3D PROSTHODONTICS WIRE BENDING MECHANISM WITH A LINEAR SEGMENTATION ALGORITHM

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ABSTRACT: This study proposes the idea of automated 3D wire bending mechanism which is flexible and capable of making any type of bend for dentistry applications. Till recently, wire bending in orthodontics and prosthodontics applications has been manually bent by a skillful dental technician. Manual wire bending has a huge tendency to create errors, thus affecting the efficiency of the wire for the specified treatment, in parallel with the elongation of the treatment time. Besides, it can simultaneously increase the bending time due to some additional major adjustments and leads to bender fatigue. In general, the accuracy of the bend is inconsistent and depends on many factors, mostly on the expertise of the bender. Hence, due to these limitations in the manual wire bending and some urgency to decrease the dependency on the bender's competency, this article introduces a theoretical framework of the 3D linear segmentation algorithm to realize the proposed bending mechanism.

KEYWORDS: *3D bending, wire bending mechanism, line segmentation, algorithm*

1.0 INTRODUCTION

Wire bending in orthodontics and prosthodontics applications is done manually by a dental technician. Several disadvantages of the manual practice were reported by [1]-[5] in their studies. Manual wire bending in orthodontics, for instance has a high tendency to create errors that weaken the exact expression of corrective force which can lead to ineffective treatment or medical accidents sometimes [1]. Generally, any mistake in wire bending can automatically increase the treatment time and cost due to several adjustments and certainly leads to bender fatigue [1][4]. In prosthodontics, manual wire bending is difficult due to the irregular dental anatomy. For that reason, a precisely bent wire is crucial and minor inaccuracies in wire design or manufacture can produce undesirable clinical consequences [6].

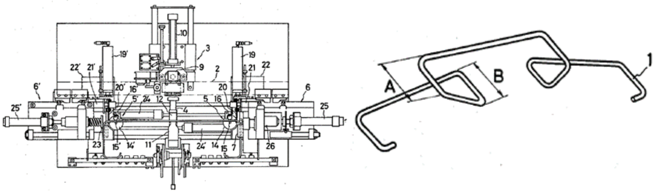
Wire bending is an experience-dependent task in both orthodontics and prosthodontics [7]. All the bending parameters and criteria are professionally recognized by knowledge and experience of the clinical orthodontist or prosthodontist [15]. Clinical experience is more dominant than scientific evidence which strictly discourages a dentist to rely on the opinion of just one dental technician [8]. Cooperation between an experienced dental specialist and a skillful technician is often needed to produce high quality dentures with a low revision rate [2]. High level of randomness is the main concern in dentistry applications due to shape complexity, uncertainty of manual operation and level of difficulty to realize personalized wire bending [9]. In addition, the bender's expertise contributes the most to the wire bending accuracy [4][5]. Considering a very high dependency on human and several uncertainties as literally clarified, there is a great need for a practical, reliable and efficient automated design and manufacturing system to resolve these concerns.

Several attempts to automate the wire bending process have been done in the prior art. However, all of those inventions are related to archwire bending in orthodontics. Basically, there are two approaches to the archwire manufacturing, one is based on a flat archwire and customized brackets and the latter approach is based on a customized archwires and off-the-shelf brackets. The first approach only demands a simple U-shape archwire bending that does not require a combination of translation and rotational motion contrary to the second approach. The development of an automated wire bending mechanism for both methods is taking place in robotics technology and also in a computer numerically controlled (CNC) machine. CNC machine inventions by [1][15] fall under the first approach while robots have been chosen for the latter category with the introduction of robotic arms [11][13], a cartesian robot [5] and a gantry robot [6].

This study discusses a theoretical algorithm for the proposed bending mechanism which can automatically bend a straight wire into a real 3D wire equivalent to the virtual curve based on the relative spatial parameters of the adjacent 3D line segments (L-the length, θ-the deflection angle, β-the twist angle, γ-the radial deflection angle). The principle and algorithm of bending any 3D wire are discussed, which include 3D linear segmentation to replace 3D curve with 3D short line segments for certain features.

2.0 COMPUTER-AIDED WIRE BENDING SYSTEMS

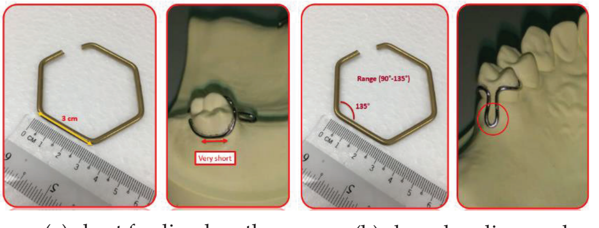
2.1 Industrial Wire Bending Machines



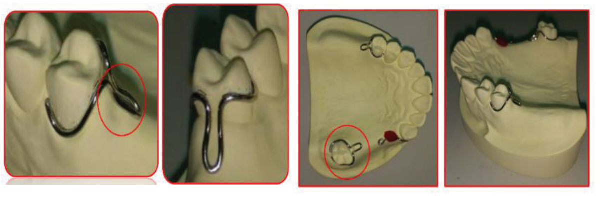
(a) large dimension (b) simple shape output

Figure 1: Example of the existing CNC machine [10]

Industrial wire bending machines are available in the manufacturing industry with various types of machines for different wire diameter and material. Many manufacturers around the world have successfully developed their own CNC bending machine with different specifications, price, advantages and also limitations. However, the wire bending in dentistry is rather complicated and requires a high degree of accuracy to ensure perfect fixation to customer's mouth which could not be performed by the existing technology. In addition, the size of the machine is gigantic and only enables to bend thick wires, contrary to the needs in dentistry which demands a thinner wire which is less than 1.3 mm [4].



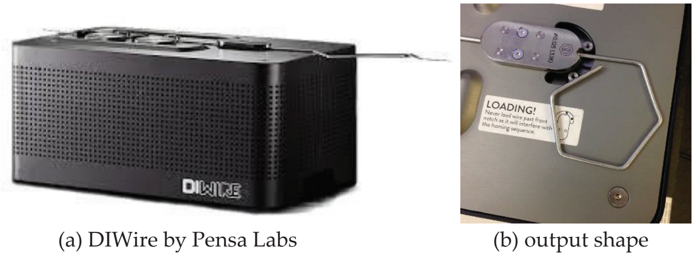
(a) short feeding length (b) sharp bending angle



(c) alleviation of height (d) follow tooth contour

Figure 2: General requirements for the dentistry bending machine

A review of 40 existing CNC machines has shown several drawbacks which are significant in dentistry wire bending. To conclude, DIWire which is a desktop CNC bending machine was initially chosen as a benchmark to this study considering three factors. Firstly, it comes in a desktop size, secondly it is light and thirdly, it is capable of bending to a minimum of 1 mm wire diameter. However, several drawbacks have been gathered after a few trials on DIWire. Firstly, the machine is not capable of producing a sharp bend since it offers a minimum of 45 degrees bending angle. This is written in the machine manual and afterwards confirmed by DIWire design engineer that with different materials and wire sizes, the angle differs. For example, with a 1/8" steel wire a maximum angle closer to 130 degrees but with 1/16" steel the maximum bend angle is closer to 135 degrees. The reason is different amounts of spring back after a bend which depends on wire materials and sizes. Secondly, the feeding length in between bend is lengthy as the minimum feed between bends is generally in the range of 12 to 15 mm and depends on how tight the bends are on either side of that feed length. The information was also confirmed by the DIWire design engineer. Thirdly, the DIWire is only capable of producing a simple shape. The dentistry shape, on the other hand follows the shape of a tooth contour. Since the prerequisites in dentistry wire bending are to allow a sharp bending in between bend, to tolerate a very short feeding length in between bending and to make a very customized bending per trial; therefore all condition are still lacking and unavailable in the existing technology.



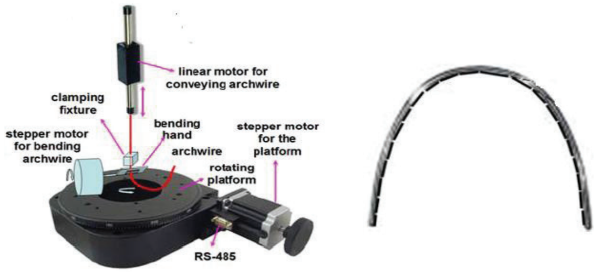
(a) DIWire by Pensa Labs (b) output shape

Figure 3: DIWire and an example of the output shape [14]

2.2 CAD CAM Innovations in Dentistry Wire Bending

Recently, manufacturing techniques and systems have been introduced into dentistry. Computer-aided design (CAD) and computer-aided machining (CAM) systems are commercially available for virtual, three-dimensional design and fabrication of a removable partial denture (RPD) framework [6]. Recent work has shown that, in principle, CAD/CAM/RP technologies can be successfully applied to the fabrication of

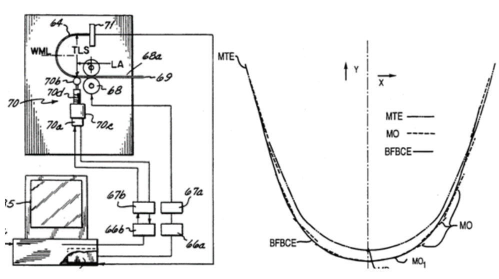
RPD alloy frameworks [7]. However, even though the fabrication of the RPD in the cast metal framework type of RPD could be made by CAD/CAM application, the bending of wire clasp is still done manually. CAD/CAM innovations have not been used successfully on a wide scale [8].



(a) ABAM (b) labial archwire

Figure 4: Automated Bending Archwire Machine (ABAM) and the output [1]

The existing CNC wire bending machine technology can only bend a simple shape for mass production and it is not designed for a specific dentistry application. Wire bending in dentistry is far more complicated due to the variation of tooth size, tooth contour and tooth position which demands a detail and manual workmanship by dental technician. Until to date, there is no automatic CNC machine introduced commercially to the industry to perform the dentistry wire bending. There was an introduction to ABAM (Automated Bending Archwire Machine) by [1] in 1993 and another invention by [15] in 1995, but both designs are however, limited to a customized bracket approach and it cannot produce any complex and twist bends in the wire.

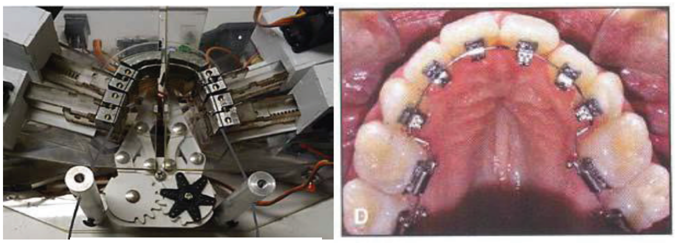


(a) wire bender (b) the designed archwire

Figure 5: Numerically controlled archwire bending machine [15]

2.3 Robotics Innovations in Dentistry Wire Bending

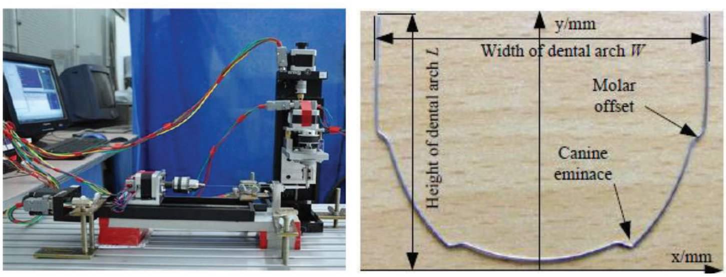
The development of robotics applications in prosthodontics and orthodontics is growing [9]. Various countries in the world have taken helpful exploration in robot to dental implantology and orthodontics archwire bending, but it still remains at theoretical research and preliminary experiment level. However, only a small amount of research, patents and products are reported and most of the researchers were focusing on archwire automated bending technology[5][6][11][13], for both labial and lingual cases, in general.



(a) LAMDA robot (b) lingual archwire

Figure 6: A gantry robot (LAMDA robot) and the output [6]

Gantry robot was introduced by [6] to bend the lingual archwires. However, this robot has a limited degree of freedom and it works only on the x and y axes. Even though the LAMDA wire bending robot is simpler than robots used in commercially outsourced systems, it can manufacture only first order bends.



(a) prototype (b) labial archwire

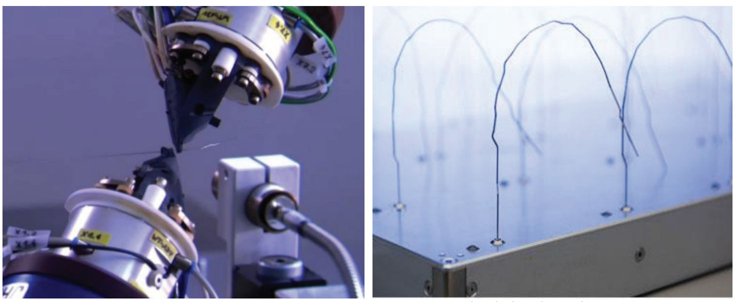
Figure 7: Cartesian robot prototype and the output [5]

Another researcher [5] has made an effort to design a prototype for a Cartesian type archwire bending robot and that is still under experimental level. The robot, however, is designed for a specific labial archwire bending only.

(a) orthorobot (b) labial archwire

Figure 8: Orthorobot and the output [13]

There are two commercialized robotic arms which are designed for archwire bending in orthodontics, namely the Orthorobot [13] and the Suresmile [12]. Orthorobot system is possible for both labial and lingual braces in creating individual bracket bases and bend a precise and customized individual archwires. However, this system only allows for simple archwires bending, containing only first order bends.



(a) Suresmile robot (b) labial archwire

Figure 9: Suresmile archwire bending manipulator and the output

A Suresmile robot, which is the archwire bending robot with 6 axes from the American SureSmile company can bend only the basic archwire's shape, but not the complex 3D shape in detail [1]. The robot bending system is able to form archwires with any required second and third order bends quickly with high precision [11]. The Suresmile robot, however had successfully proven in reducing treatment time than conventional approaches and improved the quality [12].

In the bending process, the moving distances of bending robot are relatively short, but the requirements for movement accuracy is high [5]. With the development of correlation technique and theory, such as new structure, and sensor and control theory, the robot will be widely applied in prosthodontics and orthodontics in the future, despite the complexity of wire bending principles and methods [9]. To conclude, successful robotics innovations for wire bending in the future might help to tremendously improve the operation time and quality, respectively.

3.0 LINEAR SEGMENTATION ALGORITHM

This section presents the theoretical explanation on how to realize the bending mechanism. In this study, a pair of robotic manipulators is proposed which act as a holder and a bender, respectively. The bending action would be realized by the bender, in consideration to the stated algorithm for certain features.

3.1 The proposed wire bending mechanism

In this study, a pair of robotic manipulators are proposed which act as a wire holder and a wire bender, respectively. The main design target of the bending mechanism is a flexible bend which in other words, the mechanism must has the capability to bend any type of features with no restrictions. Based on the literature presented earlier, it clearly shows that there is still no wire bending mechanism available to date, which offers flexibility in 3D bending, particularly for both prosthodontics and orthodontics applications. All of the wire bending mechanisms have limitations, which is only for the first degree bend. In addition, all of the innovations in dentistry wire bending are focusing in the orthodontics application, which is specifically for the archwire bending.

3.2 The target output of the study

In this study, the following features has been chosen as the target output. The selection of the feature is made in consideration to the type of bends in orthodontics which are a right angled bend, a loop, a curve and control of planes in space (flatness). All of the mentioned bends are represented in this orthodontics application, which is commercially known as a retainer.

(a) target shape (b) 2d sketch

Figure 10: The target shape in this study in a real application and in 2D sketch

Even though the priority of the bending mechanism is focusing to prosthodontics application since the bend is more complex, the selected shape is made to theoretically demonstrate how the proposed bending mechanism works in this paper. Therefore, the target output consists of three segments, which are a right angled bend (i), a loop (ii) and a curve (iii).

In this proposed mechanism, the bending is comprised of the presented segmentation algorithm and also a template bending. A template bending approach means that certain shapes can be bent by using the template features available in the holder-manipulator design, while a segmentation algorithm is referring to the a series of straight lines bending, just like in the manual wire bending methodology for a right angled bend. Therefore, for those three segments, a right angled bend is adopting the linear segmentation algorithm, while the loop implements the template bending. The curve, however, could be made of either the linear algorithm, or the template bending. A detail of the template design would be done in the next stage of this study, in relation to both manipulators design.

3.3 Theory of line segmentation

In this theory of 3D linear segmentation, a 3D curve is firstly segmented into ultra-short curve segments and finally replaced with ultra-short straight line segments. The whole 3D curve wire is composed by a sequence of many ultra-short straight line segments in order to be bent easily by the robotics manipulators. This theory was proposed by [1] in his study. The bending of 3D real curve is made based on the relative spatial parameters (L-the length, θ- the deflection angle, β-the twist angle, γ-the radial deflection angle) of the adjacent 3D line segments.

3.4 Algorithm of 3D wire bending based on line segmentation

In the manual wire bending, a curve is made by a series of multiple straight line bending. Usually, in order to produce a single curve, overly flattened area and overly bent area exist and need to be corrected until a smooth and continuous curvature is produced. In consideration of this methodology, a 3D linear segmentation approach is adopted. However, the adoption of this theory would be applied to some possible features, not necessarily to a curve only. The design of robotic manipulators which would be conducted in the subsequent stage of this study plays a significant role to determine which features might be using this theoretical algorithm.

3.4.1 Algorithm of the deflection angle θ

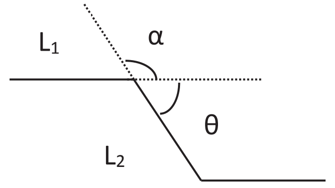


Figure 11: A 2D sketchof the deflection angle θ and the included angle *α*

L: The length of straight line segment
θ: The deflection angle between the adjacent line segments
α: The included angle between the adjacent line segments

Based on Figure 11, the length (L), can be calculated through coordinate values of its two endpoints. Therefore, for a 3D representation, the vector-valued function is used to represent those lengths in the vector form. For example, a vector representation for both lines in Figure 11, L_1 and L_2 are as follows;

$$L_1 = (x_2 - x_1)\,\mathbf{i} + (y_2 - y_1)\,\mathbf{j}$$

$$L_2 = (x_3 - x_2)\,\mathbf{i} + (y_3 - y_2)\,\mathbf{j}$$

Since the real application involves a 3D representation, therefore, the following equations explain the values;

$$\vec{S1} = (x_2 - x_1)\,\mathbf{i} + (y_2 - y_1)\,\mathbf{j} + (z_2 - z_1)\,\mathbf{k} = m_1\mathbf{i} + n_1\mathbf{j} + p_1\mathbf{k}$$

$$\vec{S2} = (x_3 - x_2)\,\mathbf{i} + (y_3 - y_2)\,\mathbf{j} + (z_3 - z_2)\,\mathbf{k} = m_2\mathbf{i} + n_2\mathbf{j} + p_2\mathbf{k} \tag{1}$$

$$\cos\theta = \frac{\vec{S1}\vec{S2}}{|\vec{S1}|.|\vec{S2}|} \tag{2}$$

$$\alpha = \pi - \theta \tag{3}$$

3.4.2 Algorithm of the torsion angle β

Since every line segments are the 3D spatial line segments, they are usually not in the same plane. So there is a torsion angle β on the space between them [1]. The included angle between the adjacent planes is the torsion angle β between its adjacent segments. Algorithm of the torsion angle β is shown as the equation (4), adapted from [1].

$$\cos \beta = \frac{|A_1A_2 + B_1B_2 + C_1C_2|}{\sqrt{A_1^2 + B_1^2 + C_1^2}\sqrt{A_2^2+B_2^2 + C_2^2}} \tag{4}$$

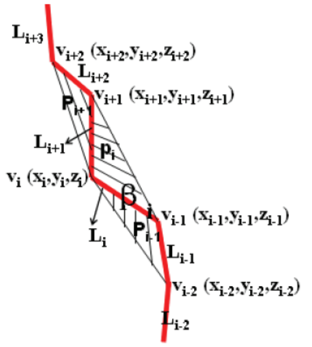


Figure 12: A 2D sketch of the torsion angle β [1]

In the equation 4,

$A_1 = (y_i-y_{i-2}) (z_{i-1}-z_{i-2})-(y_{i-1}-y_{i-2}) (z_i-z_{i-2})$
$B_1 = - (x_i-x_{i-2}) (z_{i-1}-z_{i-2})-(x_{i-1}-x_{i-2}) (z_i-z_{i-2})$
$C_1 = (x_i-x_{i-2}) (y_{i-1}-y_{i-2})-(x_{i-1}-x_{i-2}) (y_i-y_{i-2})$
$A_2 = (y_{i+1}-y_{i-1}) (z_i-z_{i-1})-(y_i-y_{i-1}) (z_{i+1}-z_{i-1})$
$B_2 = - (x_{i+1}-x_{i-1}) (z_i-z_{i-1})-(x_i-x_{i-1}) (z_{i+1}-z_{i-1})$
$C_2 = (x_{i+1}-x_{i-1}) (y_i-y_{i-1})-(x_i-x_{i-1}) (y_{i+1}-y_{i-1})$

4.0 CONCLUSION

The present study is essential to minimize errors in manual wire bending which in turn affects the time and cost of the specified treatment. The realization of this study might be beneficial to reduce the dependency towards a skillful bender. Finally, through the theoretical algorithm discussed, the accuracy and effectiveness of the desired shape could be secured during the physical implementation in the later stage. This contribution is considered significant to the innovation of the wire bending technology.

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