) vision machine usually will be fixed at one place which its position and orientation are already pre-determined relative to base frame. So, the relation between vision machine and robot arm base will always be fixed. This is the known relation. When a dental configuration is presented in the working area, its position and orientation can be determined only from a CBCT vision machine. The CBCT vision machine has its mean to calculate the distance of work piece from its coordinate frame and thus it is able to determine the exact position and orientation of dental model related to its frame. However, it will be a different case with the robot arm base. It does not have any mean to calculate the position and orientation of dental model from its frame. But, the position and orientation of dental model referred to robot arm base is required by the robot system to move the robot arm to the dental model position. When three values are available, if at least two of them are known, then the

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third value is possible to find. In this situation, the relation of vision machine and robot arm base is known and relation of dental model and vision machine also is known. By using these two known relations, the relation between dental model and robot arm base can be determined. The method will be explained in the next section.

To define the position and orientation of teeth, the dental system can be related to robot arm kinematic and machine vision system [10]. Tooth represents the work piece while the reference frame of machine vision is represented by imaging devices coordinate system and the reference frame of the robot is represented by base of the robot. The relationship between the reference frame of the imaging system and of the robotic system involved direct and inverse kinematic problems. The relationship between the coordinate system can be presented in matrix called transformation matrix.

The dental kinematic system deals with the analytical study of the geometry of motion of teeth with respect to a fixed reference coordinate system as a function of time without concern of the forces/moments that produce the motion. Due to that, this system deals with the analytical description of the spatial displacement of the teeth as a function of time, in particular the relations between the joint-variable space and the position and orientation of the end-effector of a robot arm. There are two fundamental questions of both theoretical and practical interest in this kinematic analytical:

1. For a given tooth, given the joint angle vector $q(t)=(q_1(t), q_2(t), q_n(t))^2$ and the geometric link parameters, where n is the number of degree of freedom, what is the position and orientation of the tooth with respect to a reference frame?

2. Given a desired position and orientation of the tooth and the geometric link parameters with respect to a reference frame, can it reach the desired prescribed position and orientation? How many configurations will thus be needed?

The first question is usually referred to as the direct (or forward) kinematics problem, while the second question is the inverse kinematics (or arm solution) problem. A simple block diagram indicating the relationship between these two problems is shown in Figure 1 below.

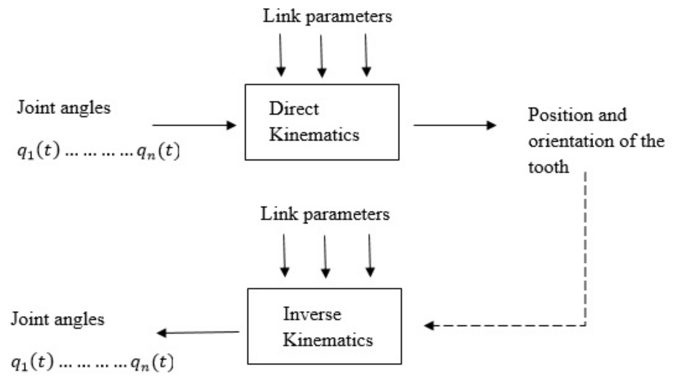

Figure 1: The Direct and Inverse Kinematics Concepts[10].

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Since the teeth may rotate and/or translate with respect to a reference frame, the total spatial displacement of tooth is due to the angular rotation and linear translation of teeth. In general, the inverse kinematic problem can be solved by several techniques. Most commonly used methods are the matrix algebraic, iterative, or geometric approaches. A geometric approach based on the link coordinate systems and the manipulator configuration will be presented in obtaining a closed form joint solution for simple manipulator with rotary joints. Then a more general approach using 4×4 homogeneous matrices will be explored in obtaining a joint solution for simple manipulator [10].

3. KINEMATIC CONCEPT

The conceptual dental operatory has been set up with a vision machine in Figure 2. The machine already knew the origin of the base coordinate system. It can see the teeth to be manipulated by dentist or robot. A local frame has been established from the machine vision. From local frame, tooth frame can be determined.

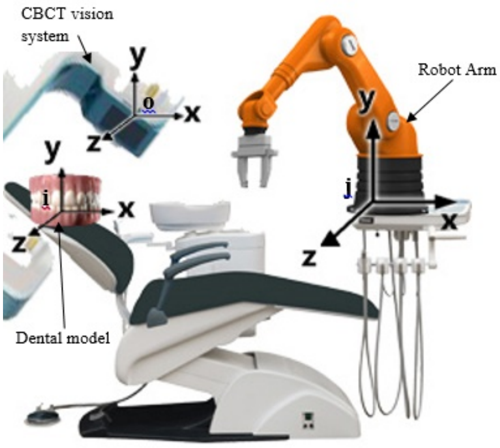

Figure 2: Conceptual Robot Assisted Dental Operating Theater.

3.1. CENTROID POSITION AND ORIENTATION OF TOOTH

Currently, there is only limited quantitative approach for a standard definition for tooth centroid. In this research, it is very important to define the most suitable centroid to be used to represent the tooth as a whole. The centroid is different for a single root tooth which is incisor, canine, and premolar, and multiple root teeth for first molar and second molar teeth. This centroid must be able to be viewed from 3-dimensional (3D) view. We need to consider for both position and orientation. One definition is suitable to find the position but it gives difficulty to find the orientation of tooth. For molar teeth which have more than one root, it will need a different definition of centroid, because the length of the roots is different from one another.

In this study, the definition for centroid of a tooth is 1/3 of the length (L) of a tooth root. This definition is for tooth with one root only. For tooth with two or more roots, if the same definition is used, it will have difficulty to determine which root or average of the root length. So, for this type of tooth, it is easier to use bifurcation point as its centroid. Bifurcation is the point where roots started to divide. Centroid is needed to determine orientation because it is

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the point where the tooth is considered to be rotated. Orientation is measured in form of angle value in degree (°) while positive and negative signs represent the direction of the rotation from its initial assumed condition, whether clockwise or counterclockwise. Using right hand rule will be the easiest way to determine rotation sign for tooth orientation. If Y-axis is pointing upward, according to the right hand rule, the counterclockwise rotation will be positive, and the clockwise direction will be negative.

The determination of orientation of tooth is done after locating the centroid position (Xc, Yc, and Zc). Using the cone beam coordinate system as a reference frame, the orientations are measured from its respective axes using image processing algorithm developed in this study. For a single root tooth, a straight line that will pass through 3 points of dental features which are the root, the centroid, and the peak point of a tooth will be constructed and considered as Y-axis of the tooth frame. For a multiple roots tooth, a straight line that will pass through 3 points of dental features which are the root, the centroid, and the lowest point of the top tooth surface will be used. Meanwhile the X-axis will be perpendicular to Y-axis and pass through the centroid point. Similarly, Z-axis will be constructed accordingly using right hand rule Cartesian coordinate system as shown in Figure 3. The orientation of a tooth is as follows; rotation in X-axis, yaw (Ψ), rotation in Y-axis, pitch (θ), and rotation in Z-axis, roll (ϕ).

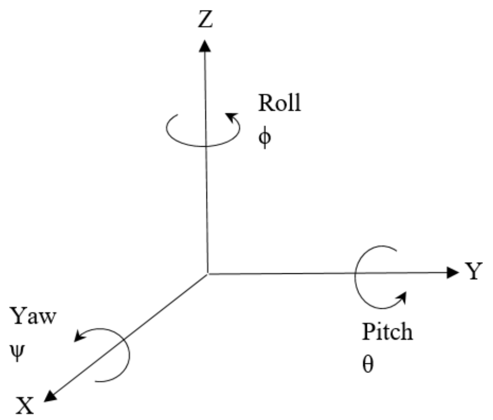

Figure 3: Basic Orientations

3.2. HOMOGENEOUS TRANSFORMATION MATRIX OF DENTAL SYSTEM

To get into a desired position and orientation, a tooth might go through several operations that involved both translational and rotation transformation matrix. The transformation matrix can operate in a sequential manner, for example, translate, translate, translate, rotate, rotate, and rotate [10]. This combination of six transformations is what gave the tooth its desired position and orientation. Since 3×3 rotation matrix does not give any provision for translation, a fourth component is used to a position vector in three-dimensional space. This homogeneous-coordinate concept that represent points in a three-dimensional euclidean space is useful in developing matrix transformation such as translation and rotation. Of course it also can be used for scaling and perspective transformation, but this study focuses only on two components; translation and rotation.

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The homogeneous rotation and translation matrices can be multiplied together to obtain a composite homogeneous transformation matrix called the T matrix. Two coordinated systems are used. For instance, one is the fixed reference coordinate frame; OXYZ or cone beam axes and the other is the moving (translating and rotating) coordinate frame; OUVW or tooth axes. To describe the spatial displacement relationship between these two coordinate systems, a 4×4 homogeneous transformation matrix is used. Since the tooth frame axes (OUVW) is rotating/translating about the principal axes of the OXYZ frame, then pre-multiply the previous (resultant) homogeneous transformation matrix with an appropriate basic homogeneous rotation/translation matrix. So, the sequence of operations will be:

1. Rotating on z-axis with θ angle.
2. Rotating on y-axis with ϕ angle.
3. Rotating on x-axis with α angle.
4. Translating along z-axis with c distance.
5. Translating along y-axis with b distance.
6. Translating along x-axis with a distance.

The detail operation of translation and rotation, six 4×4 of homogeneous transformation matrices are used as general Equation 1 below:

$$ {}_{i}^{0}\mathbf{T} = \mathbf{T}_{x,a}\mathbf{T}_{y,b}\mathbf{T}_{z,c}\mathbf{T}_{x,\alpha}\mathbf{T}_{y,\phi}\mathbf{T}_{z,\theta} $$

$$ = \begin{bmatrix} C\theta\, C\phi & -S\theta\, C\phi & S\phi & a \\ S\theta\, C\alpha + C\theta\, S\phi\, S\alpha & C\theta\, C\alpha - S\theta\, S\phi\, S\alpha & -C\phi\, S\alpha & b \\ S\theta\, S\alpha - C\theta\, S\phi\, C\alpha & C\theta\, S\alpha + S\theta\, S\phi\, C\alpha & C\phi\, C\alpha & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

3.3. ARBITRARY POINT RELATIVE TO TOOTH AXES

Dental occlusion does not deal with only a single tooth, it involves the whole dental system. That is whysometimes there is a need to determine an arbitrary point that is relative to the adjacent tooth. As example, the arbitrary point, p, as shown in Figure 4 can be determined its position referring to the reference frame, but its position from tooth is unknown. This arbitrary point can be determined by using “chain product” rule as shown in Equation 2 below:

$$ {}^{\mathrm{i}}\mathbf{P} = {}_{\mathrm{o}}^{\mathrm{i}}\mathbf{T} \quad {}^{\mathrm{o}}\mathbf{P} \quad (2) $$

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Assume frame i is the tooth frame while frame o is the reference frame. Where ^{o}P defines point p relative to frame o and T (o,i) is homogeneous transformation matrix that relates between reference frame to tooth frame.

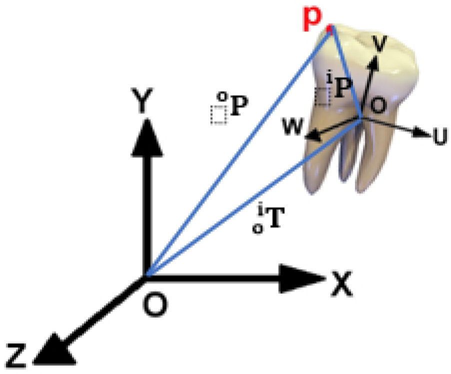

Figure 4. Arbitrary point on a tooth.

3.4. COMPOUND TRANSFORMATION MATRIX BETWEEN TEETH

By using Equation 1, the relation between teeth is also possible to be determined. Assume that relation between incisor and canine need to be determined. Tooth LR1 will represent incisor and tooth LR2 will represent canine. The relation between tooth LR1 and tooth LR2 can be determined using Equation 3.

$$ {}^{\mathbf{LR1}}_{\mathbf{LR2}}\mathbf{T} = \left({}^{\mathbf{o}}_{\mathbf{LR1}}\mathbf{T}\right)^{-1} {}^{\mathbf{o}}_{\mathbf{LR2}}\mathbf{T} = {}^{\mathbf{LR1}}_{\mathbf{o}}\mathbf{T} \quad {}^{\mathbf{o}}_{\mathbf{LR2}}\mathbf{T} \tag{3} $$

If the homogenous transformation matrix LR2 and LR1 relative to frame O is known, then LR2 relative to LR1 can be determined.

Hence, arbitrary point P relative to tooth LR1 frame can be determined using Equation 4.

$$ {}^{\mathbf{LR1}}\mathbf{P} = \left({}^{\mathbf{o}}_{\mathbf{LR1}}\mathbf{T}\right)^{-1} {}^{\mathbf{o}}\mathbf{P} = {}^{\mathbf{LR1}}_{\mathbf{o}}\mathbf{T} \quad {}^{\mathbf{o}}\mathbf{P} \tag{4} $$

4. RESULTS

To demonstrate this formulation, an arbitary point P relative to tooth LR1 frame can be determined. Assume that the position of point P is at (80.4, 33.6, 130.4) relative to the reference frame, O. The centroid position of tooth LR1 is (80, 35.2, 132.8) and its orientation is (42.1°, -28.81°, 4.76°). It is required to move tooth LR1 centroid along x-axis with a distance of 1 mm along x-axis to a new position at 81 mm. So, the point P will have a new position. In this first operation, there is no rotational operation involved. Since P is just a point, so it does not have any orientation, but the orientation of tooth will affect P position. Note that P is a point on tooth LR1,and so by moving tooth LR1, the position of P in relation to reference frame will change, but its position in relation to tooth LR1 will remain the same. To show that this formula can be used to obtain any relation for teeth, we also took LR2 to find the relation of point P with other tooth. The results were recorded in Table I below. Table

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II shows the result when LR was rotated -5°, while Table III shows the result when combining both translation of 1 mm and the rotation of -5°.

Table 1: Positions of Point P After LR1 Moved 1 mm Along X-axis

	X (mm)	Y (mm)	Z (mm)
${}^{0}_{current}\mathbf{P}$	80.4	33.6	130.4
${}^{LR1\ current}_{current}\mathbf{P}$	-0.22	-2.78	-0.82
${}^{LR1\ new}_{new}\mathbf{P}$	-0.22	-2.78	-0.82
${}^{LR1\ new}_{current}\mathbf{P}$	-1.09	-2.71	-0.36
${}^{0}_{new}\mathbf{P}$	81.4	33.6	130.4
${}^{LR1\ current}_{new}\mathbf{P}$	0.65	-2.87	-1.30
${}^{LR2\ current}_{new}\mathbf{P}$	4.10	-0.68	-2.02
${}^{LR2\ current}_{current}\mathbf{P}$	3.25	-0.48	-1.52

Table 2: Positions of Point P After LR1 Rotated -5° on X-axis

	X (mm)	Y (mm)	Z (mm)
${}^{0}_{current}\mathbf{P}$	80.4	33.6	130.4
${}^{LR1\ current}_{current}\mathbf{P}$	-0.22	-2.79	-0.81
${}^{LR1\ new}_{new}\mathbf{P}$	-0.22	-2.79	-0.81
${}^{LR1\ new}_{current}\mathbf{P}$	-1.09	-2.71	-0.36
${}^{0}_{new}\mathbf{P}$	80.4	33.4	130.55
${}^{LR1\ current}_{new}\mathbf{P}$	-0.11	-2.84	-0.60
${}^{LR2\ current}_{new}\mathbf{P}$	3.36	-0.56	-1.31
${}^{LR2\ current}_{current}\mathbf{P}$	3.25	-0.48	-1.52

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As mentioned earlier, since the point P is the point on tooth LR1, so no matter where tooth LR1 is moved, its position in relation to tooth LR1 will remain the same, which is why in Table 1, its new position is the same as its current position. The new position of point P in relation to reference frame had just increased 1 mm in x-axis which was the same amount of movement of tooth LR1. This is logic since the tooth was moved along the x-axis of the reference frame. Thus, point P also moved to the same direction and same value. But, if the new point P relates to the current tooth LR1, of course there will be a change for x position, but y and z positions will also change. This is because the orientation of the tooth affects the new position of P. Point P may move along x-axis of reference frame, but for current tooth LR1 frame, point P moves in 3 directions; x, y, and also z. That is why the positions of y and z also have changed.

Table 3: Positions of Point P After LR1 Moved 1 Mm Along X-Axis and Rotated -5° on X-Axis

	X (mm)	Y (mm)	Z (mm)
${}^{0}_{current}\mathbf{P}$	80.4	33.6	130.4
${}^{LR1\ current}_{current}\mathbf{P}$	-0.22	-2.79	-0.81
${}^{LR1\ new}_{new}\mathbf{P}$	-0.22	-2.79	-0.81
${}^{LR1\ new}_{current}\mathbf{P}$	-0.33	-2.71	-1.02
${}^{0}_{new}\mathbf{P}$	81.4	33.4	130.55
${}^{LR1\ current}_{new}\mathbf{P}$	0.76	-2.92	-1.08
${}^{LR2\ current}_{new}\mathbf{P}$	4.20	-0.75	-1.81
${}^{LR2\ current}_{current}\mathbf{P}$	3.25	-0.48	-1.52

5. CONCLUSION

This robotic work cell concept can be used in dental operating room with the availability of vision machine that is needed to determine the positions and orientations of teeth referring to its coordinate frame. From that information, it is possible to find the teeth positions and orientations relative to the base frame. Hence, the final objective of this research will enhance the dentist performance and satisfy the functional, esthetics and phonetics requirements in the dental treatment.

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