Integration of CAD/CAM in developing the CNC dental wire bending machine

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Abstract
This paper describes the idea of adopting CNC wire bending technology into dentistry wire bending. Till recently, the dentistry wire bending is traditionally performed in the hand-made operation. Innovations in the field of archwire bending in orthodontics have been reported which use robots to execute the desired wire bending operation. In contrast, CNC wire bending technology has not been successfully explored. In this regard, the manufacturing workflow which integrates CAD/CAM into the system is proposed. In addition, several interfaces to execute the bend points planning for different cases are introduced. The B-code generation program, which automatically converts the XYZ Cartesian coordinates for each bend point into the desired theoretical wire bending parameters \((L, \beta, \theta)\) has been developed with no consideration of the material properties. The feasibility of this methodology is demonstrated through an example, starting from the bend points planning, follows by the XYZ coordinates extraction and ends with the B-code generation. Moreover, the graphical simulation of the wire bending operation by the designed mechanism is also presented.

Keywords: CNC dental wire bending, CAD/CAM, Concurrent engineering, Bend points planning, Bending code

1. Introduction

This paper discusses a methodology to plan the desired bend points for several types of cases and converts the information into computer-aided manufacturing (CAM) data for computer numerical control (CNC) dental wire bending operation. CAD/CAM for dental restorations has been introduced in the mid-1980s to replace traditional restorative procedures. This is a treatment to restore the function, integrity, and morphology of missing tooth structure resulting from caries or external trauma as well as to the replacement of such structure supported by the dental implant (Klim et al., 2012). The dentistry wire bending operation, on the other hand, is different from the dental restoration as it deals with the manufacturing of wire for the desired dental treatment for both orthodontics and prosthodontics applications. Therefore, the bend points planning has to be done accordingly and consecutively been processed to generate the wire bending operation sequence to realize the actual wire bending steps. According to literature, a few researchers like Zhang (2013) and Andreiko and Payne (2000) have started to use CAD/CAM technology to automate the wire bending procedures but both inventions are only focusing on the archwire manufacturing in orthodontics (Hamid and Ito, 2016a). Contrarily, the other wire-related treatments in orthodontics and prosthodontics applications like I-bar clasp and C-clasp are still traditionally produced in the handmade operation. Thus, this paper made an attempt to propose the idea of using CNC wire bending technology to fabricate more flexible target shapes other than the archwire. In this preliminary study, the consideration of different wire materials for the calculation of bending parameters has not been studied. According to Kapila and Sachdeva (1989), recent advances in dentistry wire alloys have resulted in a varied array of wires that exhibit a wide spectrum of properties. Also, spring back phenomenon evidently exists in dentistry wire bending due to
its high strength and high elasticity which mainly depends on the material properties and also the cross-section of the wire. However, the wire bending prediction for each material is hard to be conducted due to the non-standardized material properties which heavily rely on the manufacturer (Zhang et al., 2013), in addition to the different cross-sectional of the wire. For example, the China stainless steel has different material properties in comparison to the Australian stainless steel. For this reason, the negligence of material properties in this present work is made. Therefore, only the theoretical prediction of the wire bending parameters is included to basically show the idea of this proposal, in addition to the introduction of the proposed manufacturing workflow for some defined cases. Moreover, a 3D model of a CNC wire bender has been developed as one of the laboratory’s projects to demonstrate the sequence of the wire bending operation in accordance with the calculated bending parameters. The proposed methodology would be discussed in Section 2, in addition to the preparation of the control data. Then, the developed CNC wire bender would be introduced in Section 3. Finally, the 3D simulation of the wire bending operation would be elaborated in Section 4 through a case study.

2. Methodology

Figure 1 exhibits the traditional manufacturing workflow of dentistry wire bending procedure. In the conventional approach, a repetitive number of bending is required to produce a single bend which has caused fatigue to the bender. Normally, the orthodontist or prosthodontist will mark the desired bend point on the wire in reference to the pre-designed wire path on the dental cast model. Then, the bending operation will be executed by using human hand and specific pliers. This manual wire bending operation heavily relies on the expertise of the bender. Most commonly, the pre-bent wire has to be bent again for a couple of times until the desired shape is achieved. This increase the bending time simultaneously due to some major adjustments and leads to bender fatigue (Ito et al., 2016). In addition, it has a huge tendency to create errors, thus affecting the efficiency of the wire for the specified treatment. Hence, cooperation between experienced dental specialist and a skilled technician is often needed to produce high-quality dentures with a low revision rate.

2.1 Mathematical formulae to calculate the bending code (B-code)

Figure 2 illustrates the relative spatial parameters \((L, \beta, \theta)\) between adjacent 3D linear segments. This information represents the desired wire bending parameters which should be generated to inform the machine how to make the desired wire bending operation. A theory of 3D linear segmentation as introduced by Zhang (2013) is adopted to this recent work for the case of freeform target shapes. In this theory, the final shape is constructed from a series of 3D linear segments, which indicates multiple-bends of wire to manufacture the specified target shape. This theory has been proposed in Hamid and Ito (2016b) and subsequently been explored in this paper. In this context, each line segment can be bent one by one according to its relative spatial parameters \((L, \beta, \theta)\) between adjacent linear segments, known as the B-code. The concept of 3D vectors is extensively studied and adapted to theoretically establish the desired parameters. In this approach, each 3D linear segment represents a 3D vector and by using the 3D vectors concept, each parameter \((L, \beta, \theta)\) could be theoretically calculated by using the XYZ Cartesian coordinates between adjacent 3D points \((P_1, P_2, P_3)\), as shown by Eq. 1 – Eq. 4. The verification of these spatial parameters has been conducted in Hamid and Ito (2016c).
Fig. 2  Definition of bending parameters between adjacent 3D linear segments; with $\mathbf{S}_1 = 3$D linear segment 1, $\mathbf{S}_2 = 3$D linear segment 2, $\theta =$ bend angle, $\alpha =$ included angle and $\beta =$ plane rotation angle.

According to Fig. 2, the bend point (P1) is located between adjacent 3D linear segment 1 and 3D linear segment 2, represented by $\mathbf{S}_1$ and $\mathbf{S}_2$, respectively. Equation 1 is used to calculate the straight length of the 3D linear segment ($L$). In this formula, $x$, $y$, and $z$ refer to the coordinate of a start point and the end point for each 3D linear segment, where the root sum square is adopted in calculating the length, or the magnitude of the position vector, as follows;

$$L_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2}$$  \hspace{1cm} (1)

In this context, $\mathbf{S}_1 = (x_1 - 0)i + (y_1 - 0)j + (z_1 - 0)k = m_1i + n_1j + p_1k$; $\mathbf{S}_2 = (x_2 - x_1)i + (y_2 - y_1)j + (z_2 - z_1)k = m_2i + n_2j + p_2k$

In the meantime, Eq. 2 is utilized in generating the plane rotation angle ($\beta$). The formula calculates the length of vectors perpendicular to the end plane and the plane before the bend is executed. In this equation, $s_i \cdot s_{i+1}$ is the dot product of the two vectors and $||s_i||$, $||s_{i+1}||$ are the norms of vectors for $s_i$ and $s_{i+1},$ respectively.

$$\beta_i = \arccos \left( \frac{s_i \cdot s_{i+1}}{||s_i|| \cdot ||s_{i+1}||} \right)$$  \hspace{1cm} (2)

$$A_1 A_2 + B_1 B_2 + C_1 C_2 \hspace{1cm} \sqrt{A_1^2 + B_1^2 + C_1^2 \cdot \sqrt{A_2^2 + B_2^2 + C_2^2}}$$

Lastly, Eq. 3, and Eq. 4 describe the formulae for the bending angle ($\theta$). In this calculation, firstly, the length of a vector for each adjacent 3D linear segment is calculated and the included angle ($\alpha$) between these two vectors is determined through Eq. 3. In this equation, $s_i \cdot s_{i+1}$ is the dot product of the two vectors and $||s_i||$, $||s_{i+1}||$ are the norms of vectors for $s_i$ and $s_{i+1},$ respectively.

$$\alpha_i = \arccos \left( \frac{s_i \cdot s_{i+1}}{||s_i|| \cdot ||s_{i+1}||} \right)$$  \hspace{1cm} (3)
\[ \alpha_i = \arccos \left( \frac{m_1 m_2 + n_1 n_2 + p_1 p_2}{\sqrt{m_1^2 + n_1^2 + p_1^2} \cdot \sqrt{m_2^2 + n_2^2 + p_2^2}} \right) \]

where; \( m_1 = (x_{i+1} - x_i); n_1 = (y_{i+1} - y_i); p_1 = (z_{i+1} - z_i); m_2 = (x_{i+2} - x_{i+1}); n_2 = (y_{i+2} - y_{i+1}); p_2 = (z_{i+2} - z_{i+1}) \)

Finally, \( \theta_i = 180^\circ - \alpha_i \) \hspace{1cm} (4)

These formulae have been used to construct the interface to calculate the desired theoretical bending parameters in Excel and also Matlab. At first, Excel was used to compute the parameters but due to the incapability to indicate the rotational sign for the plane rotation angle (\( \beta \)), another converter in Matlab was established with a reference to Mousali (2004). As previously explained, the Cartesian XYZ coordinates of all bend points are required as inputs to these converters which could be obtained through the bend points planning procedure, as briefly described in Section 2.2.

2.2 Bend points planning

Figure 3 illustrates the proposed manufacturing workflow to plan the desired bend points until the generation of B-code is accomplished. It is hoped that this study could be a start for more exploration by the other researcher in this field. In this procedure, several cases have been considered. Firstly, in case if we have the pre-bent physical wire obtained from the dentist office, the wire could be scanned and used for the bend points planning in CAD. Secondly, if there is no physical wire available, the estimation of the feature line of the target shape could also be done through 3D digitizing devices. Thirdly, the preparation of the bending points planning data could also be made through the use of the patient’s 2D teeth image. Therefore, a few methods have been explored in relation to this type of cases. In this regard, different types of interfaces have been introduced in the bend points planning stage and a brief overview of these interfaces would be elaborated in the following sub-chapters through some examples. The final aim of this stage is to acquire the desired XYZ Cartesian coordinates of each bend point, regardless of which interface is used.

![Fig. 3 Proposed wire bending manufacturing workflow.](image-url)
2.2.1 Method 1: Physical data exists

In the first case, CAD software is used for the bend points planning. Figure 4 demonstrates the idea of this method. In this approach, a laser scanner was used to initially digitize the wire clasp. Then, the bend points planning of the wire clasp was executed on the scanned wire clasp to duplicate the intended shape. This is more like a reverse engineering approach where the pre-bent physical wire of the dental clasp was used to directly aid the bend points planning. This method could be applied if the improvement of the initial target shape is planned to be carried out and in our case, we have used this method in the beginning of our study to actually help in understanding the details of the dentistry wire bending operation.

![Fig. 4](a) Digitized dental cast and the produced wire clasp model, (b) dental clasp fitting.

2.2.2 Method 2: No physical data

In the second method, the digital estimation of the target feature line is completed by using a magnetic sensor which resulted into a collection of 3D point cloud data. In a manual wire bending operation, a dental technician draws the desired wire outline with a pencil on top of the patient’s dental cast. Therefore, an idea to digitize that line has been explored, leading to the introduction of a few more processes to filter the generated noise and to choose the desired 3D bend point, as depicted in Fig. 5. These noise frequently belong to objects which surround the test sample being digitized, such as fixtures, measurement table, or some other part of the assembly to which the digitized part belongs (Igor, 2012). Those noise have to be eliminated in order to maintain the quality of surface reconstruction. In this example, the red line shows the target feature line which has to be digitized. The digitized 3D point cloud data has to be filtered and the refined data is consecutively processed in the 3D point selection interface, adopted from Taati (2005), where the desired 3D points are selected and the coordinates of these points would be automatically printed in Excel. Subsequently, the coordinates are used to generate the CAM data using the developed B-code generation program. Some analysis of this type of case has been conducted in Hamid and Ito (2017a) to test the feasibility of the introduced programs.

![Fig. 5](The manufacturing workflow to process 3D point cloud data.)
2.2.3 Method 3: 2D teeth image

In the third method, a 2D image is used as input to the 2D polyline selection interface in Matlab. This type of input data could be employed for the lingual archwire treatment planning. In this approach, the 2D image file is imported into the program, adopted from Ursell (2013), where the user can estimate the desired bend points for the treatment plan of the patient, as indicated in Fig. 6a. The program exports the XY Cartesian coordinates of all selected points in Excel, as shown in Fig. 6b and these coordinates would be employed by the B-code generation program for the establishment of the required CAM data. In this example, the number of selected points is 14. Details about this B-code generation program would be briefly explained in Section 2.4.

![Number of points: 14](image)

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![Table of coordinates](image)

2.3 XYZ coordinate extraction

The subsequent process after the bend points planning is the XYZ coordinate extraction. As previously discussed, the ultimate target of the bend points planning is to acquire the XYZ Cartesian coordinates of the desired bend points. The coordinates could be directly obtained from the discussed interfaces which are the 3D point selection and 2D polyline selection, respectively. However, for the planning of bend points in CAD, an additional coordinate extraction program from the Initial Graphics Exchange Specification (IGES) file has been developed and discussed in Hamid and Ito (2017b). The extraction program considers the line entity, with regard to the theory of 3D linear segmentation where the final target shape is constructed from multiple 3D linear segments, as indicated in Fig. 7a. In this section, a brief overview concerning to the IGES extraction would be briefly demonstrated by using an example.

After the estimation of the target shape is completed, the file is saved in the IGES format, giving the ASCII format.
as shown in Fig. 7b. Based on this IGES file, the coordinate extraction program reads the parametric data (P) section, which listed all the start point and the end point coordinate for each 3D line segment. The line geometry is numbered as 110 in this text file format. Therefore, the coordinate for P1-P11 is extracted automatically from row to row along the parameter data (P) section, as summarized in Fig. 7c. This XYZ table is consecutively used in the B-code generation program through the discussed mathematical equation (Eq. 1 – Eq. 4) which produces the B-code table, as illustrated in Fig. 7d. The use of the generated B-code (L, β, θ) to simulate the CNC wire bender would be demonstrated in Section 4, as an extension of this example. In this simulation, the role of each parameter (L, β, θ) in controlling the movement of the CNC wire bender will be described. Thus, an introduction to the mechanisms of the developed CNC wire bender would be elaborated in Section 3. On the other hand, the interface to generate the desired wire bending parameters (B-code) would be subsequently demonstrated.

Fig. 7 (a) Shape example which consists of 10 linear segments (L1-L10), and 11 3D points (P1-P11), (b) IGES file of the example which shows the parametric section (P) with all XYZ coordinates for each LINE geometry (L1-L10), numbered as 110 per column, (c) XYZ table which is generated from the IGES file, and (d) B-code table.

2.4 B-code generation

In this section, an example of the calculation for each parameter would be briefly illustrated. For this demonstration, the data from a target shape as depicted in Fig. 7 is adopted and the calculation results of the developed converter in Excel are subsequently exhibited (Fig. 8a- Fig. 8c). Therefore, all points (P1-P11) for this calculation are referring to this figure. The coordinate for every point is inserted into each formula (Eq. 1 – Eq. 4), accordingly. Figure 8a, Fig. 8b and Fig. 8c illustrate the screenshot of this converter in Excel for all conversion of parameters (L, β and θ). On the other hand, (Eq.1 – Eq. 4) are also used to establish another converter in Matlab, as an alternative to indicate the clockwise (CW) or counterclockwise (CCW) signs of the plane rotational angle, β. This is considered as an improvised version of the initial converter in Excel. Figure 6d summarizes the output of the Matlab converter, annotated as B-code table in this work. In this context, the generated rotation angle (β) of the Matlab converter indicates the positive or negative signs, as a result of CW or CCW rotation, respectively. On the other hand, the calculated rotation angle (β) from the Excel converter has no indication of these signs, as shown in Fig. 8b.

### Fig. 8a
Screenshot of the converter which shows the feeding length (L) generation process.

<table>
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<th>Points (P1, P2)</th>
<th>XYZ Cartesian Coordinates</th>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>A2</th>
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Fig. 8b
Screenshot of the converter which shows the rotation angle (β) generation process.

Fig. 8c
Screenshot of the converter which shows the bending angle (θ) generation process.

### 3. CNC wire bender

In this CNC wire bender, three bending parameters have been recognized to control the machine, known as the feed length (L), the rotation angle (β), and the bending angle (θ). The connection between these parameters and the wire bender is straightforward where the CNC wire bender is constructed from three main mechanisms, in terms of the wire feeding mechanism, the rotating mechanism and lastly, the bending mechanism. The working principle of this wire bender is uncomplicated where with regard to the B-code (L, β, θ); L controls the feed of a straight length of wire in mm, (β) instructs the rotating mechanism to make a significant rotation (in degrees) either clockwise or counterclockwise in relation to the sign of (β) and finally, (θ) determines the corresponding bending angle for each bending operation. The
rotation ($\beta$) of counterclockwise is considered as negative (-ve), while the clockwise rotation is alternatively represented as positive (+ve). The rotation angle ($\beta$) indicates a change of plane between the previous bend and the subsequent bend and the rotating mechanism has to adjust to this change in preparation for a successive bending operation.

![CNC dental wire bender](image.png)

Fig. 9 CNC dental wire bender, consists of a feeding mechanism, a rotating mechanism and a bending mechanism.

### 4. 3D simulation: a case study

![3D simulation diagram](image.png)

Fig. 10 Final target shape with the desired parameters for each bending section, represented by the variables from the Excel interface ($L$, $R$, $A$) which represent ($L$, $\beta$, $\theta$), respectively.

In this section, a demonstration of the B-code operation in relation to the CNC wire bender is carried out. The B-code table as depicted earlier in Fig. 7d is fed into this system. The purpose of this demonstration is to elaborate on the role of each parameter ($L$, $\beta$, $\theta$) in controlling the movement of the CNC wire bender mechanisms through graphical examples. Figure 10 represents the summary of the wire bending parameters, annotated by $L$, $R$, and $A$ as the variables to indicate ($L$, $\beta$, $\theta$), respectively. Figure 11 (a-i) show the bending sequences in relation to the control parameters ($L$, $\beta$, $\theta$) for each bend point. At first, a straight wire is fed into the system, indicated by a start position. The working principle of this CNC wire bender is based on feed, rotate and bend. Therefore, the movement of this CNC wire bender for each bend is executed according to this sequence. For example, in the last bend, a feed of 30 mm is forwarded by the feeding mechanism through a set of rollers. Then, a change of plane around 22 degrees (CCW) is performed by the rotating mechanism. Finally, the bending operation is executed by the bending mechanism for a bend angle of 65 degrees. The bending operation ended when the last feed of a straight wire is forwarded by the feeding mechanism, in this case equals to 60 mm. This demonstrates the simulation of the CNC wire bending operation for the specified target shape.
\[ \theta_1 = 66^\circ \]
\[ L_1 = 60 \text{mm}, \beta_1 = 0^\circ \]
Fig. 11a First bend.

\[ \theta_2 = 94^\circ \]
\[ L_2 = 30 \text{mm}, \beta_2 = 19.83^\circ \]
Fig. 11b Second bend.

\[ \theta_3 = 145^\circ \]
\[ L_3 = 30 \text{mm}, \beta_3 = 108.84^\circ \]
Fig. 11c Third bend.

\[ \theta_4 = 65^\circ \]
\[ L_4 = 40 \text{mm}, \beta_4 = 178.73^\circ \]
Fig. 11d Fourth bend.

\[ \theta_5 = 25^\circ \]
\[ L_5 = 75 \text{mm}, \beta_5 = -3.61^\circ \]
Fig. 11e Fifth bend.

\[ \theta_6 = 65^\circ \]
\[ L_6 = 75 \text{mm}, \beta_6 = 0.90^\circ \]
Fig. 11f Sixth bend.
5. Conclusion

In this study, the idea of automating the dentistry wire bending operation through a portable CNC wire bender is proposed. Therefore, an introduction to the manufacturing workflow has been discussed, with a brief overview of each case described in the workflow. In this paper, the first case which uses CAD as the interface is further explored with the use of an orthodontics retainer as the target shape. Therefore, the preparation of B-code has been demonstrated for this case study with a sharing of some screenshots of the converter in Excel. In addition, the proposed mathematical formulae have been used to establish another converter in Matlab which is capable to indicate the rotational sign of the bending angle (\( \beta \)). A 3D simulation of the B-code by using the CNC wire bender model has been successfully executed in order to demonstrate how the B-code (\( L, \beta, \theta \)) control the mechanisms of the wire bender through a feeding mechanism, a rotating mechanism and a bending mechanism, respectively. Through the observation in accordance to Fig 11a- Fig 11i, the B-code (\( L, \beta, \theta \)) have successfully controlled the movement of the wire bending mechanisms in the expected ways and this has simultaneously validated the developed converter in Excel/Matlab. As for future work, a study on the spring back factor which affects the prediction of the bending angle (\( \theta \)) would be explored for some types of dental wires. It is hoped that this study could be a start for more exploration in the field of CNC dental wire bending in the future to promote a better digital manufacturing workflow over the traditional method.

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