GRADO EN INGENIERÍA EN TECNOLOGIAS INDUSTRIALES

TRABAJO FIN DE GRADO

DENTAL X-RAY ALIGNMENT DEVICE

Autor: María Tornos Serrano

Director: Enrique Gutiérrez-Wing

Madrid

Junio de 2020

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título "Dental X-Ray Alignment Device"

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2019/2020 es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada

Fdo.: María Tornos Serrano Fecha: 07/05/2020

Autorizada la entrega del proyecto

Fdo.: Dr. Enrique Simón Gutiérrez Wing Fecha: 03/JUN/2020.

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Acknowledgments

I would first like to thank to my colleague during the development of this project, Varinder Singh. He has helped me to carry out this project by coming up with great ideas and by guiding me through the resources that Boston University can offer the students.

I would like to thank Professor Gutierrez for his guidance and support throughout the project during the first semester. I would also like to thank Professor Hauser for his continuous guidance and support during the whole year. He has been a tremendous asset in dealing with the problems which arose due to Covid-19, and I cannot thank him enough.

I would also like to thank to the Mechanical Engineering Department at Boston University for their support and funding throughout the development of the project.

Special thanks to Dr. Hussein Khimani for providing me with such an interesting and rewarding project, and for his help throughout the process.

Special thanks also to Dra. Beatriz Serrano de Haro and her son Dr. Javier Calatrava Serrano de Haro, dentists at Madrid, who have helped me come up with some conclusions about the project and have oriented me on certain decisions that needed to be made.

I would finally like to thank to my family, for their continuous support and help during the whole year.

DISPOSITIVO DE ALINEACIÓN DE RADIOGRAFÍAS DENTALES

Autor: Tornos Serrano, María.

Director: Gutierrez-Wing, Enrique

Entidad Colaboradora: Boston University – ICAI Universidad Pontifica Comillas

RESUMEN DEL PROYECTO

1. Introducción

Ciertos dientes traseros tienen múltiples raíces que pueden estar situadas unas detrás de otras. Cuando estos dientes son radiografiados perpendicularmente, las raíces delanteras ocultan las raíces posteriores e impiden su visualización. Para conseguir ver todas las raíces correctamente, las radiografías deben ser hechas desde otro ángulo diferente. Las siguientes ilustraciones muestran dos posibles vistas diferentes de uno de estos dientes, las cuales ayudan a solucionar el problema. En la Ilustración 1 se puede observar una vista perpendicular de un diente con múltiples raíces, donde se aprecia que con esta vista la raíz posterior queda oculta. Sin embargo, la Ilustración 2 muestra una vista de este mismo diente desde otro ángulo, y en ella se pueden visualizar ambas raíces.

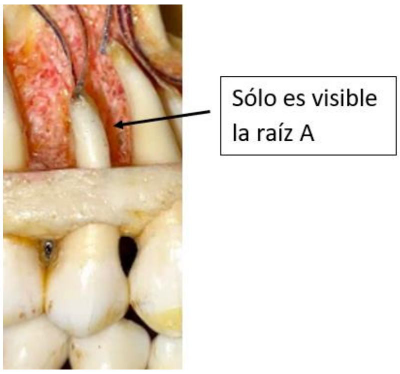

Ilustración 1. Vista perpendicular de un diente con múltiples raíces.

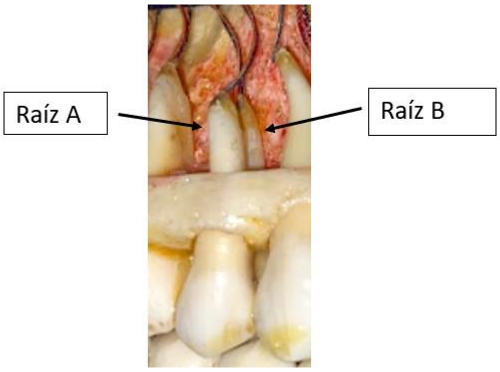

Ilustración 2. Vista con otro ángulo del mismo diente con múltiples raíces.

El procedimiento estándar para hacer radiografías perpendiculares consiste en situar un sensor (en amarillo en la Ilustración 3) dentro de la boca del paciente, alineado con el diente que se quiere radiografiar. La parte vertical de este sensor se sitúa dentro de la boca del paciente, y éste muerde sobre la parte horizontal. Una barra metálica se engancha a este sensor, saliendo una parte de la misma de la boca del paciente. Para poder alinear el cañón de rayos X con el sensor y el diente, se sitúa un anillo (también en amarillo en la Ilustración 3) en esta barra metálica. Posteriormente, se alinea el cañón de rayos X con este anillo. El proceso puede observarse en la Ilustración 3 y en la Ilustración 4.

Ilustración 3. Piezas utilizadas en el procedimiento estándar para hacer radiografías perpendiculares.

Ilustración 4. Representación final del procedimiento estándar para hacer radiografías perpendiculares.

2. Metodología y desarrollo del proyecto.

El procedimiento actual para hacer radiografías desde otro ángulo para poder visualizar todas las raíces se basa en cambiar de forma aleatoria el ángulo con el que se enfoca el cañón de rayos X. En este caso, el anillo amarillo no es utilizado y el dentista rota el cañón de rayos X intentando mantenerlo alineado con el diente. Este método no asegura que el cañón esté correctamente alineado con el diente que va a ser radiografiado, lo que provoca que el dentista probablemente tenga que hacer varias radiografías hasta que tanto el diente como sus múltiples raíces se visualicen correctamente, exponiendo al paciente de manera innecesaria a múltiples dosis de radiación de rayos X.

Este problema ha sido expuesto y analizado por el cliente Hussein Khimani, dentista en el Boston University Dental School. Desde hace algún tiempo, el Dr. Khimani está intentando solucionar este problema y ha desarrollado dos aparatos que podrían solucionarlo, los cuales han servido como punto de partida de este proyecto.

El objetivo de este proyecto es proporcionar al cliente un aparato que permita alinear correctamente el cañón de rayos X con el diente cuando la radiografía deba tomarse con un ángulo distinto al perpendicular, tanto para poder reducir errores a la hora de hacer radiografías como para poder minimizar la radiación a la que el paciente es expuesto. Adicionalmente, se ha incluido como otro objetivo de este proyecto permitir al dentista conocer el ángulo con el que se hace la radiografía, con el fin de poder repetirla con exactitud si es preciso.

En este proyecto se proponen dos dispositivos, los cuales utilizan ángulos predefinidos por el cliente, que han demostrado ser válidos a la hora de mostrar correctamente todas las raíces. El cañón de rayos X se engancha a cada aparato en uno de estos ángulos, para así poder garantizar la alineación del cañón con el diente en el ángulo deseado.

El Prototipo A está compuesto por dos piezas y se puede observar en la Ilustración 5. Una de las piezas se engancha a la barra metálica que se conecta al sensor, mientras que la segunda pieza, con forma de anillo, conecta el cañón de rayos X con el resto del aparato. Se utilizan los salientes de la primera pieza para conectar ambas entre sí, y a continuación se engancha el cañón de rayos X al resto del aparato insertándolo a través de la segunda pieza, de una forma muy similar a como se hace en el procedimiento estándar para hacer radiografías perpendiculares.

Por otro lado, el Prototipo B consta de una sola pieza con seis ángulos diferentes, dispuestos de forma simétrica, tal y como puede observarse en la Ilustración 6. En este caso, se utiliza un anillo azul proporcionado por el cliente, el cual se engancha al aparato B mediante alguno de los salientes del mismo. Por último, el cañón de rayos X se ajusta a este anillo utilizando el mismo sistema que en el caso del anillo amarillo utilizado en el procedimiento estándar para radiografías perpendiculares.

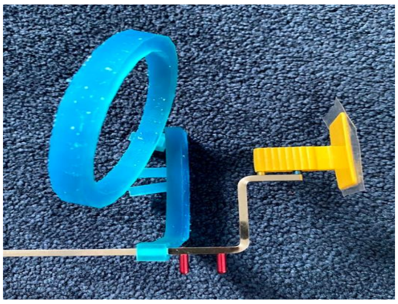

Ilustración 5. Representación del Prototipo A.

Ilustración 6. Representación del Prototipo B.

3. Resultados y conclusiones

Tal y como se puede ver en la Ilustración 5 y en la Ilustración 6, los prototipos propuestos se han impreso en 3D para poder realizar pruebas con ellos y comprobar su funcionamiento. Sin embargo, debido a la pandemia del Covid-19, no he podido realizar yo misma estas pruebas, ya que tuve que abandonar Boston y volver a España antes de poder realizarlas.

Los prototipos fueron entregados al cliente, y él ha sido el encargado de analizarlos y probarlos. Una vez que ha podido realizar pruebas con ellos, ha sugerido algunos cambios para mejorar el funcionamiento de ambos prototipos. Dada la situación actual por la crisis del Covid-19 y la falta de tiempo y recursos, las modificaciones a realizar en el Prototipo B son más fáciles de realizar que las necesarias en el Prototipo A. Además, este Prototipo B es más fácil de usar que el Prototipo A.

Por lo tanto, el Prototipo B se ha simplificado eliminando el ángulo de 40 grados, ya que no aportaba información adicional, y se ha modificado ligeramente la angulación vertical, para hacer el prototipo más preciso y más simple. El funcionamiento general de este prototipo no ha cambiado con estas modificaciones.

En opinión del cliente, este prototipo cumple todos los objetivos del proyecto y podría ser utilizado ya en la clínica una vez que se utilizase el material adecuado. Gracias a este aparato, el procedimiento para visualizar todas las raíces mediante las radiografías desde otro ángulo se podría simplificar, reduciendo el número de radiografías necesarias para visualizar correctamente todas las raíces y por lo tanto reduciendo el nivel de radiación al que está expuesto el paciente.

4. Referencias

Toda la información e imágenes mostradas en este resumen han sido elaboradas por el equipo de desarrollo del proyecto.

DENTAL X-RAY ALIGNMENT DEVICE

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Collaborating Entity: Boston University – ICAI Universidad Pontifica Comillas

ABSTRACT

1. Introduction

Certain teeth of the rear part of the mouth have multiple roots which are right next to each other, front-to-back. When straight angled radiographs of these teeth are taken, it is not possible to see all of the roots, as the roots in the front block the visualization of the roots in the back. In order to visualize all of the roots, it is necessary to take the radiograph at an angle. This issue can be seen in the following illustrations, where two views of a tooth with multiple roots can be seen. A straight angled view of the tooth can be seen in Figure 1. Straight view of a tooth with multiple roots., where only the front root can be seen. However, Figure 2 shows an angled view of the same root, where both roots can be correctly seen.

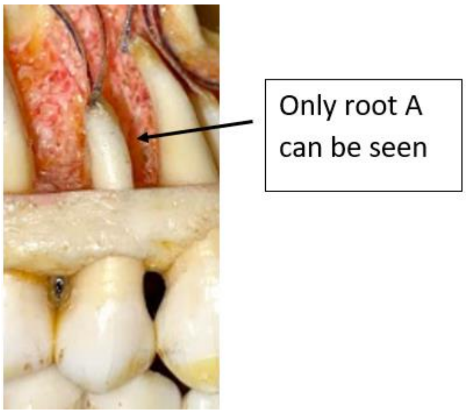

Figure 1. Straight view of a tooth with multiple roots.

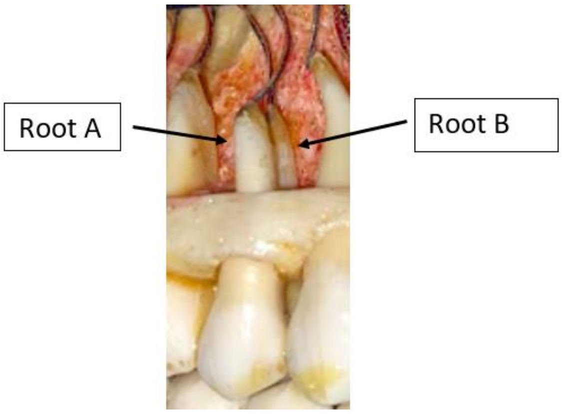

Figure 2. Angled view of the same tooth with multiple roots

The standard procedure for taking straight angled radiographs consists in placing a sensor (in yellow in Figure 3) inside of the patient's mouth, aligned with the tooth that needs to be radiographed. The vertical part is situated behind the tooth, and the patient bites on the horizontal section. A metal bar is attached to the sensor and stands outside of the mouth. In order to align the x-ray cannon with the sensor and the tooth, a ring (in yellow in Figure 3) is connected to the metal bar, and then the x-ray cannon is aligned with this ring. This can be seen in both Figure 3 and Figure 4.

Figure 3. Parts used in the standard procedure for taking straight angled radiographs.

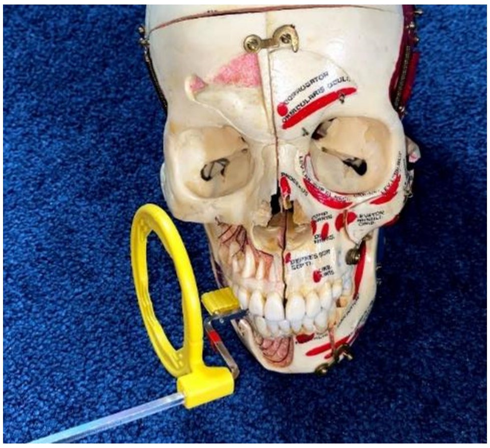

Figure 4. Final display of the standard procedure for taking straight angled radiographs.

2. Methodology and development of the project.

The current method for taking angled radiographs where all of the roots can be seen is based on randomly changing the x-ray cannon angle. In order to do this, the ring is not used, and the dentist rotates the x-ray cannon trying to keep it aligned with the tooth. This method does not ensure that the cannon is correctly aligned with the tooth that must be radiographed, which makes the dentist take several radiographs until the tooth is correctly seen, exposing the patient to multiple doses of x-ray radiation.

This problem has been stated and analyzed by the customer, Hussein Khimani, dentist at the Boston University Dental School. He has been trying to solve this problem for some time and has come up with two different devices, which have been used as the starting point.

The objective of this project is to provide the customer with a device that can consistently align the x-ray cannon with the tooth when the radiograph must be taken at a non-straight angle, in order to reduce errors made by the dentist and reduce the patient's exposure to radiation. It is also required that the device proposed allows the dentist knowing the angle from which the radiograph is being taken, so as to enable the dentist to repeat the exact same radiograph if it were needed.

There are two design solutions that are being proposed. They both use angles that have been predefined by the customer and that have proven to be useful for correctly showing all the roots. The x-ray cannon gets attached to these devices in one of those angles, in order to ensure its alignment with the tooth in the desired angle.

Prototype A, which can be seen in Figure 5, is made of two parts. One of the parts gets attached to the metal bar that is connected to the sensor, while the second part, which is ring-shaped, is the one that connects the x-ray cannon with the rest of the device. These two parts are first connected together by the shafts found in the first part, and the x-ray cannon is then connected to the device by inserting it through the second part, in a very similar way as it is done in the standard procedure for taking straight angled radiographs.

Prototype B consists of one single part with six different angles, displayed in a symmetrical way, which can be seen in Figure 6. A blue ring provided by the customer, which works in the same way as the yellow ring used in the standard procedure for taking straight angled radiographs, is attached to the proposed device, and finally the x-ray canon is aligned with this ring.

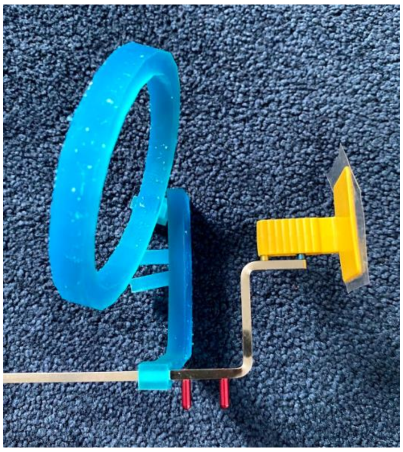

Figure 5. Overall display of prototype A.

Figure 6. Overall display of prototype B.

3. Results and conclusions

As can be seen in Figure 5 and in Figure 6, the proposed designs have been 3D-printed in order to make testing possible. Given the Covid-19 outbreak, I haven't been able to do real life testing myself, since I had to leave Boston before I could meet the customer and test the devices.

The prototypes were handed out to the customer, and he has been the one in charge of analyzing and testing them. Once he has been able to test them, he has suggested several modifications to improve the functioning of both of the prototypes. Given the challenging situation due to the Covid-19 pandemic and the lack of time and resources, the adjustments that were needed in Prototype B were easier to make than the ones needed in Prototype A. It also has to be considered that Prototype B is also easier to use than Prototype A.

Therefore, Prototype B has been simplified eliminating the 40 degrees shaft, since it did not provide additional information, and the vertical angulation of the shafts has been slightly modified, in order to make the prototype more precise and simpler. The overall functioning of this prototype has not changed with these modifications.

The customer believes that this prototype fulfills all the requirements of the project and could be used in the clinic once the appropriate materials were used. Thanks to this device, the procedure for visualizing all the roots through angled radiographs could be simplified, reducing the number of radiographs needed to correctly visualize all the roots and therefore reducing the patient's exposure to radiation.

4. References

All the information and illustrations shown in this abstract have been prepared by the project developing team.

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List of figures

DOCUMENT 1. REPORT

1.1. DESCRIPTIVE REPORT

The problem analyzed in this project has been brought to me by the customer, Dr. Hussein Khimani. Dr. Khimani is a graduate student at the Boston University Henry M. Goldman School of Dental Medicine. He himself has done some research and come up with some ideas before handing the project to the Mechanical Engineering department of Boston University. This project has been carried out with the help of Varinder Singh, who is a senior mechanical engineering student at Boston University.

1.1.1. Introduction and background

When a tooth needs to be analyzed, normally a straight angled radiograph of that tooth is taken, since this type of radiograph allows the visualization of the tooth and it can be taken in an easy way. However, some of the teeth of the rear part of the mouth have multiple roots, and when these are the ones being analyzed, at least two radiographs are needed, one taken in a straight angle and another one taken from a different angle. This is due to the fact that if only one straight radiograph is taken, the roots in the front will block the visualization of the roots in the back. For this reason, in order to correctly visualize all of the roots, it is necessary to take an additional radiograph from another angle.

This is based on the SLOB rule, which stands for Same Lingual Opposite Buccal. This rule describes a radiographic technique used to analyze the correct position of objects in relation to a reference [OXFO] [SEEB15]. In this case, the reference is the tooth being analyzed, and the objects whose correct positions need to be analyzed are the roots of that tooth. This rule consists in changing either the horizontal or vertical angulation of the x-ray cannon in order to allow the visualization of the tooth from another perspective. By changing the angulation that is used when the radiograph is taken, the visualization of all the roots can be achieved. [KHIM19]

1.1.1.1. Nature of the existing problem

The following illustrations show what the geometric nature of the problem is, that is, they explain why a dentist needs several views of a tooth with multiple roots instead of a single straight angled radiograph, and why these additional views need to be taken from a different angle. The bottom part of a tooth with multiple roots can be seen in an isometric view in Figure 7, and in a top view in Figure 8. For the sake of clarity, colors have been used in these illustrations to differentiate roots and faces of the tooth from each other.

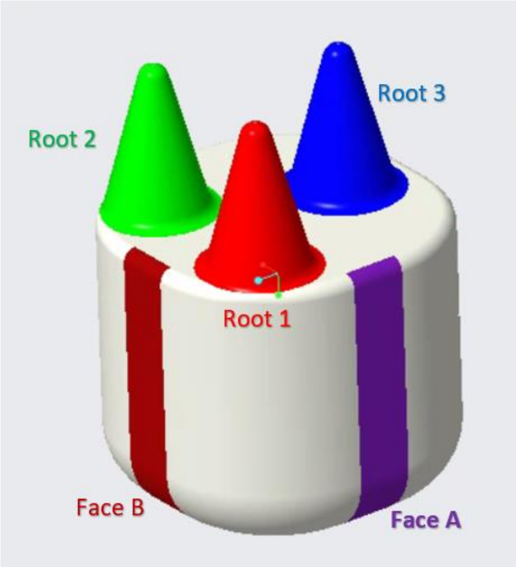

Figure 7. Isometric view of the bottom part of a tooth with multiple roots.

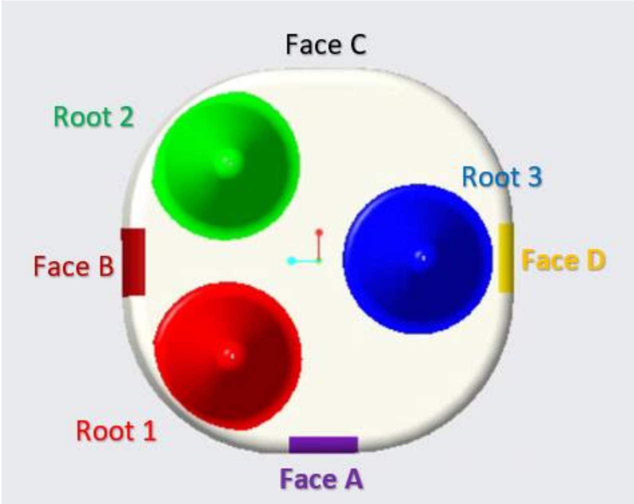

Figure 8. Top view of the bottom part of a tooth with multiple roots.

Different views of this tooth are going to be analyzed, in order to explain why the angulation from which the radiograph is taken affects the visualization of the roots.

The first view that is going to be analyzed is the straight one. As can be seen in Figure 9, when the straight view is taken, only roots 1 and 3 can be seen, while the visualization of root 2 is being blocked by root 1. It can also be appreciated in this illustration that only face A is seen in this view of the tooth. The straight view of the tooth is being shown right next to the previously shown isometric view in order to allow for a better understanding.

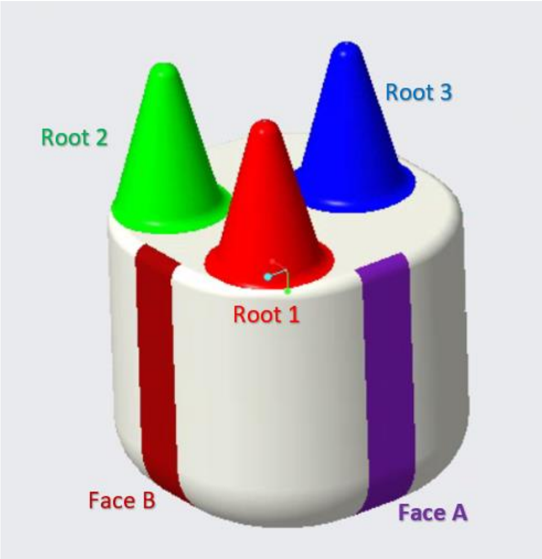

Figure 7. Isometric view of the bottom part of a tooth with multiple roots.

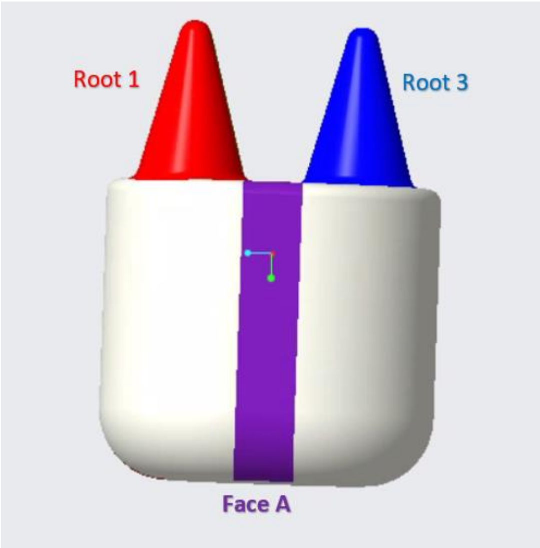

Figure 9. Straight view of the tooth, where only two of the roots can be seen.

The next views that are going to be analyzed are the ones obtained when the angle from which the radiograph is being taken is changed. When the angle is changed to the left, the view obtained is the one that can be seen in Figure 10. In this case, all of the roots can be seen, and it can be appreciated that only root 1 appears to be in front of the other two roots. Both face A and face B of the tooth can be seen in this view. Moreover, when the angle is changed to the right, all of the roots can also be seen, as shown in Figure 11. However, when this view is obtained, it can be seen that both roots 1 and 3 appear to be in the front, while root 2 remains in the back.

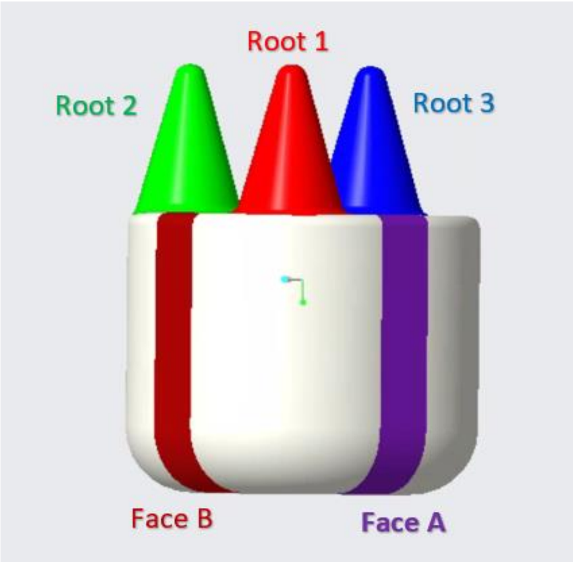

Figure 10. View taken changing the angle to the left, where all of the roots can be seen.

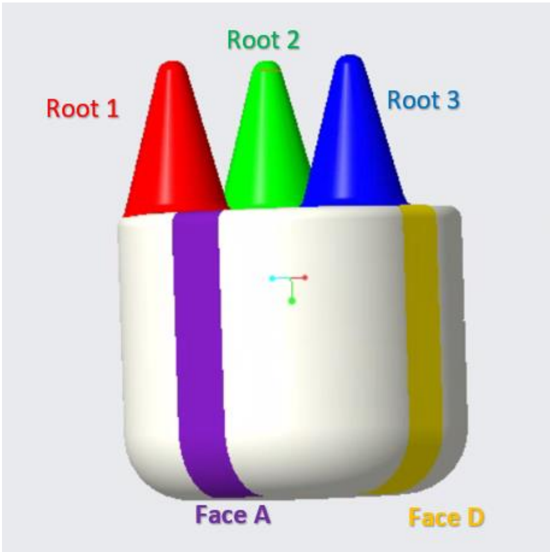

Figure 11. View taken changing the angle to the right, where all of the roots can be seen.

The reasoning of the SLOB rule can be fully appreciated in these illustrations. Depending on the angle from which the view is being taken, some of the roots are visible, while others remain unseen. In the same way, the position of the roots in relation to the tooth seem to change, as in the case of root 3, which seems to be in the back in Figure 10 but seems to be in the front in Figure 11. This is the reason why two radiographs need to be taken, one from a straight angle and the other one from a different angle, in order to compare them and be able to determine the real position of each of the roots.

The previous illustrations have shown what the geometric nature of the problem is in the case of a tooth with three roots, with the help of a CAD model. It may seem from looking at those illustrations that this problem only appears when teeth with three roots are being radiographed. However, if the tooth only has two roots, the visualization of the root in the back also gets blocked by the root in the front if a straight angled radiograph is taken. This can be appreciated in Figure 12 and in Figure 13, where both a straight and an angled view of a tooth with two roots can be seen, marked in blue. In the case of Figure 12, only the root on the front is visualized, while both roots can be visualized in Figure 13.

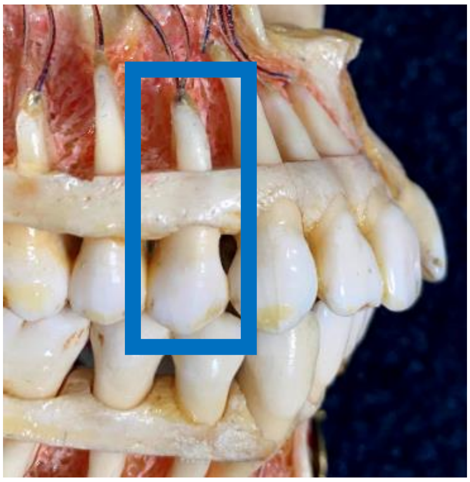

Figure 12. Straight view of a tooth with two roots, where only one root can be seen.

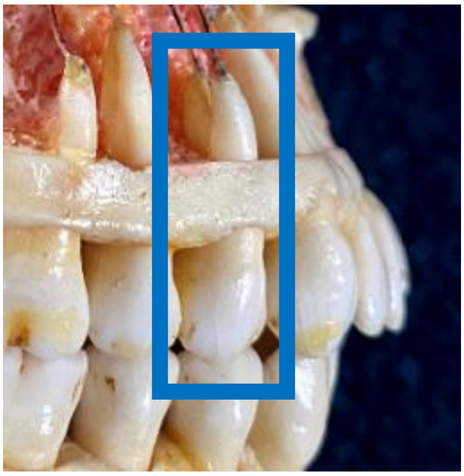

Figure 13. Angled view of the same tooth with two roots, where both roots can be seen.

1.1.1.2. Differences between teeth with multiple roots

As has been just explained, this problem appears when the tooth being radiographed has more than one root, and when these roots are placed right next to each other, front-to-back. Figure 14 shows the number of roots that each tooth has, and the teeth that are rounded with a brown circle are the ones that have more than one root. Molars with the numbers 1, 16, 17 and 32 are the wisdom teeth, and these might not be present in a patient, since they may have been taken out. Taking this fact into account, the number of teeth that have multiple roots can vary from 10 to 14.

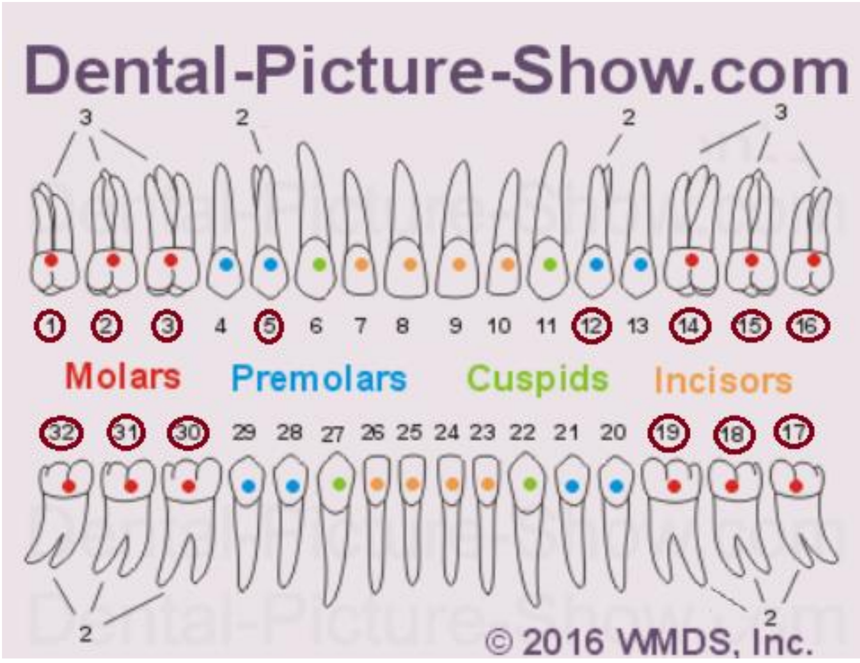

Figure 14. Number of roots in each tooth. [1]

In this illustration, teeth marked in red are the molars, and all of them have more than one root. The six molars in the superior jaw have three roots, and one of these roots is placed behind the other two roots, which means that this root is the one that would not be visualized if the radiograph was taken from a straight angle. On the other hand, the six molars in the inferior jaw only have two roots, and these roots are placed next to each other in the direction of the jaw. Therefore, if any of these teeth in the inferior jaw were radiographed from a straight angle, both roots would be correctly visualized and no problem would arise.

Teeth marked in blue are the premolars, and only two out of eight of them, found in the superior jaw, have more than one root. These two premolars have two roots, and one of them is placed behind the other root. The visualization of this root in the back will be blocked by the root in the front if the radiograph is taken from a straight angle, so they also have to be considered.

Taking all this information into account, there can be from 6 to 8 teeth that need to be radiographed from an angle different than the straight one, in order to be able to correctly visualize all of the roots. These teeth are two premolars and six molars, with numbers 1, 2, 3, 5, 12, 14, 15 and 16, all of them found in the superior jaw. Molars number 1 and 16 are the ones that might not be present in a patient's mouth, as they are the wisdom teeth.

1.1.1.3. Current procedure for taking straight angled radiographs.

The standard procedure for taking straight angled radiographs is now going to be explained, in order to be able to compare the current procedure for straight angled radiographs and the current procedure for angled radiographs, which is the one that this project looks forward to improve.

When a straight-angled radiograph is going to be taken, three main standard parts are used. Figure 15 shows a display on how these standard parts would be set in the patient's mouth when a straight angled radiograph needs to be taken. The x-ray cannon would be then placed aligned with the yellow ring. The skull that can be seen in this illustration is a real human skull provided by the customer.

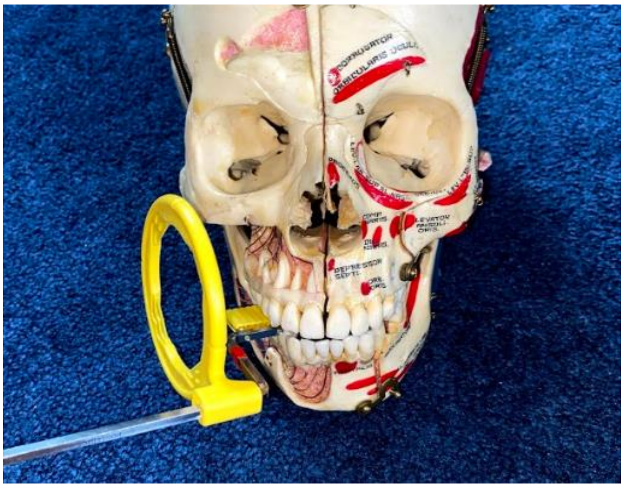

Figure 15. Display on how straight angled radiographs are currently taken.

- The first component that is used is the one that will hold the sensor and align it with the tooth (sensor holder). This component is the L-shaped part that can be seen in yellow in Figure 16. The sensor will be placed parallel to the vertical part of this component, and these two parts will be set inside of the mouth of the patient, behind of the tooth that needs to be radiographed. The patient will then bite on the horizontal part of this component, as can be seen in Figure 15.

- The next component to be used is the metal bar that can be seen in Figure 16. The sensor holder is attached to this bar, and the bar stands out of the mouth of the patient, as can be seen in Figure 15.

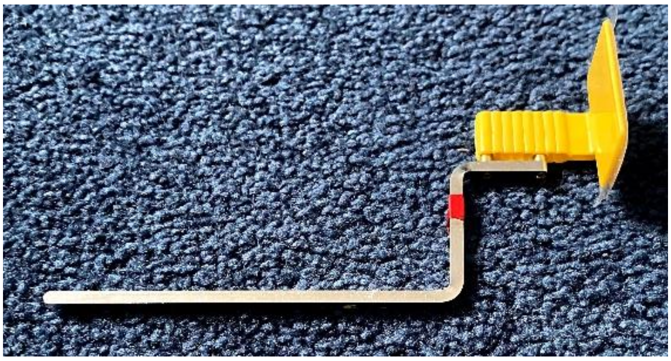

Figure 16. First two components that are used in the standard procedure for taking straight angled radiographs.

- The last component which is used in this procedure is the ring that can be seen in yellow in Figure 17, which is the one that connects the x-ray cannon with the two other components, i.e. the sensor holder and the metal bar. The x-ray cannon is aligned with the ring and, thanks to it, it remains aligned with the sensor and the tooth throughout the whole process.

Figure 17. Sensor holder, bar and ring used for taking straight angled radiographs.

An illustration showing how the tooth would be visualized when using these standard parts to take straight angled radiographs can be seen in Figure 18. The tooth that is marked with a red arrow has two roots, even though the one in the back cannot be seen when this type of radiograph is being taken.

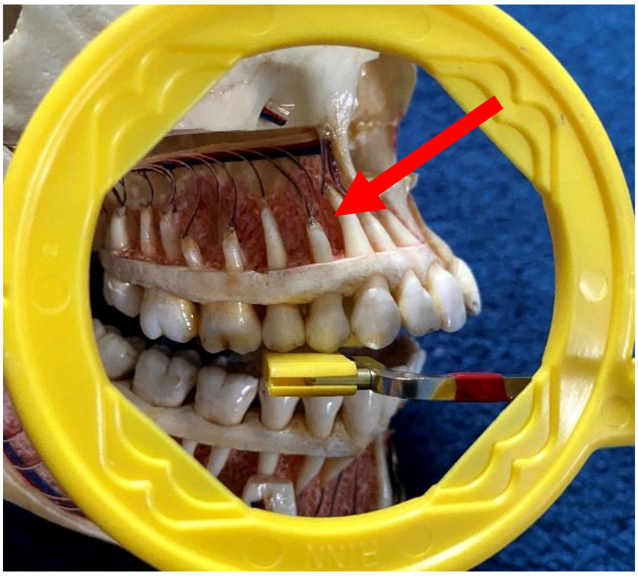

Figure 18. View of the two-root tooth being radiographed in a straight angle.

1.1.1.4. Current procedure for taking angled radiographs and solution concept.

The current procedure that is carried out by dentists for taking angled radiographs is based on a trial and error method that consists in randomly changing the angle in which the x-ray cannon is positioned. In order to do this, the ring described in the standard procedure for taking straight angled radiographs is not used, and the dentist rotates the x-ray cannon trying to keep it aligned with the tooth, but without having any reference on where the tooth is.

This is not a precise or calibrated method; therefore, it is not ensured that the x-ray cannon is aiming at the correct tooth. Since the dentist does not know if the tooth is going to be shown in the radiograph, several radiographs might need to be taken in order to get the correct one, which exposes the patient to multiple undesired doses of x-ray radiation.

Another problem that arises from not being able to change the angulation of the x-ray cannon in an accurate way is that when one radiograph is taken, the angle from which it was taken is not a fixed and known one but a random one. This means that if the radiograph were to be repeated, it cannot be taken in the exact same way, since the angle was changed randomly.

Given the above stated problems, the design solution would consist of a device that allows the dentist taking angled radiographs in an accurate way. So as to achieve this, the device must allow the dentist orientating the x-ray cannon towards the desired tooth from several known different angles, and it must ensure that it is correctly aligned with the tooth, therefore ensuring that both the tooth and the multiples roots will be seen in the radiograph. This solution concept can be seen in Figure 19, courtesy of William Hauser, who has been another supervisor of this project. In this illustration, the sensor holder is represented by the red plate, and the x-ray cannon is represented by the grey cylinders. It can be appreciated that the x-ray cannon is aligned with the desired tooth from different angles.

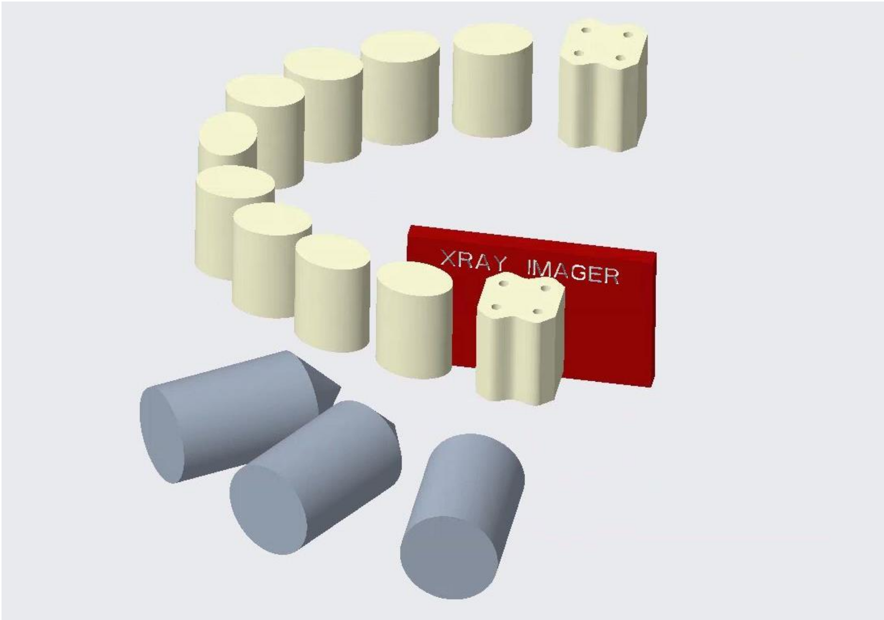

Figure 19. Solution concept (Image courtesy of William Hauser). [2]

1.1.2. Motivation

Angled radiographs are needed in order to correctly visualize all the roots when a tooth with multiple roots is being analyzed, since the straight angled radiographs will not show all the roots as the ones in the front will block the visualization of the ones in the back. There is currently no way to take these angled radiographs in a precise way, which forces the dentist to take angled radiographs by randomly changing the angle at which the x-ray cannon is aiming at the tooth.

Since the x-ray cannon is positioned at a random angle, there is no way to ensure that it is correctly aiming at the tooth, and, consequently, several of the radiographs that are taken miss the tooth. As was explained in the Introduction, this leads to having to take several radiographs in order to get the correct view of the tooth and the roots and exposing the patient to multiple doses of x-ray radiation.

In fact, in one of the visits to the clinic, the customer showed that several radiographs were needed in order to get the desired results, due to the non-precise and non-calibrated method that is currently used for taking these angled radiographs. Some of the failed radiographs that the customer has taken during his investigation can be seen in Figure 20. It can be appreciated in these illustrations that neither the tooth or the roots can be correctly seen in these radiographs, which is due to the fact that the dentist is rotating the x-ray cannon to a random angle without having any reference on where the tooth is.

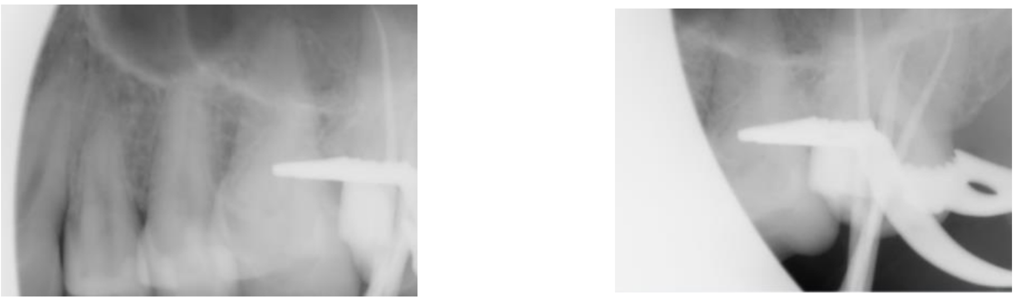

Figure 20. Unsuccessful radiographs taken by the dentist, where the tooth is not being aimed correctly. [3]

Moreover, it may happen that an angled radiograph is taken successfully, and it needs to be taken in the exact same way a few months later, in order to check the evaluation of the roots. Since the dentist does not know the angle that was used a few months ago when the successful radiograph was taken, there is no way to take the new radiograph in the exact same way, as it is not ensured that the x-ray cannon is aiming at the tooth with the exact same angle.

Due to these two main factors, an aligning device is needed to ensure that the x-ray cannon can be positioned in a different angle from the straight one in a calibrated way, in order to be able to visualize all the roots. This aligning device must also ensure that, when this is done, the x-ray cannon will be correctly aiming at the desired tooth. It must also be ensured that when these angled radiographs are taken, the angle that is being used is always known, in order to be able to repeat the radiograph in the exact same way.

Thanks to this device, the procedure for taking angled radiographs to visualize all the roots could be simplified, therefore reducing the patient’s exposure to radiation and reducing radiograph costs for the dentist, as the number of needed radiographs would be reduced.

1.1.3. Objectives

The main objective of this project is to allow dentists taking angled radiographs in order to be able to visualize all the roots when a tooth with multiple roots is being analyzed. In order to achieve this, a device that allows the dentist taking an angled and correctly aimed radiograph must be built. This angled radiograph must be taken knowing the angle that is being used and ensuring that the tooth and all its roots will actually be correctly seen in the radiograph.

Thanks to this device, the dentist should be able to correctly visualize all the roots in the radiograph, as well as being able to know which angle is being used when the radiograph is taken, making possible the repetition of the radiograph in the exact same way if it were needed.

Therefore, there are three main objectives of this project:

- Build a device that allows the dentist taking angled radiographs in a precise way, in order to allow the correct visualization of all the roots.
- This device must ensure that the x-ray cannon is correctly aiming at the tooth, thus ensuring that the tooth and the roots will be correctly seen in the radiograph.
- This device must also ensure that the radiograph can be repeated in the exact same angle, therefore the angle that is being used when the radiograph is taken must always be known.

1.1.4. Current status

This issue has been stated by the customer, and it has been previously analyzed in several research projects. These projects have been carried out in order to study which angles are the ones that should be used when taking angled radiographs. Two of these research papers have been analyzed, as proposed by the customer, so as to come up with a range of angles that will ensure the visualization of all the roots.

The first project [HAGH07] that has been examined was carried out in 2007 by Jahangir Haghani and Maryam Raoof, from the Dental School of Kerman University of Medical Sciences, and Sadegh Pourahmadi, in Kerman, Iran. The purpose of this project was to evaluate which horizontal angles should be used when rotating the x-ray cannon in order to correctly visualize the roots of the first mandibular molars. In order to achieve this, forty-four mandibular molars were radiographed at 10, 15, 20 and 25 degrees angulations, and the results obtained showed that the 20 degrees angulation improved the visualization of all the roots.

The second project [MART99] that has been studied was carried out in 1999 by Miguel Ángel Martínez-Lozano, Leopoldo Forner-Navarro and José Luis Sánchez-Cortés, from the University of Valencia, in Valencia, Spain. The objective of this project was to analyze the effect of x-ray cannon inclination when visualizing the root canal system in multiple roots teeth. This project was carried out by taking radiographs of 100 premolars in different vertical and horizontal angulations, being 0, 20 and 40 degrees the horizontal angles used. The results obtained showed that varying the horizontal angle from which the radiograph is taken improves the visualization of all the roots, while changing the vertical angle has no significant impact on the visualization of all the roots. If the horizontal angle is increased to 40 degrees, all the roots can be correctly visualized.

Given the results obtained in these two research projects, it was concluded along with the customer that the proposed prototypes would need to implement several angles within the range from 20 to 40 degrees, since it had been proved that this range of angles allows the visualization of all the roots. Once these prototypes were manufactured and tested, the radiographs taken from each of these angles would be analyzed in order to decide which angles gave the best results. The angles that provided the best results in terms of being able to correctly allow the visualization of all the roots would be implemented in the final designs.

Apart from analyzing these research projects in order to know which angles are the best ones for correctly visualizing all the roots, two devices have been used as the starting point of this project. These two devices have been designed by the customer, and they try to solve the problem of not being able to take angled radiographs in a precise and calibrated manner.

The first design that the customer has thought about are the “fixed angle sleeves” [KHIM19]. These devices are the small black parts that can be seen in Figure 21. They get attached to the metal bar that is connected to the sensor holder, and they rotate the ring and therefore the x-ray cannon. They allow the dentist taking the radiograph from a fixed and known angle, as can be seen in Figure 22 and in Figure 23, where the fixed angle sleeves are rounded in red. The fixed angle sleeve that was being used when Figure 22 was taken is the one corresponding to 10 degrees, and the one that was being used when Figure 23 was taken is the 30 degrees one. The x-ray cannon was not used when these pictures were taken, but it would be aligned with the yellow ring, as it is done in the standard procedure. All of these illustrations were taken by the customer, Dr. Khimani [4].

Figure 21. Fixed angle sleeves (Image courtesy of Dr. Khimani)

Figure 22. Ring rotated by using the 10 degrees fixed angle sleeve (Image courtesy of Dr. Khimani)

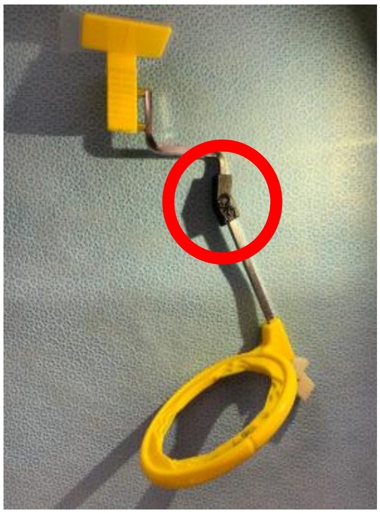

Figure 23. Ring rotated by using the 30 degrees fixed angle sleeve (Image courtesy of Dr. Khimani)

As is going to be explained in the "Specifications" section, this device would not work ideally due to the big distance between the ring and the sensor holder, which would cause the radiograph to be blurry.

The second device that the customer has come up with is the one that can be seen in Figure 24. This device consists of changing the standard metal bar for a new, curved bar that will allow rotating the ring. The standard ring gets attached to this new bar, and the x-ray cannon gets aligned with the ring as it is done in the standard procedure. [KHIM19]

Figure 24. Device proposed by the customer, where a new bar that allows rotating the ring and the x-ray cannon is used.

This new bar allows the dentist changing the angle that will be used when positioning the x-ray cannon, by changing the position at which the ring is being placed. This new bar has been designed in a way that it is ensured that the ring will always be correctly aiming at the tooth being radiographed. Since the x-ray cannon is then aligned with the ring, it will also end up being correctly aiming at the tooth. This ensures that the tooth will appear on the radiograph, therefore decreasing the number of times that the radiograph has to be repeated.

Additionally, since the angle from which the radiograph is being taken can be changed, the visualization of all the roots will be possible when using this device. However, the problem with this device is that the angle at which the ring is being positioned is not known, since the new bar does not have any marks to know where the ring is placed.

Given these facts, this device fulfills the first two requirements, since it allows the dentist taking angled radiographs in a precise way in order to correctly visualize all the roots and it ensures that the tooth is being correctly aimed by the x-ray cannon, therefore ensuring that both the tooth and the roots will be correctly shown on the radiograph. Nevertheless, as has been already mentioned, this device does not fulfill the third requirement, as, due to the missing marks, it does not allow repeating the radiograph in the exact same way, since the angle at which the ring and the x-ray cannon are being positioned is not known.

Using these two proposed devices as reference, the prototypes proposed have been designed by focusing on being able to set the x-ray cannon at some of the angles within the range proposed by the previous research projects and the customer, as well as on ensuring that the x-ray cannon is correctly aiming at the desired tooth. Another important factor that has been kept in mind is that the radiograph must be repeatable, therefore the devices have also been designed by focusing on making sure that the angle that is being used when taking the radiograph is always known.

1.1.5. Specifications

There a number of specifications and requirements which need to be considered in the prototypes that have to be designed.

The most important specification that needs to be taken into account is that the x-ray cannon needs to be placed close to the patient's mouth. This is due to the fact that, if the x-ray cannon is placed too far from the patient's mouth, the radiograph taken will not be a clear one and instead it will be blurry. This was an important constraint that needed to be overcome.

Another important specification that needs to be taken into account is that the device cannot be neither too big nor too heavy. The device must be able to stay in place on its own, since the dentist cannot be in the room when the radiograph is being taken and therefore cannot be holding the device or the x-ray cannon. If it is a large device, there might be the risk that it won't be able to stay in place on its own while the radiograph is being taken.

The device must allow taking angled radiographs from different angles, so the roots can be visualized from different points of view. In order to achieve this, the device must have different angle offsets. The number of angle offsets that have been initially chosen is arbitrary, only for testing purposes. After testing, the number of angle offsets would be chosen based on practicality and functionality.

The angles that are going to be implemented in the proposed designs will be within the range that has been discussed previously, from 20 to 40 degrees.

1.1.6. Work methodology

Chronograph showing how this project has been carried out can be seen in Figure 25.

Figure 25. Chronograph.

First step that needed to be made in this project was meeting with the customer and knowing what the main requirements of this project were, as well as doing some research on the topic and getting familiar with the new field and terminology.

Once this was done, brainstorming was needed to come up with some ideas that could work. Several ideas were needed in order to ensure that at least some of them would work correctly. Once these ideas were found, they were presented to the customer to see if they met the stablished requirements. After some ideas that fulfilled the requirements were found, the required measurements and calculations were done, in order to come up with CAD models that could be 3D printed. Once these designs were 3D printed, they were tested. The ideal testing procedure involved going to the clinic and testing the devices on site with the actual x-ray cannon. However, when it was not possible to go to the clinic to test them, a skull provided by the customer was used in order to check the aiming and the basic characteristics of the proposed devices.

This project was an iterative process. The ideas and prototypes developed were presented to the customer and tested, and he was the one that decided which prototypes were discarded or which ones could be modified in order to get to a better design. He decided what changes should be done in each of the prototypes to achieve a solution that better accomplished the objectives. Changes and adjustments were done according to his comments and more 3D printed models were done.

The initial objective of the project was, once one of the prototypes fulfilled all the customer requirements, to build a final device, with the appropriate materials and manufacturing processes. This final device would also be tested in the clinic and with the x-ray cannon, in order to ensure that it worked as the 3D printed prototype.

However, the two final prototypes were going to be tested in the clinic on March 18th, but, due to the Covid-19 outbreak, the clinic was closed and testing could not be done. The prototypes were sent by mail to the customer, hoping that he would be able to test them once the crisis was over and the clinic reopened.

Once this happened, he was able to test the prototypes and suggested some adjustments on both of them. Only the changes on one of the prototypes were modified, given the difficulties of the situation due to Covid-19, and this modified prototype was sent to the customer at the end of May so that he could test it.

1.1.7. Resources and materials used

As has been previously explained, this project involves an iterative process. In order to be able to build prototypes in a rather cheap and fast way, 3D printing has been used. This 3D printing was achieved by using the 3D printers located in the Engineering Product Innovation Center (EPIC), the workshop at Boston University. This manufacture method has been chosen because, as several and continuing modifications were made throughout the project as the prototypes were tested and discussed with the customer, 3D printing allowed building the new parts faster than any other manufacturing process.

Modifications in the 3D printed models were needed throughout the project, due to two main factors. The first factor has been already mentioned, as some of the modifications were needed due to the customer's feedback. These adjustments were done once the prototypes had been tested and discussed with him. The other factor that led to alterations in the models was the poor tolerance tightness that can be achieved with the 3D printing method. This resulted in the need of modifying some features of the prototypes that relied too much on tightness.

Once the prototypes were printed, testing them was crucial in order to check whether or not they worked as expected. This testing has been done by going to the customer's clinic and testing the prototypes on site with him, in order to show him how they work and receive his feedback.

This testing in the clinic hasn't been always possible, due to unexpected schedule complications. In case that this happened, a real human skull, seen in Figure 26, was provided by the customer, in order to enable testing that involves geometric issues when going to the clinic was not possible. However, when this testing method was used, a later visit to the clinic was always needed in order to test the device with the x-ray cannon.

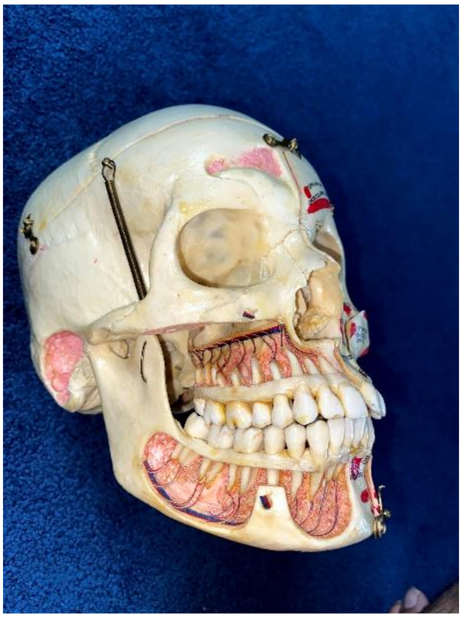

Figure 26. Real human skull, provided by the customer.

In order to be able to correctly design the prototypes, the parts used in the standard procedure were provided by the customer. Thanks to this, the necessary measurements could be taken in order to ensure that the prototype could be correctly used with some of those standard parts and to ensure that the geometry of the prototype was the correct one.

If it hadn't been for the Covid-19 crisis, once one of the prototypes had been finished and didn't need any other adjustment, this final model would have been built, using the appropriate manufacturing method and materials. Had this been possible, the materials would have been bought or taken from EPIC, and the model would have been manufactured in EPIC as well, with the help of the staff working there.

1.1.8. Proposed prototypes

Focusing on the objectives stated above and on the requirements stablished by the customer and by geometry, two prototypes have been developed. These two prototypes have been 3D printed, in order to be able to test them.

The main issue that needs to be solved first in this project, in order to fulfill the rest of the requirements, is ensuring that the x-ray cannon is correctly aiming at the desired tooth. If not ensured, it would mean going back to the initial situation, in which the dentist needs to take several radiographs without knowing whether they are correctly aiming at the tooth or not. As a way of satisfying this requirement, the necessary measurements of the standard parts have been taken, and the appropriate calculations have been made, which can be found in the "Calculations" section. These calculations were mainly aimed to find the correct angles and distances for the devices in order to make them geometrically viable.

Moreover, once it is ensured that the x-ray cannon is correctly aiming at the tooth, it was required that all the roots were correctly visualized. Therefore, the angle from which the x-ray cannon is aiming at the tooth must be a specific one, within the range exposed in "Current status" section, from 20 degrees to 40 degrees. The initial idea was to design the prototypes with specific angles within this range.

Nevertheless, this idea was modified when the first versions of the proposed prototypes were being designed, as some of the angles that were finally implemented in the proposed devices are not within this range. For instance, the 10 degrees angle was used in one of the prototypes. The reason for this modification in the used angles is that it was easier and cheaper to manufacture the prototypes with smaller angles, since if the bigger angles were used, the prototypes would be more complex and bigger. It was already known that these bigger angles correctly allowed the visualization of all the roots, and only the correct functioning of the prototypes needed to be checked. Once testing had been carried out and it had been proved that the prototypes worked correctly, they would have been modified in order to implement the bigger angles.

Along with focusing on these two requirements, the proposed prototypes would focus on making the radiograph repeatable, that is, guaranteeing that the angle from which the radiograph is being taken is known. As a way of ensuring this, prototypes have been designed with shafts that mark the desired angles.

In order to fully understand where the ideas of these prototypes came from and how they work, the first designs that were proposed are going to be analyzed now. These designs had to be modified in order to solve some of the problems that arose when testing them. When these adjustments were made, the final prototypes were achieved.

1.1.8.1. Prototype A

Previous design

Prototype A originated from modifying one of the first designs that were proposed to the customer. The initial proposed design consisted of a component that would get attached to the standard metal bar, and a laser that would get placed on the x-ray cannon. This component, seen in red in Figure 27 and in Figure 28, had three holes disposed in some angles with respect to the tooth being radiographed: 20 degrees on the left, 10 degrees on the right and straight angle on the middle. Figure 27 shows a top view of this component, while Figure 28 shows an isometric view.

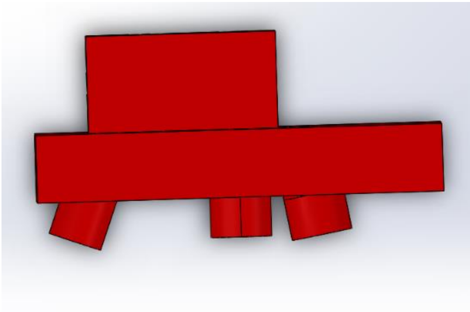

Figure 27. Top view of the first proposed design.

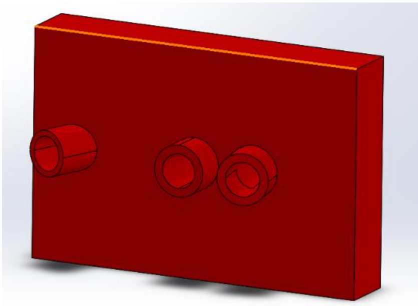

Figure 28. Isometric view of the first proposed design.

This component got attached to the standard metal bar through another bar that was specifically designed for this component. In order to aim at the desired tooth, a laser would be placed at the center of the x-ray cannon. The x-ray cannon would be then aimed at the tooth by shining the laser through one of the holes of the above shown component. If the laser appeared on the patient's cheek, that would mean that the x-ray cannon was aiming correctly at the tooth.

The geometric concept of this design can be seen in Figure 29. This component was designed to ensure that the holes correctly aimed at the desired tooth.

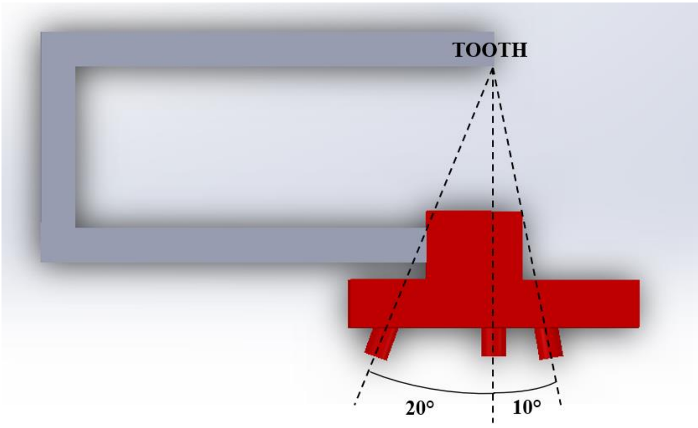

Figure 29. Geometric concept of the first proposed design.

In order to ensure that the x-ray cannon was being correctly aimed at the tooth if the laser was seen on the patient's cheek, the laser had to be placed at exactly the center of the x-ray cannon. So as to achieve this, a laser holder was designed, which would allow placing the laser at the center of the x-ray cannon in order to align it with the desired tooth. Once the laser was seen on the patient's cheek, i.e. aimed with the tooth, it would have to be removed from the center of the x-ray cannon and placed at the top of the x-ray cannon so that it wouldn't appear on the radiograph.

This mechanism can be seen in Figure 30 and in Figure 31, where the x-ray cannon would be inserted through the round hole and the laser would be placed at the end of the mechanism, in the red marked space. Only the position of the laser is shown in these figures, not the laser itself.

Figure 30 shows the aiming phase, showing how the mechanism would work when the x-ray cannon is being aimed at the tooth, that is, when the laser is being aligned with one of the holes of the previously explained component.

Figure 31 shows the radiograph phase, showing how the mechanism would work once the x-ray cannon was already aligned with the desired tooth, i.e. when the laser needs to be placed on top of the x-ray cannon so it won't appear on the radiograph.

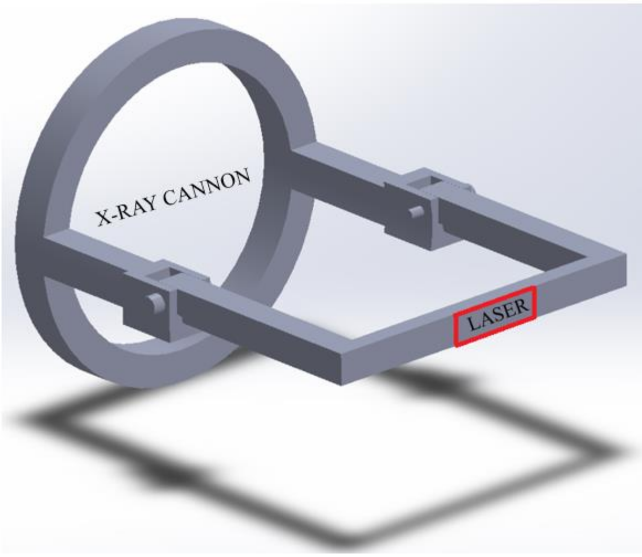

Figure 30. Mechanism showing how the laser would be placed when shining it through the holes.

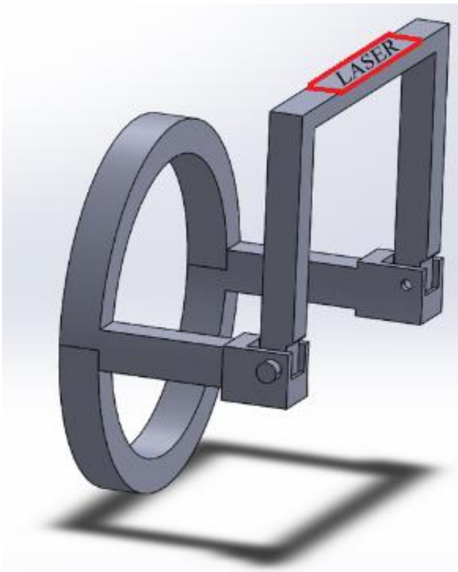

Figure 31. Mechanism showing how the laser would be removed from the radiograph.

Is it important to remark that, as has already been explained, the laser needed to be placed exactly at the center of the x-ray cannon in order to ensure that it was being correctly aimed at the tooth. Moreover, once the laser was seen on the patient's cheek, the x-ray cannon could not be moved, since it was already aligned with the tooth and any small displacement would misalign it. This ended up placing the x-ray cannon too far from the tooth being radiographed, which made the radiograph blurry, as has been already mentioned in the "Specifications" section.

However, this design was used as the starting point for one of the final prototypes, Prototype A. The main characteristic that needed to be modified was the position of the x-ray cannon, since the modified design had to place it closer to the patient's mouth. The holes on the component through which the laser would shine through were replaced by shafts, and a ring was created to be placed on those shafts. The laser element was removed in this design. These changes allowed the x-ray cannon to be placed closer both to the sensor and the tooth being radiographed.

Final design

These adjustments led to Prototype A. This prototype is made of two parts, and it works with the standard sensor holder and the standard metal bar. The first part (Part A) is the one that gets attached to the standard metal bar, and has the angle offsets. The second part (Part B) is attached to Part A through one of these angle offsets, and then the x-ray cannon gets attached to Part B. Figure 32 shows the overall display of Prototype A.

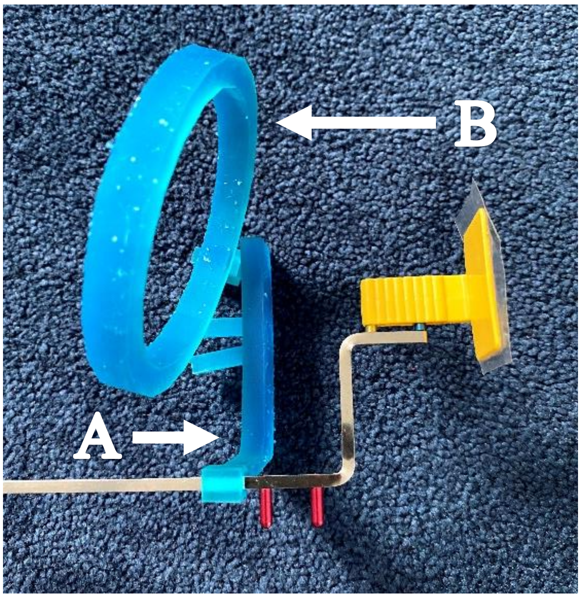

Figure 32. Prototype A: overall display.

Next step is explaining each of the components of Prototype A.

Part A of Prototype A has two main purposes. The first one is attaching the whole prototype to the standard metal bar, which is achieved by inserting this standard metal bar through a squared hole that can be found in the upper right section of Part A. This hole can be seen on a front view of Part A, seen in both Figure 33 and in Figure 34. Figure 33 shows a front view of the 3D printed part, while Figure 34 shows a front view of the CAD model.

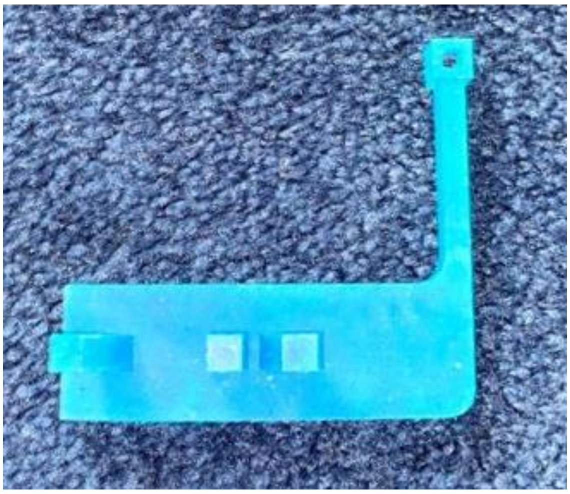

Figure 33. Prototype A: front view of Part A (3D printed part).

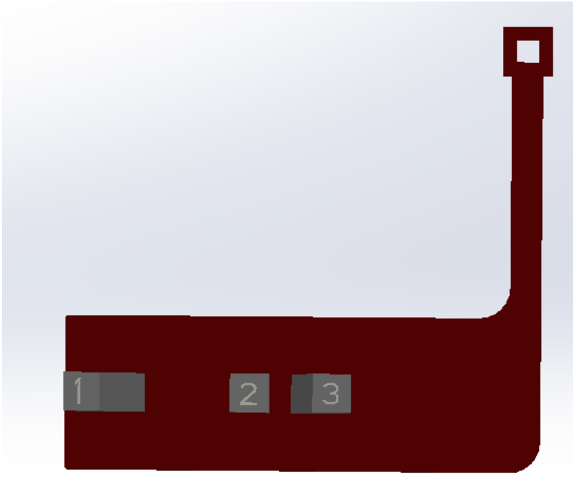

Figure 34. Prototype A: front view of Part A (CAD model).

The second purpose of this first component is marking the angles from which the radiograph is going to be taken. This is accomplished by the shafts that can be seen on both Figure 35 and Figure 36, where each of them is set at a specific angle. Figure 35 shows a top view of the 3D printed Part A, while Figure 36 shows a top view of the CAD model of Part A. The shaft on the left is set at a 20 degrees angle, the one on the right is set at a 10 degrees angle and the one on the middle is set at a straight angle, all of them with respect to the tooth that is being radiographed.

Figure 35. Prototype A: top view of Part A (3D printed part).

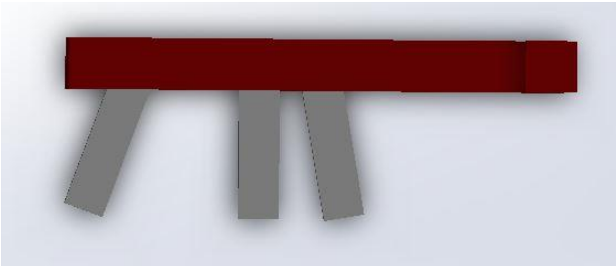

Figure 36. Prototype A: top view of Part A (CAD model).

As has already been mentioned, the 10 degrees angle is not within the proposed range. Once this prototype had been tested and it was proved that it worked correctly, this angle offset would have been changed to a bigger angle within the proposed range (20 to 40 degrees).

Part B of this prototype is the one that connects the x-ray cannon with the rest of the device. This ring-shaped component gets attached to Part A by inserting one of the shafts of Part A through a squared hole that can be found on the lower section of Part B. Depending on the angle from which the radiograph needs to be taken, Part B is inserted through one of the shafts of Part A. This can be seen in Figure 37 and Figure 38, where a front view of the 3D printed Part B is showed in Figure 37 and a front view of the CAD model of Part B is showed in Figure 38. This hole was first designed as a rounded one, but it was then changed to a squared one to prevent the undesired rotation of Part B.

Figure 37. Prototype A: front view of Part B (3D printed part).

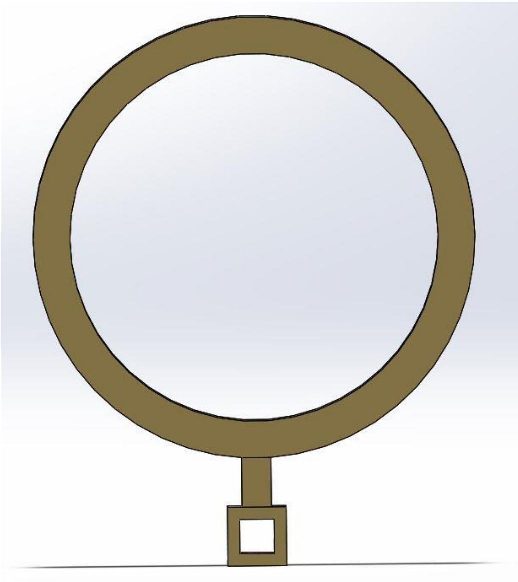

Figure 38. Prototype A: front view of Part B (CAD model).

Once Part A and Part B have been attached together, the x-ray cannon is attached to the prototype by inserting it through the big round hole found in Part B. The functioning of Part B is very similar to the functioning of the standard ring that is currently used in the standard procedure for taking straight angled radiographs. However, this ring needed to be modified in order to be able to attach it to Part A.

An obvious question that could arise here is: why not directly create Part A in a way that the standard ring can get attached to the shafts? This would mean designing the shafts in Part A with the measurements of the standard ring, so that the standard ring and not Part B is the one that gets attached to Part A. The reason why Part B was created and why Part A was not designed in this way is because, in the case of the standard ring, the x-ray cannon is only aligned with it, not inserted through it. However, the round hole in Part B is slightly bigger than the diameter of the x-ray cannon, therefore allowing that the x-ray cannon is inserted through it. This adds stability to the device and, consequently, accuracy. This also allows the x-ray cannon to be placed closer to the patient's mouth, making the radiograph clearer.

The purpose of Part B is to connect the x-ray cannon with the rest of the device, the standard metal bar and the sensor. Thanks to this component, the x-ray cannon can be connected to them at a specific angle, allowing the dentist taking the desired angled radiographs.

As can be seen, the idea of this prototype was clearly inspired by the first design that has been previously described. The idea of the holes and shining a laser through one of them was replaced by shafts and a ring attached to one of them, which would set the x-ray cannon in one of the angle offsets. The geometric concept of Prototype A can be seen in Figure 39.

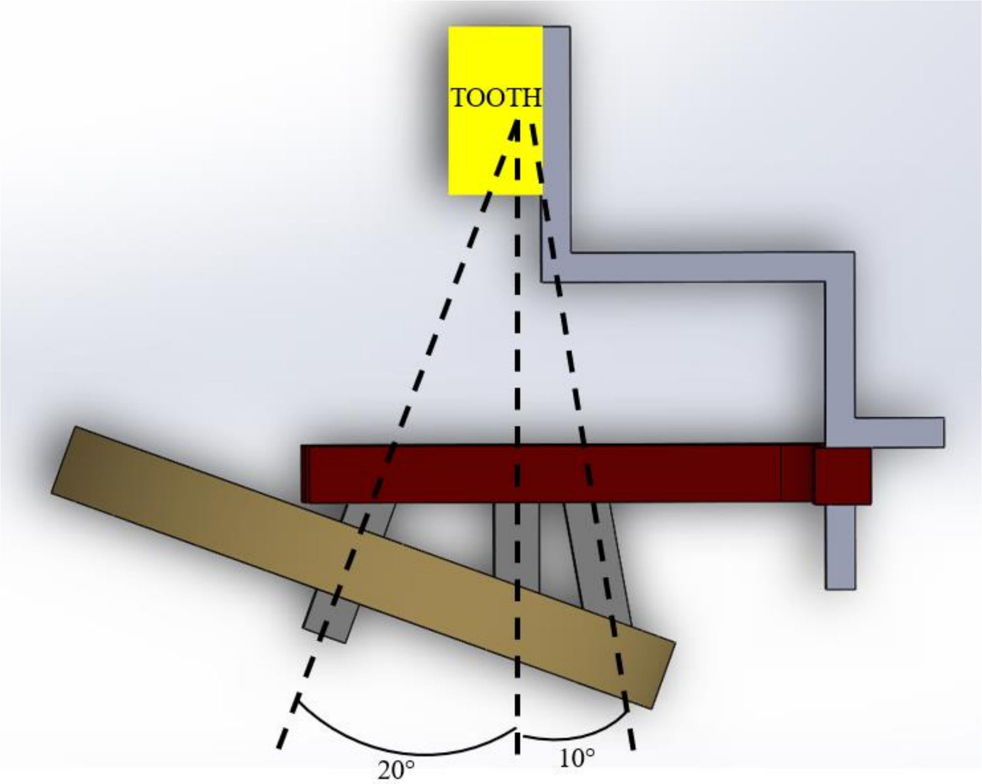

Figure 39. Prototype A: geometric concept.

Having analyzed each of the components of Prototype A separately, the final display of this device can be seen in Figure 40, which shows how the device would be assembled in the patient's mouth, using the skull that was provided by the customer. As has been previously mentioned, the x-ray cannon would be placed inside of Part B.

Figure 41 shows an illustration on how the tooth being analyzed would be seen by the x-ray cannon if the left shaft was used (20 degrees). As can be seen marked in red in this illustration, both of the roots of the premolar can be visualized when this angle offset is being used.

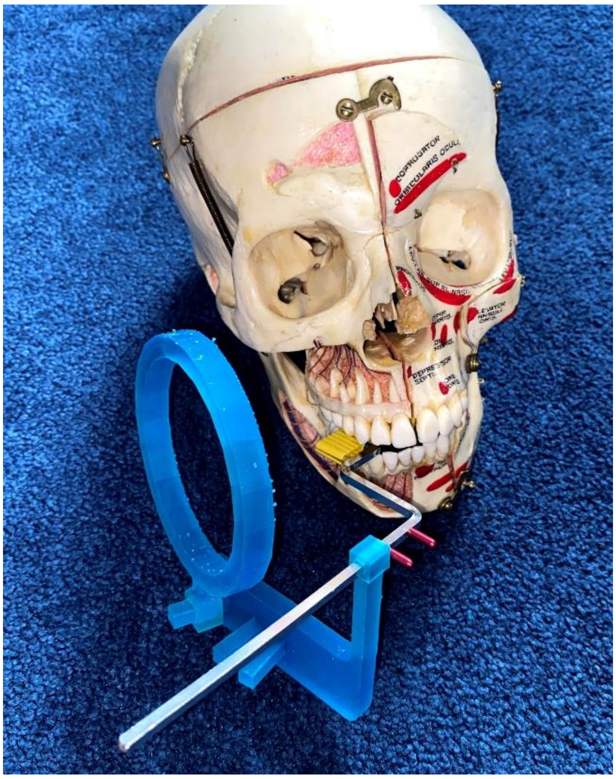

Figure 40. View of Prototype A in use.

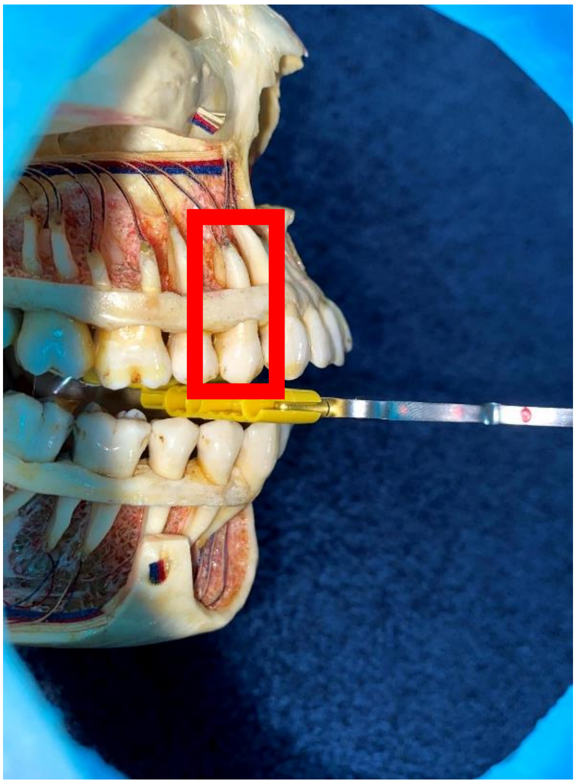

Figure 41. View of the tooth being radiographed when using Prototype A.

1.1.8.2. Prototype B

Previous design

Prototype B appeared from modifying one of the initial designs that was proposed to the customer. The original design that was proposed to the customer consisted of a single component, which would get attached to the standard metal bar through a hole on its center. This component had six shafts at varying angles, disposed in a symmetrical way, which marked the angle offsets that were used in this prototype, as can be seen in Figure 42. The shafts were raised in order to work with the standard yellow ring.

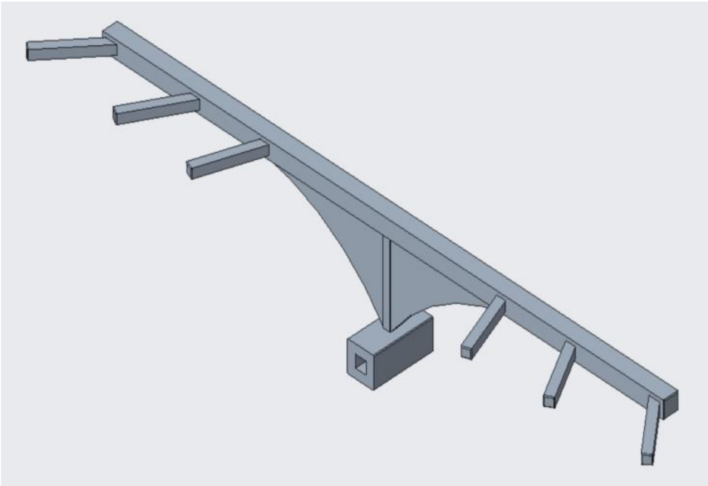

Figure 42. Isometric view of the second proposed design.

The standard ring would then get attached to one of the shafts, by inserting one of these shafts through the hole found in it. The x-ray cannon would be finally placed aligned with the standard ring, as in the standard procedure. In the end, the x-ray cannon would be aiming at the desired tooth from the angle of the shaft where the ring was attached to.

The different angle offsets of this design are 20 degrees, 30 degrees and 40 degrees, disposed in a symmetrical way. The geometric concept of this design can be seen in Figure 43. This device was designed to ensure that the x-ray cannon, which would be aligned with the ring, would always be correctly aiming at the desired tooth.

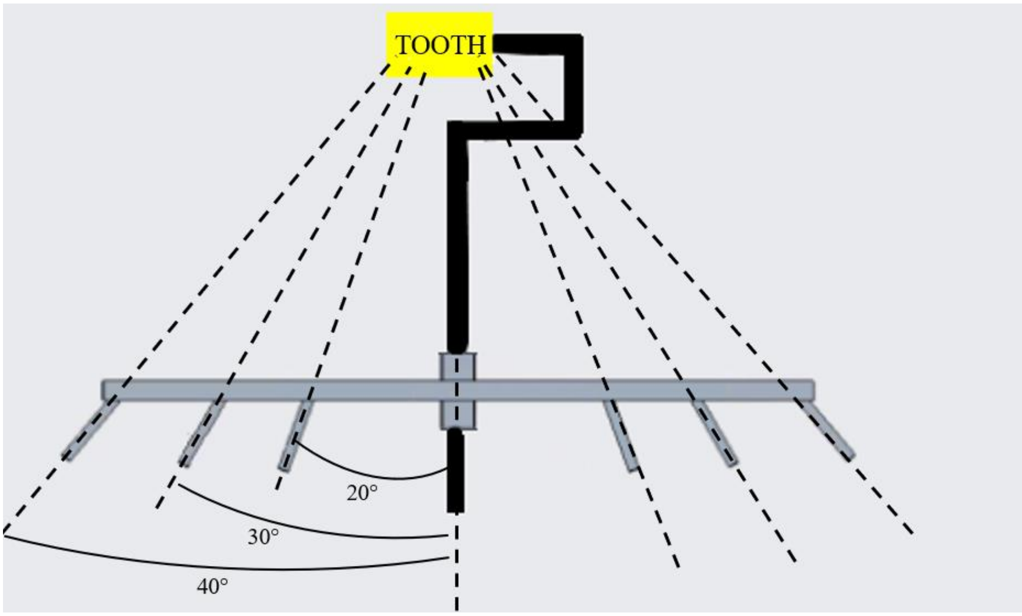

Figure 43. Geometric concept of the second proposed design.

One problem which appeared with this prototype was that it needed to be placed too far from the patient's mouth in order to ensure that the x-ray cannon would be correctly aiming at the tooth, therefore leading to blurry radiographs. Another issue with this device is that it was quite wide, which made it difficult to stay stable while the radiograph was being taken. As has been explained in the "Specifications" section, the device needs to be able to stay in place on its own, as the dentist has to leave the room while the radiograph is being taken and therefore cannot hold the device in place.

Both of these problems can be seen in Figure 44, where the 3D printed model of this device can be seen in use with a jaw model. The metal bar seen in this illustration is not the one that would be actually used with this device, and that's the reason why all the shafts except for the one that is being used in the figure don't seem to be correctly aiming at the desired tooth. As can be appreciated in this illustration, the ring that is being used is not the yellow one, being this due to the fact that I did not have this yellow ring when the image was taken.

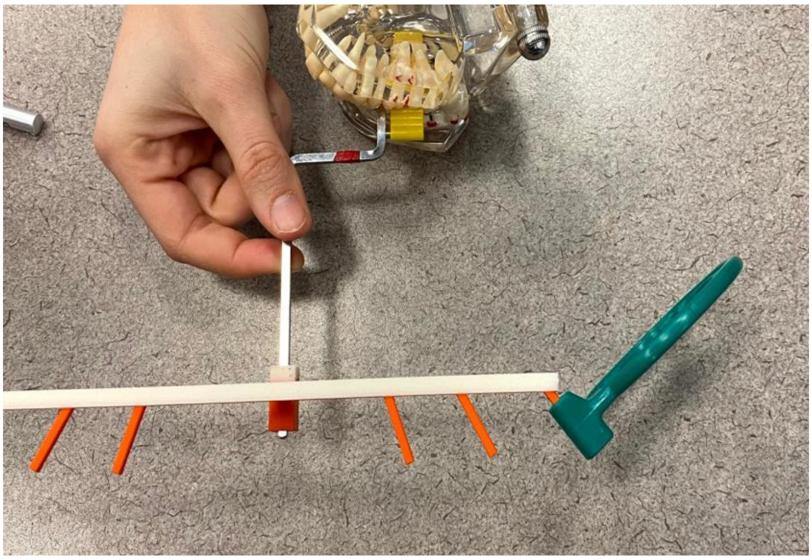

Figure 44. Display of the second proposed design in use.

Given these two problems, this prototype needed to be modified, and a few alterations were made to this design so as to overcome them. These alterations were intended to make it smaller and easier to hold, and they led to the other final prototype that is proposed in this project. A different standard ring was used, and the distance between the device and the sensor was reduced.

Final design

All of these alterations led to Prototype B. This device has just one component, and it works with the standard parts, i.e. the metal bar, the ring and the sensor. Figure 45 shows the overall display of Prototype B.

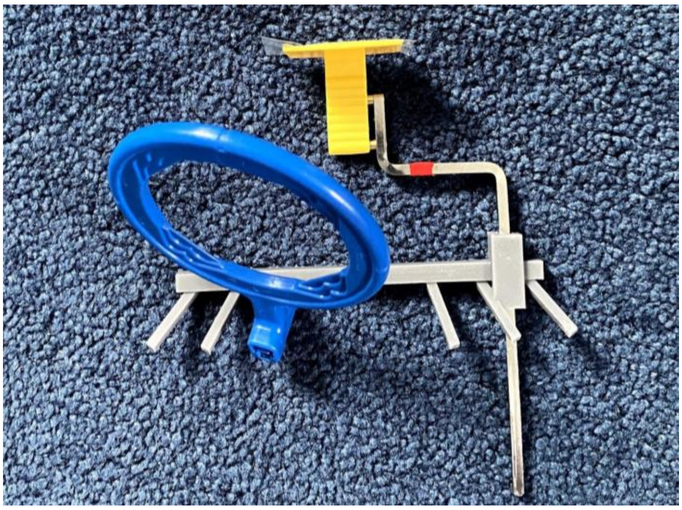

Figure 45. Prototype B: overall display.

This component consists of a straight bar, which has a hole on its right section and six shafts protruding at varying angles. These shafts are angled at 20 degrees, 30 degrees and 40 degrees with respect to the standard bar, disposed in a symmetrical way, and there are three shafts on each half of the bar, which are slightly angled in the vertical plane in order to account for the height of the ring and its alignment with the sensor.

This prototype fits onto the standard metal bar by inserting this bar through the hole found in the right section of the component. This component can be seen on a top view in both Figure 46 and Figure 47, where a top view of the 3D printed part can be seen in Figure 46 and a top view of the CAD model can be seen in Figure 47.

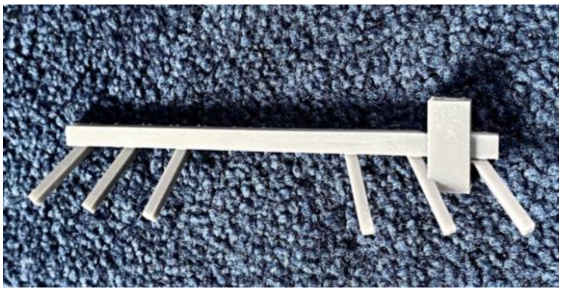

Figure 46. Prototype B: top view (3D printed part).

Figure 47. Prototype B: top view (CAD model).

This device is used with a different standard ring. The one used here is blue, which has a different orientation and geometry from the yellow ring, allowing the shafts to be closer together and therefore moving the device closer to the sensor, allowing to take clearer radiographs. This also shortens the width of the device, making it easier to stay in place. These differences in the rings' orientations can be seen in Figure 48, where top views of both the yellow and the blue ring can be seen.

Figure 48. Different types of rings used to align the x-ray cannon with the sensor. [5] [6]

Back to the device, the purpose of the hole in the right section is for the component to slide and stay on the standard metal bar, which simply positions the shafts in the correct place in relation to the sensor, allowing the ring to be placed at an specific angle in order to allow for the angled radiograph to be taken.

The x-ray cannon is placed directly in line with the ring, and the desired radiograph can be taken. This component is designed to ensure that the x-ray cannon is always going to be correctly aiming at the desired tooth from the angle of the shafts where the ring is being attached to. The geometric concept of Prototype B can be seen in Figure 49.

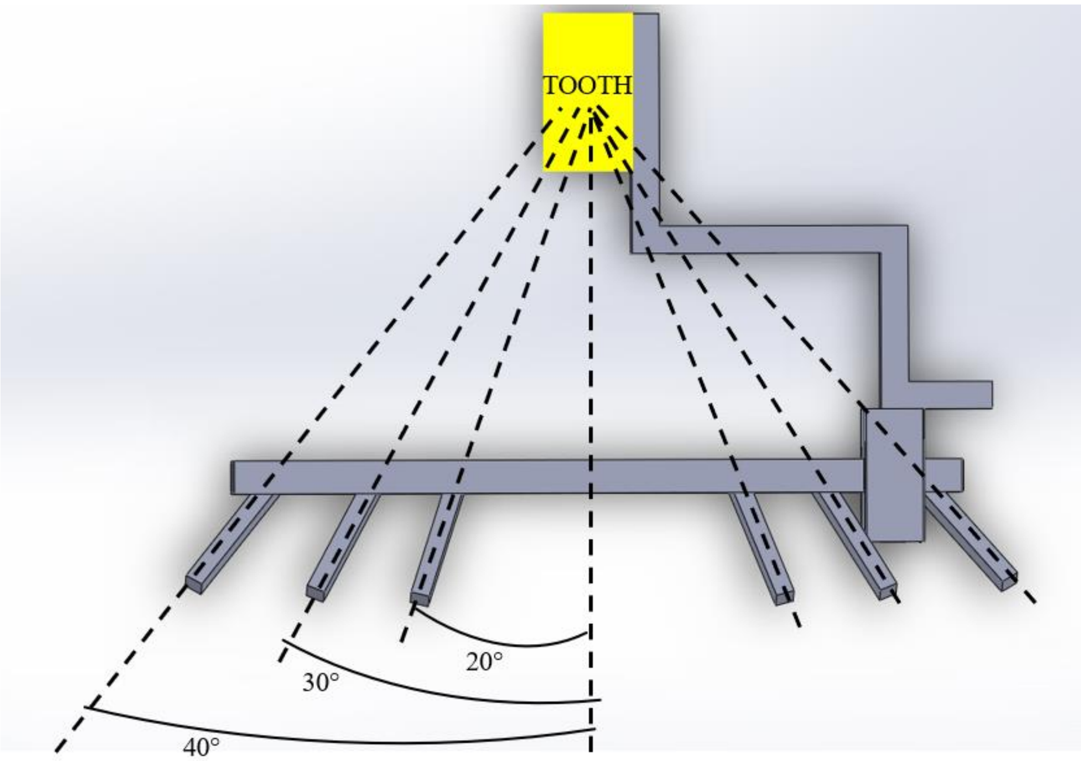

Figure 49. Prototype B: geometric concept.

This prototype is to be used in conjunction with the currently used dental tools, the standard metal bar, the standard sensor holder and the standard ring. It acts as a connecting piece between the standard bar and the standard ring, allowing the ring to be aligned with the sensor at a desired and known angle.

The final display of this prototype can be seen in Figure 50. This illustration shows how the device would be assembled in the patient's mouth, using the skull that was provided by the customer. As has been previously mentioned, the x-ray cannon would be placed aligned with the blue ring.

Figure 51 shows an illustration on how the tooth being radiographed would be seen using the right half's 20 degrees shaft. As can be appreciated in the green square, both of the roots of the premolar can be correctly visualized when this angle offset is being used.

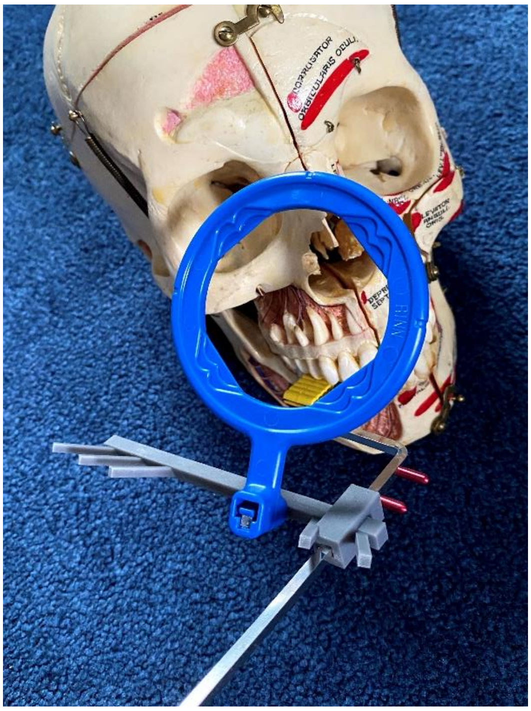

Figure 50. View of Prototype B in use.

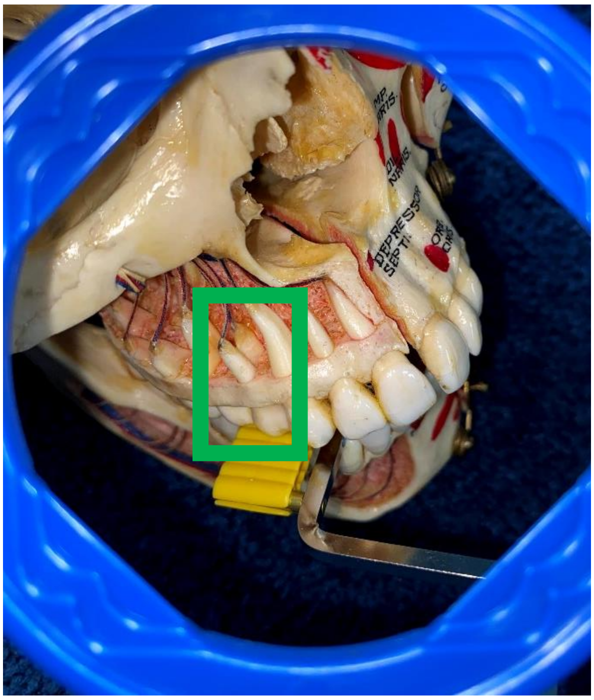

Figure 51. View of the tooth being radiographed when using Prototype B.

1.1.9. Testing procedure

As has already been mentioned, the main objective of this project is to create a device that allows taking angled radiographs in a calibrated manner, so as to correctly visualize all the roots.

As has been previously explained, at least two radiographs are needed in order to see all the roots of this type of teeth. One of these radiographs can be taken from a straight angle, but at least one of them needs to be taken from an angle different from a straight one, in order to be able to visualize the roots in the back whose visualization might get blocked by the roots in the front. If more than one radiograph is taken, and if they are taken from different angles, then each of the roots and their exact position will be better visualized.

For this reason, the testing is carried out by taking angled radiographs using the proposed prototypes.

It is also required that the device allows the dentist repeating a valid radiograph, which is the reason why the angle from which the radiograph is taken must be always known. For this reason, another factor that should be tested is checking whether or not the device being used allows repeating the exact same radiograph. This test would consist in, once a radiograph correctly showing all the roots is taken, being able to repeat the exact same radiograph by using the same angle that was originally used. This means that each of the angled radiographs must be taken at least twice.

In order to test if the device is able to repeat the radiograph in a reliable way, two radiographs taken from the same angle should not be consecutively taken. This means that one radiograph from each angle should be taken first, and once all of the angles in the device have been used, each of them should be repeated, that is, taking at least one different radiograph before repeating the angle. If the devices work correctly, both of the radiographs taken from a specific angle should show the same image.

Given these reasons, total success of either of the proposed devices would be achieved by taking two radiographs from each of the angles marked in them. Once they are taken, a few things will be analyzed:

- The first thing that needs to be analyzed is to find out which of the angles allow a better visualization of all the roots. In order to learn which of them works better, one radiograph taken from each of these angles will be taken, and all of these radiographs, each one corresponding to a different angle, will be compared.
  If some of these radiographs do not show some of the roots, then the angles from which these radiographs were taken will be discarded. Once they have been eliminated, new prototypes with new angles will be designed, in order to analyze if these angles are better than the previously used ones. On the other hand, if some of the radiographs analyzed correctly show all of the roots, then the angles from which these radiographs were taken will be kept for the final model.
- Next step is comparing if the radiographs taken from the same angle show the same image or not, taking into account that they have been taken at different moments in time. If they show the same image and the same number of roots, then the device used when

taking that radiograph would have fulfilled the requirement of making the radiograph repeatable.

This comparation may seem obvious, but one important thing that needs to be checked is whether or not small disturbances -such as a small misalignment of the x-ray cannon with the ring in the case of Prototype B- can affect the image that the radiograph is showing, therefore giving a different result.

1.1.10. Results

These prototypes were meant to be tested at the clinic on March 18th with the customer, so that he could see how they worked in real life and decide which adjustments were needed in order to get to a design that better accomplished the stablished requirements. However, due to the Covid-19 outbreak, this could not be done and the 3D-printed prototypes were sent to the customer hoping that he would be able to test them in the clinic once everything went back to normal.

Once he was able to return to the clinic and test the prototypes (on May 21st), he concluded that Prototype B was easier to use and provided better results. However, he suggested some adjustments that should be made in this device in order to better accomplish the results. He suggested decreasing the vertical angulation of the shafts to approximately 20 degrees, since the initial angulation missed a part of the tooth that was being analyzed. He also recommended eliminating the 40 degrees shaft, since it made the prototype more complex and did not provide useful information, as all the roots could be correctly visualized with the other angles, 20 and 30 degrees. A top view of this new prototype can be seen on Figure 52, where it can be appreciated that the 40 degrees shaft has been eliminated. It can also be appreciated that the overall functioning of the prototype has not changed.

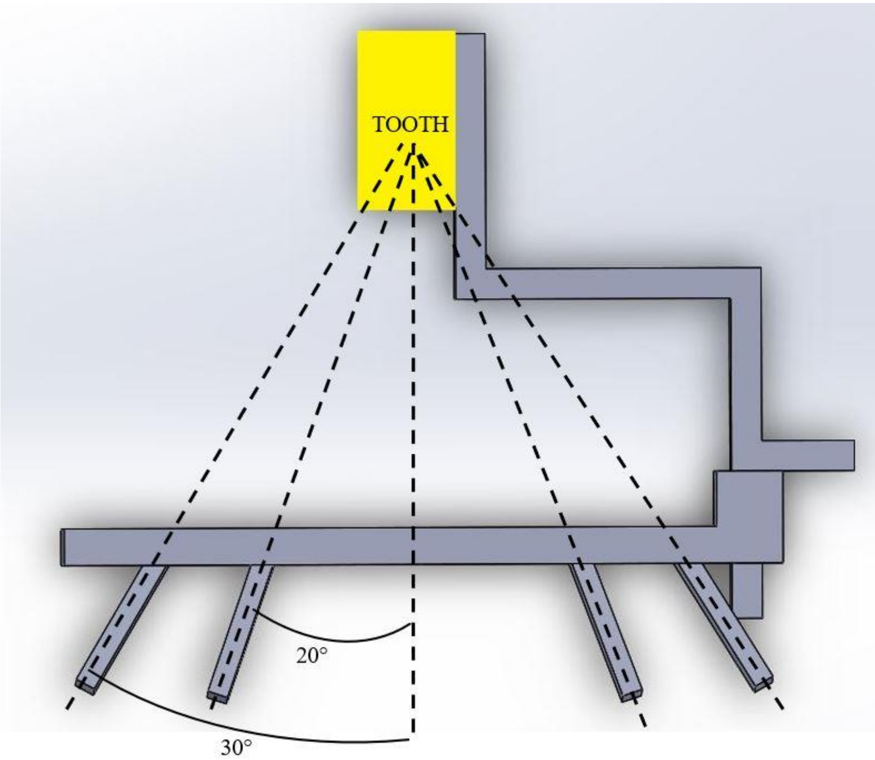

Figure 52. Top view and geometric concept of the new prototype.

The geometry of the prototype was also slightly modified, in order to be able to print it in an easier way and to avoid wrinkled surfaces. The part had four shafts suspended in air, which would lead to the need of support material while 3D printing it. The modification was meant to avoid this support material with the goal of making the surface smooth, and was achieved by creating a ramp in the prototype, aligned with the shafts. This change can be appreciated in both Figure 53 and Figure 54, where Figure 53 shows a side view of the prototype and Figure 54 shows an isometric view of the prototype.

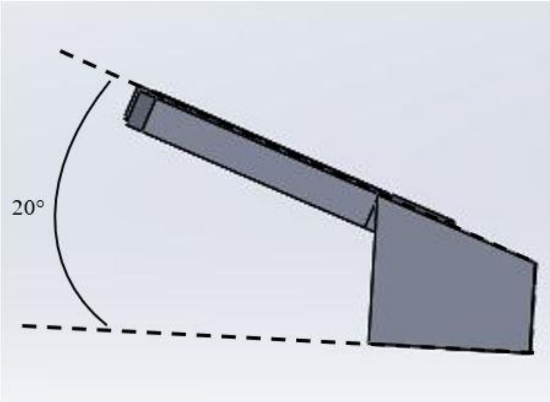

Figure 53. Side view of the new prototype.

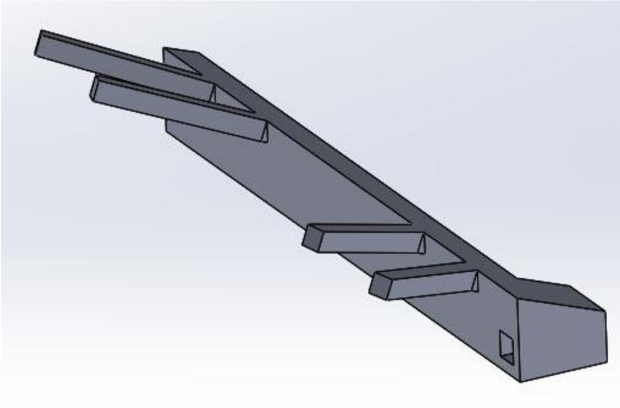

Figure 54. Isometric view of the new prototype.

The reason why Prototype A was not chosen is that its geometry was not a good one, due to the fact that, if the 10 degrees shaft was being used, it was physically impossible to insert the x-ray cannon through the hole in Part B, since the standard metal bar ended up being inserted through this same hole. This can be seen in Figure 55 and in Figure 56, where both top and isometric views of the prototype can be seen when this shaft is being used. As can be appreciated in these illustrations, the metal bar is placed where the x-ray cannon should be, therefore making it impossible to insert the x-ray cannon through Part B.

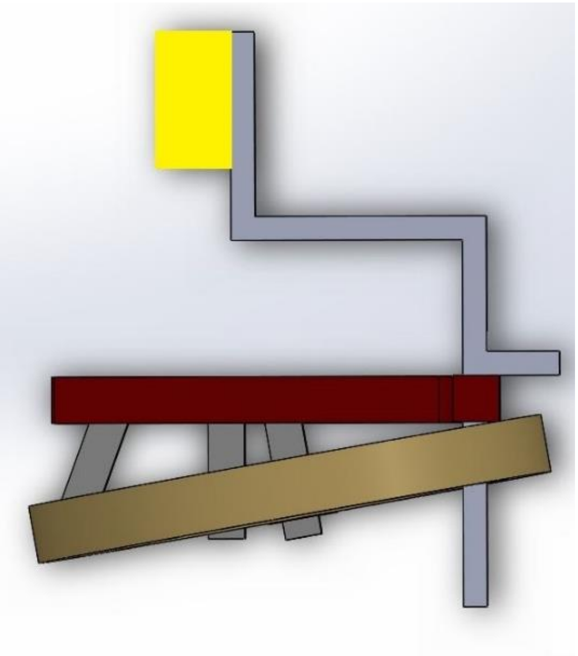

Figure 55. Top view of the geometric problem of Prototype A.

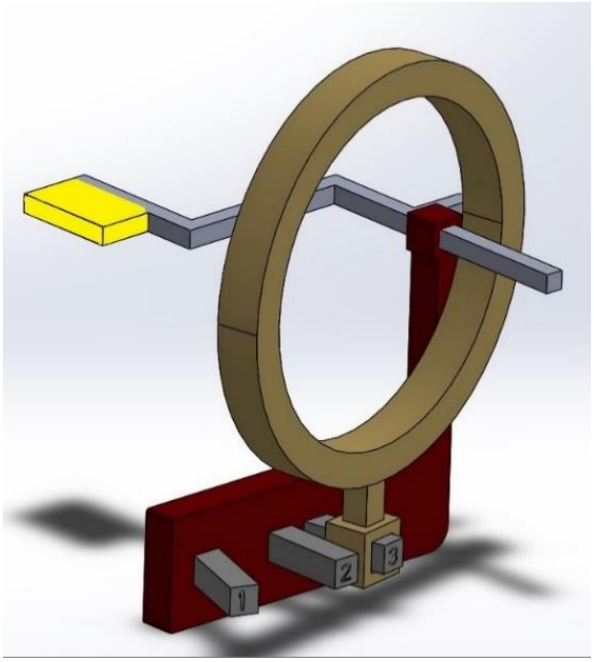

Figure 56. Isometric view of the geometric problem of Prototype A.

This failure could be avoided by implementing all the shafts on the left side, so that Part B and the x-ray cannon would not end up being in the same place as the standard metal bar.

However, due to the lack of time because of the Covid-19 pandemic and the difficulty to solve problems while being at different cities, it was decided that this prototype would be discarded, since the modifications that needed to be made in Prototype B were easier to solve.

1.1.11. Conclusions

As explained above, the objective of this project was to come up with a device that would allow taking angled radiographs in a precise and calibrated way, in order to be able to visualize all the roots when a tooth with multiple roots is being radiographed. The current procedure for taking angled radiographs does not ensure that the x-ray cannon is correctly aiming at the tooth, therefore several radiographs are needed in order to get the correct radiograph, which exposes the patient to multiple doses of radiation and also increases costs and time expenditure for the dentist.

Given this fact, the device designed needed to ensure that the tooth was being aimed correctly, and also that the angle from which the radiograph was being taken was known, in order to allow repeating the radiograph in the exact same way.

In order to fulfill these requirements, two prototypes were proposed to the customer. Due to the Covid-19 outbreak, they were mailed to the customer before leaving Boston and they haven't been tested until May 21st, as the customer's clinic was closed. Once he was able to test them, he suggested some adjustments in both of the prototypes. Due to the difficulties of the situation caused by the Covid-19 crisis, it was easier to modify just one of them, Prototype B, as it was simpler and needed less complicated adjustments.

This prototype, Prototype B, is easier to use than Prototype A, and once the required adjustments have been done in the original design of this prototype, it would allow taking angled radiographs that correctly show the tooth and all its roots, also ensuring that the angle that is being used is known and the radiograph can be repeated.

Therefore, as per conversation with the customer dated May 21st, assuring that the device would work in real life once these changes were made, I consider that all the objectives of this project have been fulfilled. The device that has been proposed in this project would help reducing the number of radiographs that need to be taken when a tooth with multiple roots is being radiographed, as only one radiograph would be needed in order to correctly show the tooth and all its roots. This would lead to simplifying the process that needs to be carried out when a tooth with multiple roots is being analyzed and reducing the patient's exposure to radiation.

1.1.12. Further developments

There are several aspects of this project that could be developed in the future, in order to improve the results that have been found throughout this project.

First task that could be done when trying to develop this project in the future would be making the necessary adjustments in Prototype A, as has been explained in the "Results" section. This would include modifying the current design in order to solve the geometric problem that arose from the shaft on the right side, which could be solved by implementing all the shafts on the left side of the prototype.

The other aspect of this project that could be developed in a future project would be manufacturing the final device, that is, using the appropriate materials and manufacturing method in order to create a real device that can be used in the clinic, since the ones that have been manufactured in this project are only for testing purposes and cannot be really used in the clinic. As has already been mentioned, this would have been done in this project if it hadn't been for the Covid-19 pandemic, but given the situation, it has not been possible to complete this aspect of the project.

An important thing to be considered is that the device that needs to be finally manufactured is going to be used close to the patient's mouth so, even though it's not going to be in direct contact with the mouth, it needs to get sterilized between one patient and the next one. Therefore, it needs to be made with a material that can stand being sterilized at high temperatures without getting damaged.

Right now, as it would be used on a reduced scale, the ideal method to manufacture this device would be 3D printing, since the geometry of the part is complex when trying to manufacture it with any other method, due to the shafts and their angulations. The appropriate material needs to be found in order to ensure that the part can be sterilized between each patient.

Fused Deposition Modelling (FDM) parts cannot be sterilized, therefore the part needs to be 3D printed using the Stereolithography (SLA) method. Formlabs has developed special resins that can be used in dental applications [FORM], such as the "Dental LT Clear Resin" [FOLT20] or the "Dental SG Resin" [FOSG19].

If this device was ever to be used on a big scale, an economical study would be needed in order to determine if this manufacturing process is the most suitable one for manufacturing it in a profitable way. Probably another manufacturing process such as injection molding would be more appropriate in economic terms, always keeping in mind that the device needs to be sterilized between each patient, therefore needing to use the appropriate material.

1.2. CALCULATIONS

All the prototypes that have been developed during this project have been designed keeping in mind that the most important factor was aligning the x-ray cannon with the sensor. In order to achieve this, the measurements of the standard tools, provided by the customer, were first taken. The prototypes were then designed using these measurements, calculating the dimensions needed in each of the parts and calculating the position of each of the shafts.

The measurements that were taken from the standard metal bar and the standard sensor can be seen in Figure 57. In both Prototype A and Prototype B, some shafts found in the metal bar were used as a reference on how far the device should be, also seen in Figure 57. When the radiograph is being taken, the tooth would be approximately placed in the + symbol.

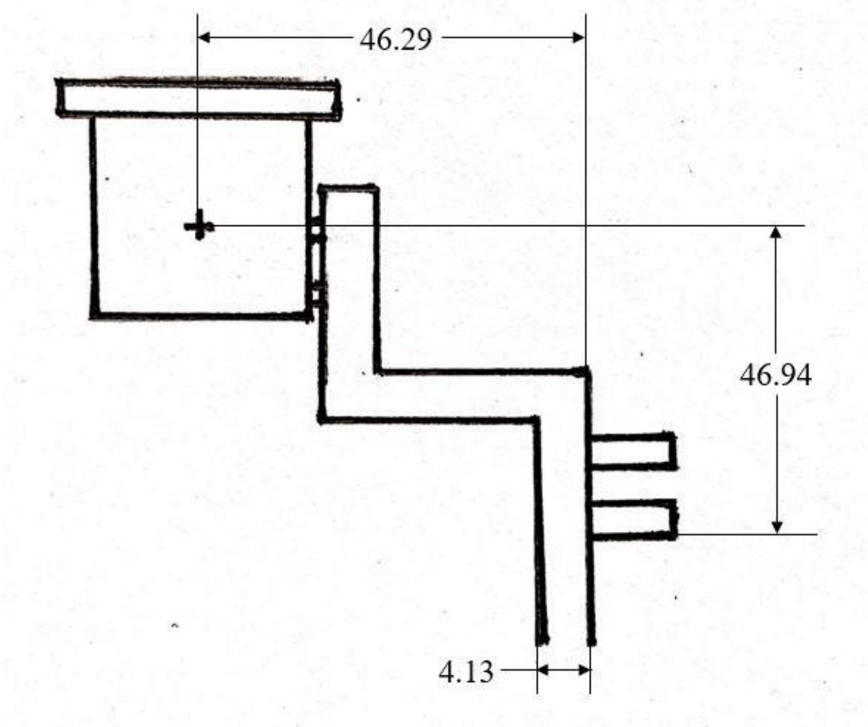

Figure 57. Measurements taken from the standard parts.

The diameter of the x-ray cannon was measured by one of the supervisors of this project, Enrique Gutierrez, when he visited the clinic. The diameter of the x-ray cannon is of 69.7 mm. Having all of these measurements, different calculations have been done for each of the prototypes.

A few assumptions were made, since they could not be measured accurately. It was assumed that the tooth, along with the roots, was 6 mm high. It was also assumed that the tooth would be placed at the center of the sensor holder, marked with a + symbol in all the illustrations.

1.2.1. Prototype A

In the case of Prototype A, the horizontal distance from the middle of the sensor (where the tooth is assumed to be positioned) to the end of the shafts was set as the maximum distance at which the device could be positioned. This distance is 46.94 mm, as can be seen in Figure 57.

The width of Part A was set to 8 mm, in order to make it wide enough that it would be able to support the weight of Part B. Using this distance, and adding it to the maximum distance at which Part A could be placed (L_T), the mid-point of each of the shafts was obtained. This was achieved by using trigonometry, using the following equations and the information seen in Figure 58, considering θ_1=10° and θ_2=20°. Figure 58 shows a top view of Prototype A and some of its measurements.

$$L_T = 8\,mm + 46.94\,mm$$

$$\tan\theta_i = \frac{x_i}{L_T} \rightarrow x_i = L_T * \tan\theta_i$$

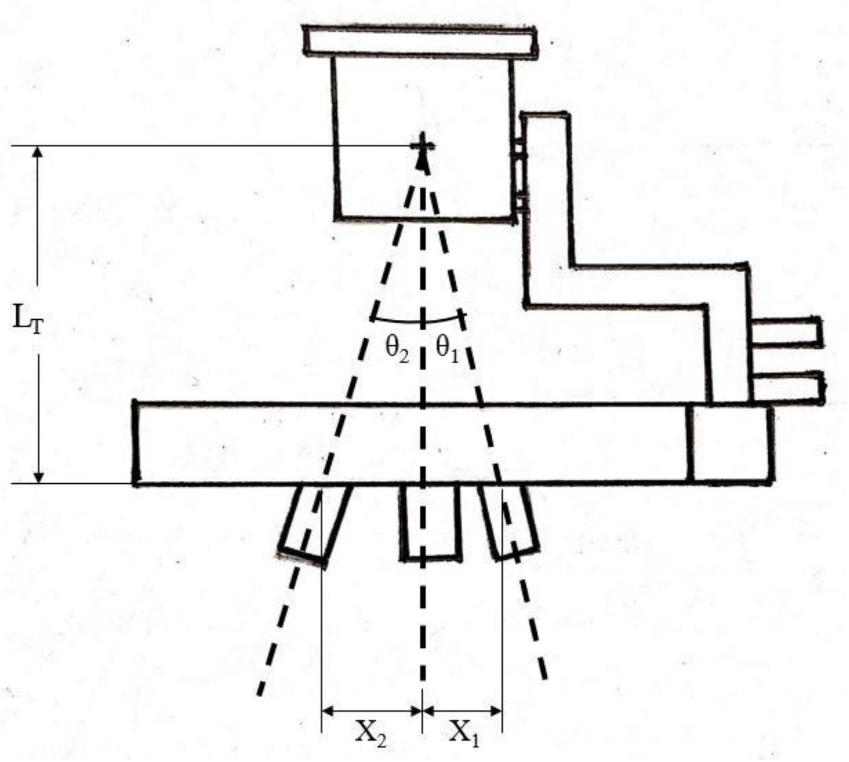

Figure 58. Geometry and information used to calculate the mid-point of the shafts (top view of Prototype A).

Using this information, X_1 was set to 9.86 mm and X_2 was set to 20.36 mm. The position of the mid-point of the shaft in the middle was calculated by using the horizontal distance between the position of the tooth (+) and the bar, which was measured to be 46.29 mm, as seen in Figure 57. Some of the other dimensions of Part A could be set randomly, since they did not depend on the measurements of the standard parts, such as the length of the part or the width of the shafts.

The squared hole used to attach Part A to the standard metal bar was designed using the dimensions of the standard bar. The initial height of the squared hole was 4.13 mm, which is the dimension of the height of the standard bar. However, since 3D printing has poor tolerance tightness, the dimensions of this hole had to be changed several times in order to ensure that the standard bar fitted correctly through the hole, not being neither too loose nor too tight. The final height of this squared hole was set to 3.58 mm.

In order to calculate the height of the part, Part B and the x-ray cannon diameter needed to be taken into account. Using the x-ray cannon diameter and setting some of the dimensions of Part B randomly, the dimension H could be defined, which is the distance between the center of the x-ray cannon and the shafts on Part A, as can be seen in Figure 59, which is a side view of the prototype and its measurements. The center of the x-ray cannon had to be placed at exactly the same height as the tooth.

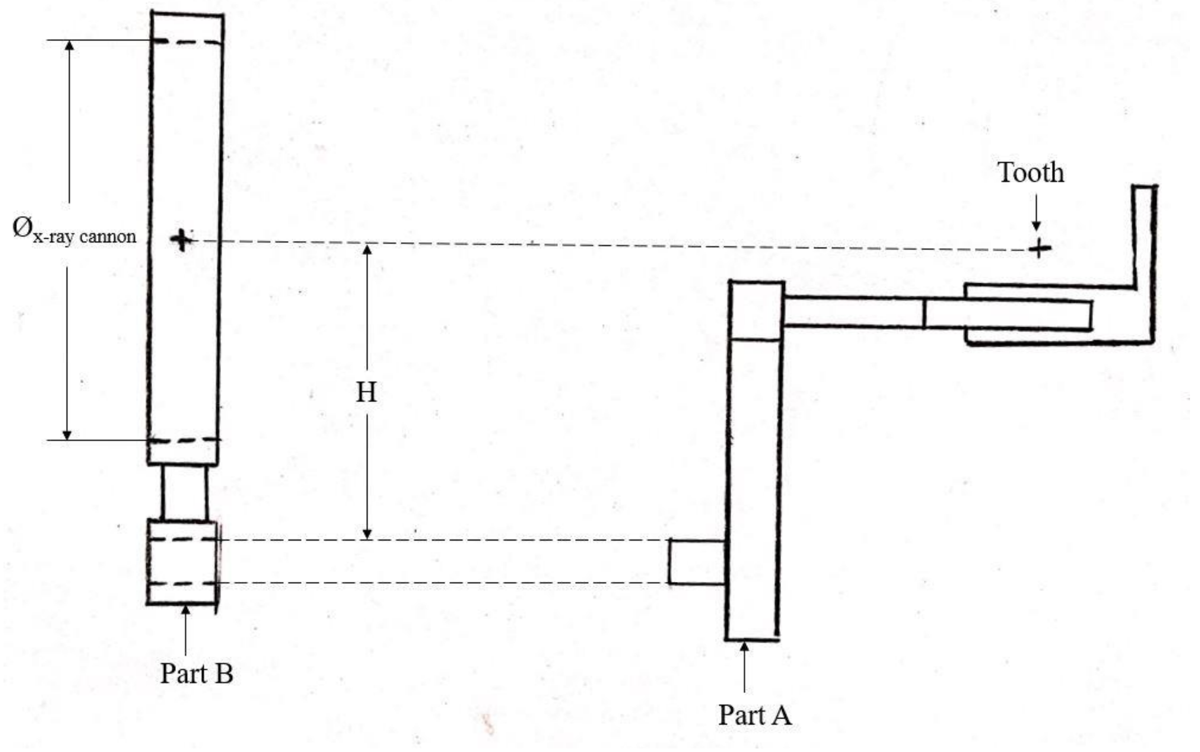

Figure 59. Side view of Prototype A and its measurements.

Once Part B's dimensions were calculated and H was determined, the remaining vertical dimensions of Part A could be calculated, as can be seen in Figure 60, which is a front view of Part A and the sensor holder.

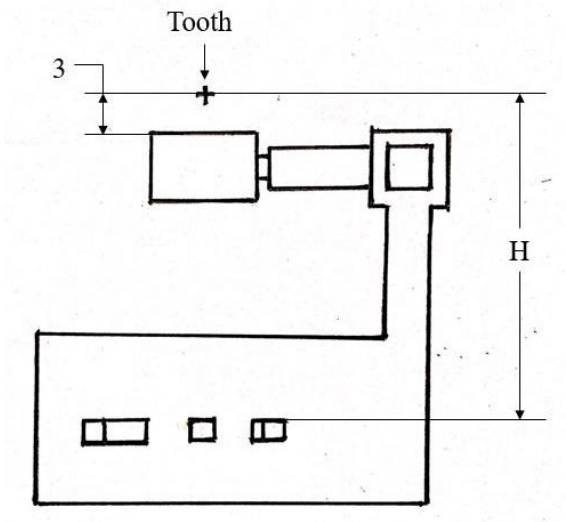

Figure 60. Front view of Part A and the sensor and its measurements.

As happened with the hole used to attach the prototype to the standard bar, shafts in Part A and the hole in Part B to insert them through had to be modified several times due to the poor tolerance tightness of 3D printing. The final squared hole in Part B is 7 mm high, while the shafts in Part A are 6.3 mm high.

1.2.2. Prototype B

In the case of Prototype B, the horizontal distance from the middle of the sensor (where the tooth is assumed to be placed) to the end of the shafts was also set as the maximum distance at which the component could be placed (46.94 mm).

The approach that was used for this device is very similar to the one that was used when designing Prototype A. The width of this component was set to 5 mm and the width of the hole through which the standard bar would be inserted was set to 20 mm, in order to make it wide enough so that the component would be able to stay in place on its own, as can be seen in Figure 61, which is a top view of the prototype. Taking these two distances into account and adding them to the maximum distance at which Prototype B could be placed (LT), the mid-point of each of the shafts was obtained, using the same reasoning as in Prototype A. This can be seen in Figure 62, which is a top view of the device. The shafts are disposed in a symmetrical way.

$$L_T = \frac{20}{2}\,mm + \frac{5}{2}\,mm + 46.94\,mm$$

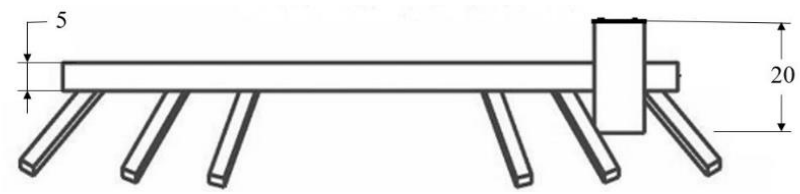

Figure 61. Width of the component.

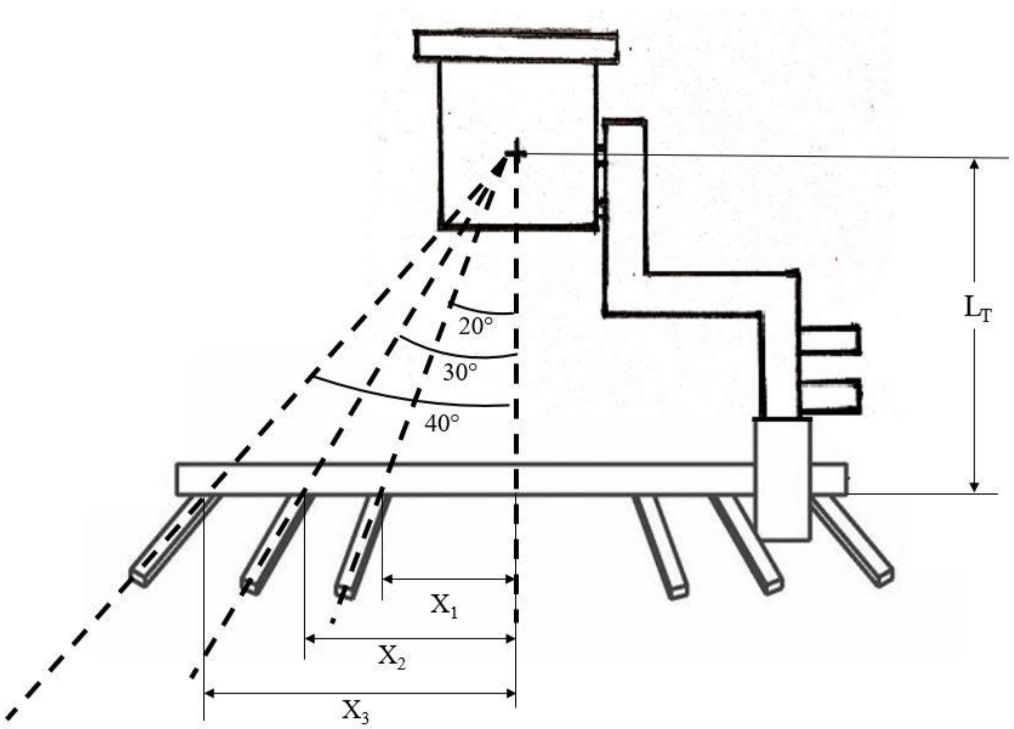

Figure 62. Geometry and information used to calculate the mid-point of the shafts (top view of Prototype B).

Using this information, X_1 was set to approximately 22 mm, X_2 was set to approximately 35.3 mm, and X_3 was set to approximately 51.4 mm. Some of the other dimensions of the component could be set randomly, such as its length or the dimensions of the shafts.

Again, as in Prototype A, the squared hole to attach this component to the standard metal bar was designed using the dimensions of the standard bar. The height of this squared hole was finally set to 3.58 mm, as in Prototype A, given the problems that have been mentioned previously of 3D printing.

As has been explained previously, the shafts are slightly angled in the vertical plane (θ), to account for the height of the ring and its alignment to the sensor. The geometry of the side view of this prototype can be seen in Figure 63. As can be seen, the angle between the shafts and the horizontal plane, θ, is the same one than the one between the standard ring and the vertical plane.

Taking this into account, the angle θ was calculated by using the triangle formed by the standard ring, the shafts and the vertical plane, as can be seen in Figure 64, since these measurements were known. The diameter of the ring had been measured as 48.5 mm approximately, and the length of the shafts had been previously set to approximately 16 mm. The vertical angulation was calculated to be of 33.3° approximately, using the following equation:

$$\tan\theta = \frac{L_{shaft}}{\frac{\emptyset_{ring}}{2}} \approx \frac{16}{\frac{48.5}{2}} \rightarrow \theta \approx 33.3^\circ$$

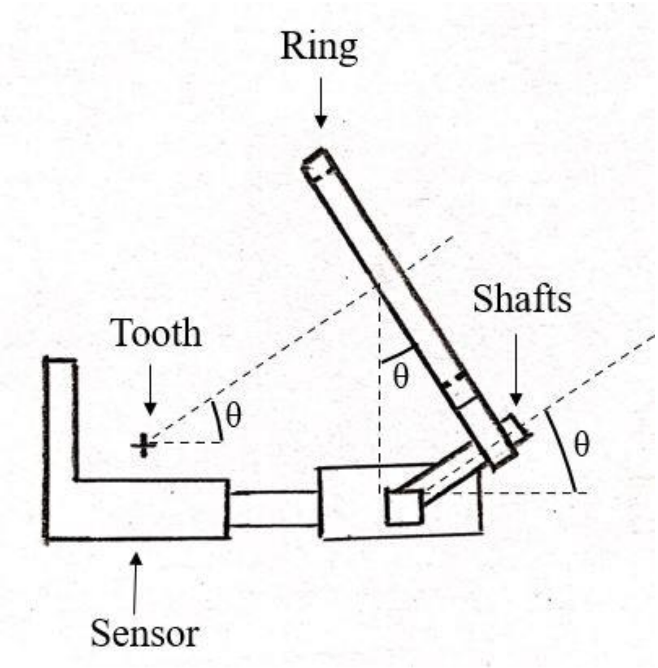

Figure 63. Side view of Prototype B and its geometry.

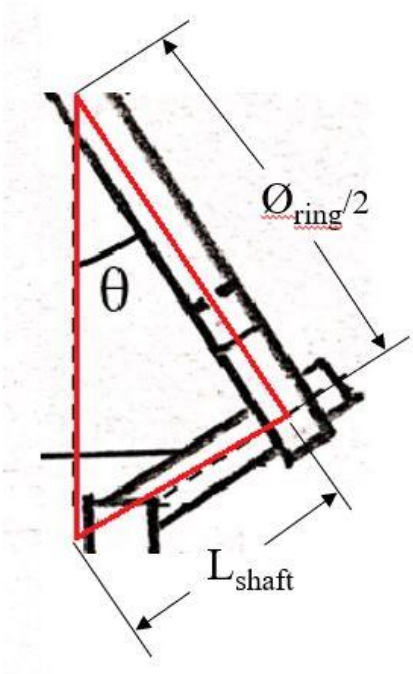

Figure 64. Triangle used to calculate the vertical angulation of the shafts, θ.

1.3. ECONOMIC ASPECTS

As has been already mentioned, due to the Covid-19 pandemic, it was not possible to analyze the real costs of producing these prototypes, as neither the manufacturing method nor the appropriate material could be correctly examined. Just as a hint, the only analysis that could be made were the costs of 3D printing the prototypes. Prototype A 3D printing costs were approximately 12 USD per unit and Prototype B ones were approximately 5 USD. However, these amounts should be considered in a very limited way, as the material used was standard plastic and not a specific medical one.

Even though it has not been possible to analyze in depth the production costs of the prototypes, it has to be considered that in every project, the economic reliability may also come through costs savings and process optimization.

Economic reliability via process optimization is clear: if less time is needed to get a correct radiograph from one patient, more patients can be examined per day.

Economic reliability via costs savings comes from the reduction of the number of radiographs needed; as less radiographs would be needed, less total costs would be achieved.

This is just a description of how the economic profitability analysis should be approached in order to quantify the final results, as none of these aspects have been quantified in detail.

1.4. ANNEXES

1.4.1. Sustainable Development Goals

The Sustainable Development Goals (SDGs) were defined by the United Nations Member States in 2015, creating the 2030 Agenda for Sustainable Development. Their intention is to provide a "shared blueprint for peace and prosperity for people and the planet, now and into the future" (United Nations). [UNMS15]

These goals are aimed to end poverty, improve health and education and reduce inequality, while fighting climate change so as to create a better world. These Sustainable Development Goals can be seen in Figure 65.

Figure 65. Sustainable Development Goals. [7]

The aim of this project is to come up with a device that allows taking angled dental radiographs in a more calibrated way, in order to reduce the number of radiographs that need to be taken until a good radiograph is achieved and reduce the patient's exposure to radiation.

In one of the visits to the clinic, the customer explained how angled radiographs are currently taken, showing that there is currently no way of taking these radiographs in a precise way. While explaining this methodology, he needed several radiographs in order to correctly show all the roots of a tooth with multiple roots in one radiograph, due to the non-precise and non-calibrated method that is currently used for taking these angled radiographs.

However, if the device that is described in this project could be finally developed, it would only take one radiograph to correctly show all of the roots, which would clearly simplify the process. By reducing the number of radiographs that need to be taken, the amount of radiation that the patient is receiving will be reduced.

If this device could be created, it would also allow dentists taking better quality angled radiographs. Thanks to this device, they will be able to take radiographs of teeth with multiple roots in a better way, increasing the quality of the radiographs taken and therefore, making these radiographs more helpful when treating patients.

Therefore, if the objectives of this project were achieved, it would mean a huge step towards increasing the quality of the procedure needed to take radiographs of teeth with multiple roots. As has already been explained, all of us have several teeth with multiple roots, which means that all of us could benefit from this device.

To sum up, I believe that creating this device could be very useful in improving the quality of x-ray treatments, which relates to the "Good Health and Well-Being" United Nations goal.

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1.4.3. Images

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DOCUMENT 2. DRAWINGS

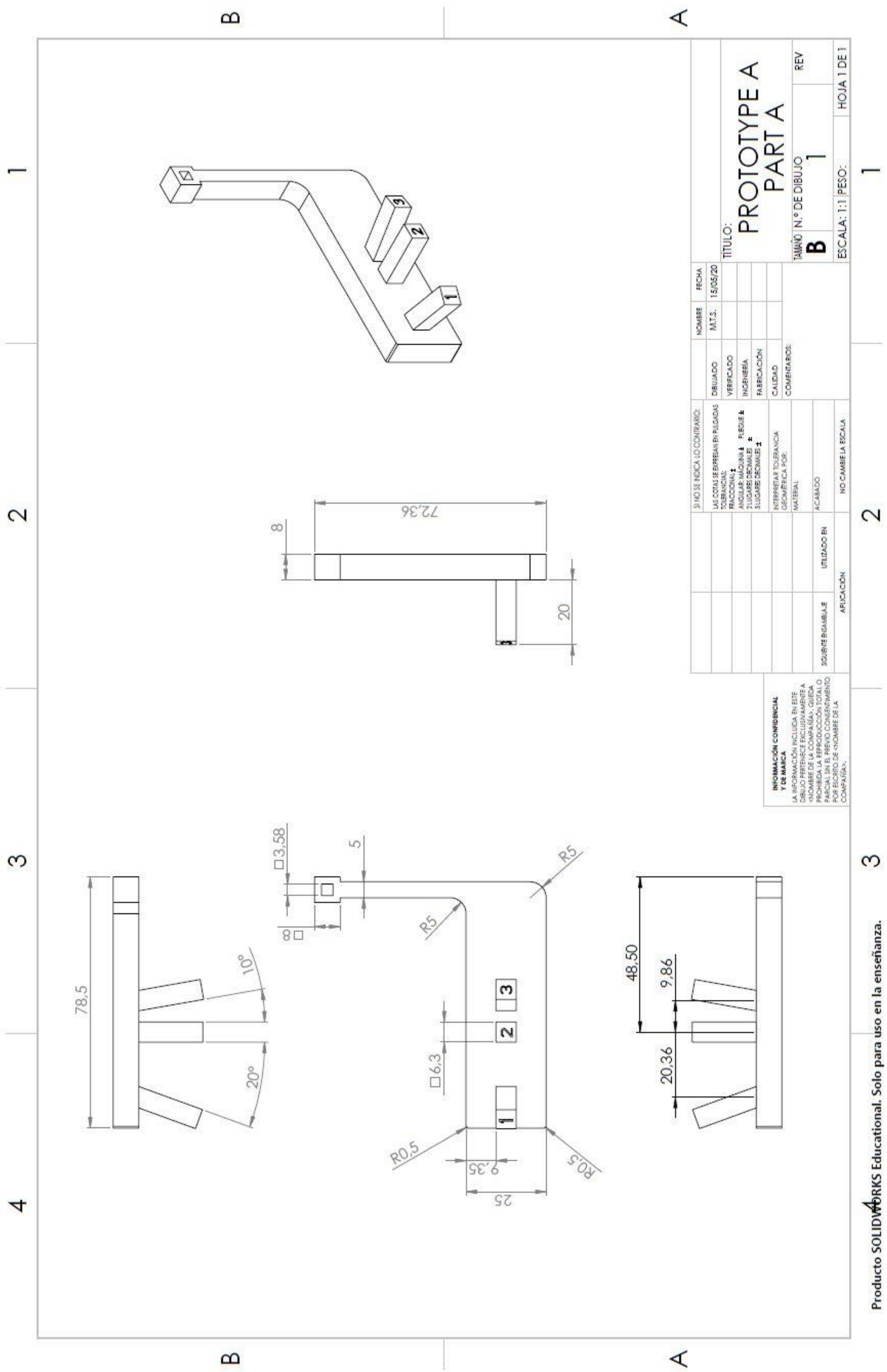
2.1. LIST OF DRAWINGS

A list of the parts that have been created during the development of this project and their drawings can be found here:

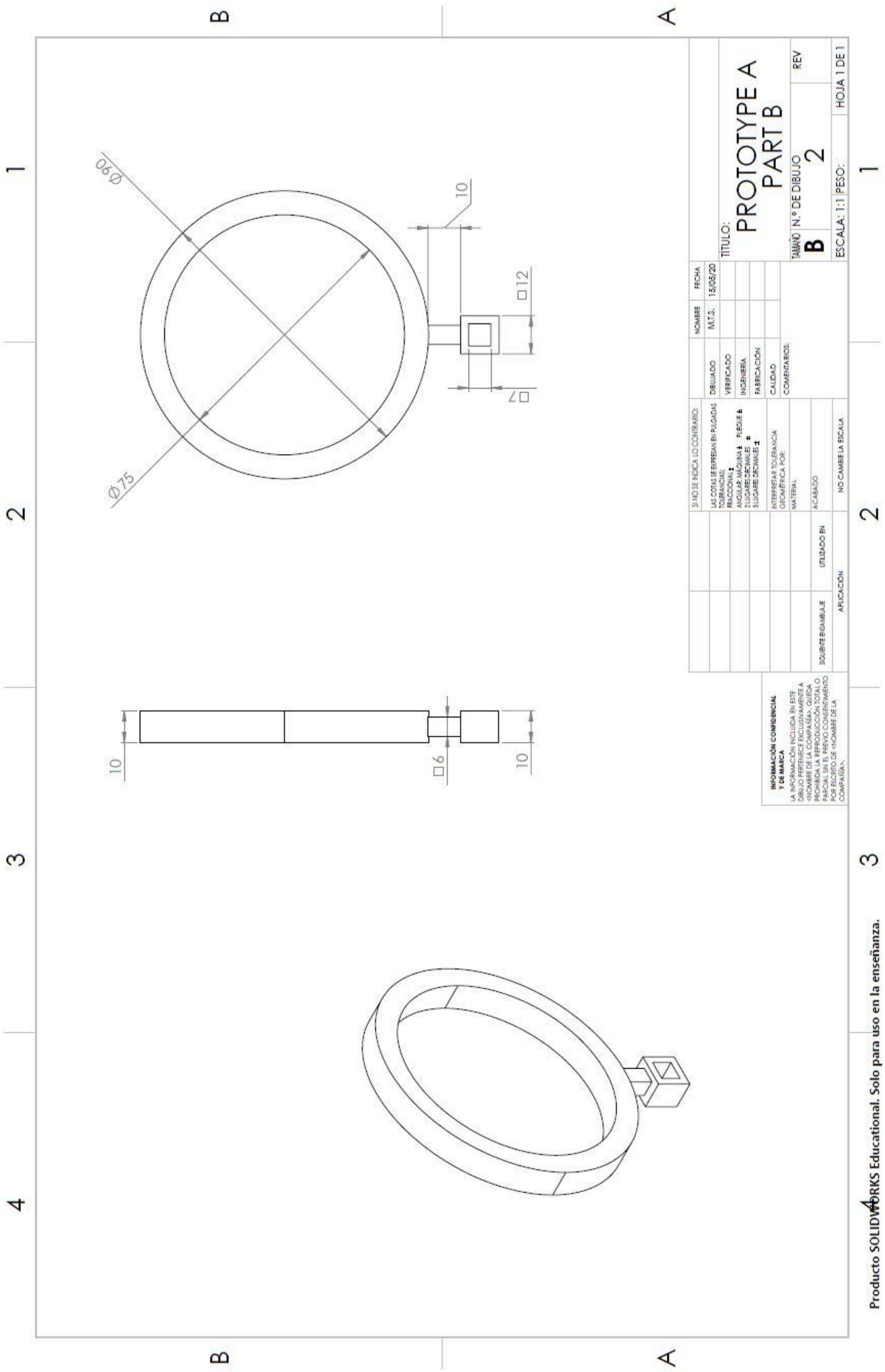
1. PLANO Nº 1. - Prototype A: Part A.
2. PLANO Nº 2. - Prototype A: Part B.
3. PLANO Nº 3. - Prototype A: Assembly.
4. PLANO Nº 4. - Prototype B.
5. PLANO Nº 5. - Upgraded Prototype B

2.2. DRAWINGS

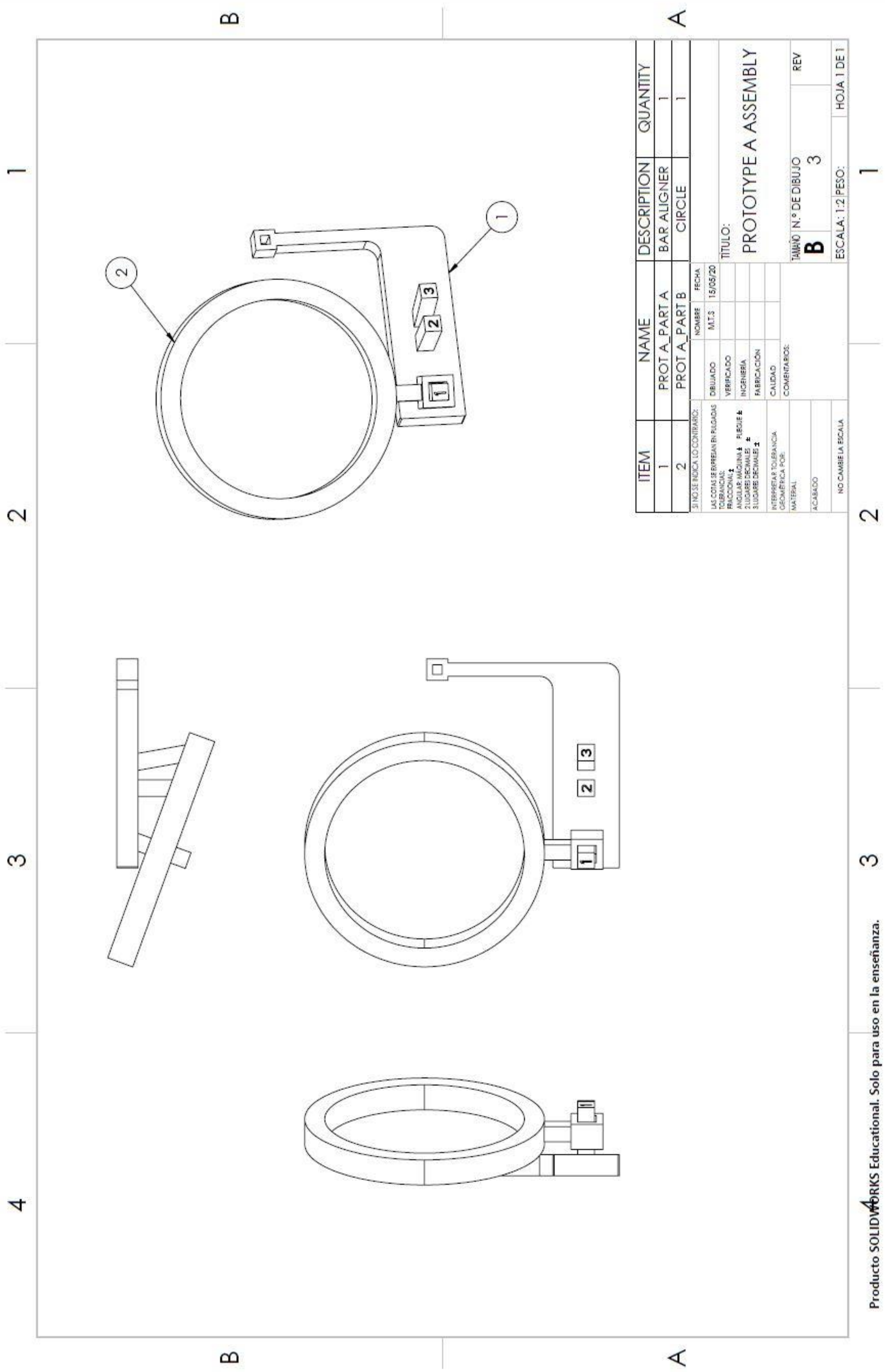
1. PLANO Nº 1. – Prototype A: Part A



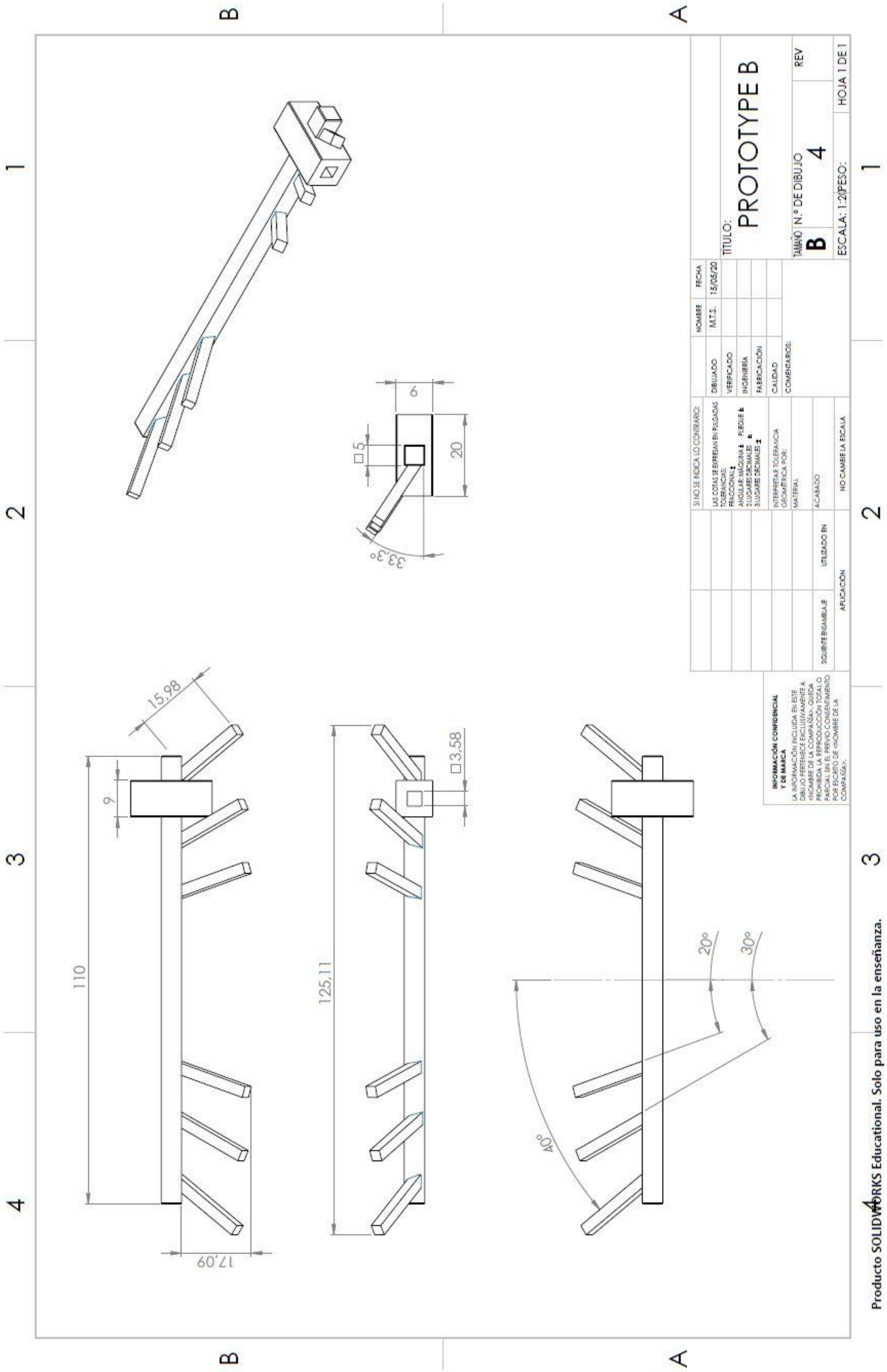
2. PLANO Nº 2. – Prototype A: Part B



3. PLANO Nº 3. – Prototype A: Assembly



4. *PLANO Nº 4. – Prototype B*



5. *PLANO Nº 5. – Upgraded Prototype B*