COMILLAS
UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

DESIGN AND MANUFACTURE OF A PATTERN LOCK

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Director: Bruce Flachsbart

Madrid

Junio de 2019

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Fdo.: Beatriz Acosta Bejarano   Date: 13/06/2019

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PROJECT SUPERVISOR

Fdo.: Prof. Bruce Flachsbart   Date: 20/06/2019

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Junio de 2019

DISEÑO Y FABRICACIÓN DE UNA CERRADURA CON PATRÓN DE BLOQUEO

Autora: Acosta Bejarano, Beatriz.

Director: Flachsbart, Bruce.

Entidad Colaboradora: ICAI - Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

Introducción

El propósito del proyecto presente es desarrollar un producto comercializable a partir de una idea, con el fin de resolver un problema. Tras la fase de ideación, se decidió centrar el proyecto en el diseño y fabricación de un innovador sistema de bloqueo mecánico.

Con el fin de identificar la necesidad del mercado, se realizó una investigación de los productos existentes hoy en día. Aunque hay muchos sistemas de bloqueo mecánico, todos presentan limitaciones que comprometen la seguridad del dueño, así como, la comodidad en su empleo. En concreto, se investigaron los mecanismos internos y puntos débiles de tres sistemas de bloqueo: la cerradura de tambor de pines, el clásico bloqueo por combinación y el candado con combinación direccional.

El objetivo del producto a desarrollar es resolver las limitaciones que amenazan la seguridad y la comodidad del cliente. El avance del proyecto ha intentado alcanzar el diseño de una nueva cerradura que cumpliese las siguientes metas:

- Imposible de trucar o descifrar.
- Sustituir la llave tradicional por un patrón adaptado al cliente.
- Fácil de instalar en las puertas y de reemplazar en las cerraduras actuales.
- Fácil de usar y personalizar, sin la necesidad de ayuda profesional.

Metodología

Después de determinar las especificaciones del proyecto, la siguiente etapa fue el desarrollo del prototipo, un proceso iterativo en el cual se diseñaba una idea inicial, se construía y, por último, se evaluaban sus aspectos positivos y negativos.

Con respecto a la creación de los prototipos, se utilizaron principalmente dos recursos: Creo Parametric 3D Modeling Software para crear los modelos a ordenador, e impresoras 3D de Modelado por Deposición Fundida (MDF) para dar forma a las partes diseñadas.

Durante la etapa final del proyecto se realizó un análisis de experimentación y optimización del diseño, y un análisis del ensamblaje de las piezas con el fin de obtener conclusiones que permitieran mejorar el prototipo.

Inicialmente la iteración del prototipo, llamada CrossLock, se basaba en movimientos direccionales con una llave genérica. Se diseñó con una placa frontal común donde un patrón determinado permite bloquear y desbloquear. En el interior hay distintos niveles con caminos para que la llave deslice, y con agujeros en ciertas posiciones que permiten empujar la llave y pasar al siguiente nivel. Tras

terminar la combinación, se presiona la llave para activar el sistema de bloqueo y desbloqueo de la cerradura. Como la llave es genérica para todas las puertas, son los movimientos de la llave los que proporcionan la seguridad de la cerradura.

En general, CrossLock combina el aspecto personal de una cerradura de combinación con la seguridad práctica de una cerradura de llave. Las figuras 1 y 2 muestran los bocetos del primer y segundo diseño de esta iteración. El primero tiene solo dos posibles direcciones, mientras que el segundo incorpora direcciones en cuatro sentidos.

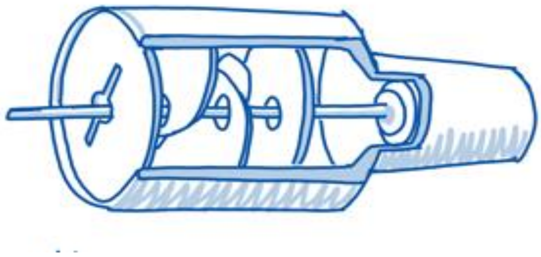


Figura - 1 - Primer diseño de CrossLock

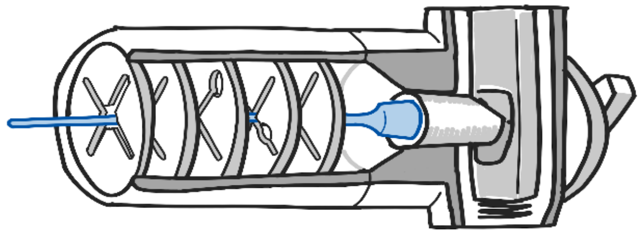


Figura - 2 - Segundo diseño de CrossLock

Esta iteración se consideró un sistema de bloqueo con un mecanismo demasiado simple y fácil de descifrar. Además, no cumplía el objetivo de evitar el uso de una llave para hacer la cerradura más cómoda de utilizar.

Es por ello que se decidió desarrollar una nueva idea que terminó convirtiéndose en la segunda iteración del prototipo. En este caso, la cerradura se basaba en movimientos rotacionales en lugar de direccionales, por tanto, ahora el patrón consistía en girar dos ruedas a unas posiciones determinadas. A pesar de que con este sistema la cerradura no requería llave, el mecanismo interno se consideró similar al de bloqueo por combinación y realmente difícil de reiniciar.

Tras estas dos iteraciones fallidas, se realizaron investigaciones para desarrollar nuevas ideas, en concreto, se buscaba desarrollar un mecanismo que transformara movimientos lineales en rotacionales. Basándose en este nuevo objetivo, los mecanismos de bolígrafos retráctiles fueron analizados.

La tercera iteración fue creada de forma muy sencilla, simplemente para probar la idea de usar el mecanismo de estos bolígrafos en la cerradura. El patrón consistía en pulsar determinados bolígrafos para liberar el sistema de bloqueo y pode mover el pestillo. Con este prototipo de prueba se observó que la entrada y salida de la punta del bolígrafo debilitaba el funcionamiento del sistema de bloqueo. Por lo tanto, esta idea fue descartada.

El mecanismo de este tipo de bolígrafos fue analizado más detalladamente para tratar de convertir el clic del botón en una rotación más precisa. Así, PenLock fue diseñado, siendo ya la cuarta iteración del prototipo. Las figuras 3 y 4 ilustran el montaje completo de la cerradura.

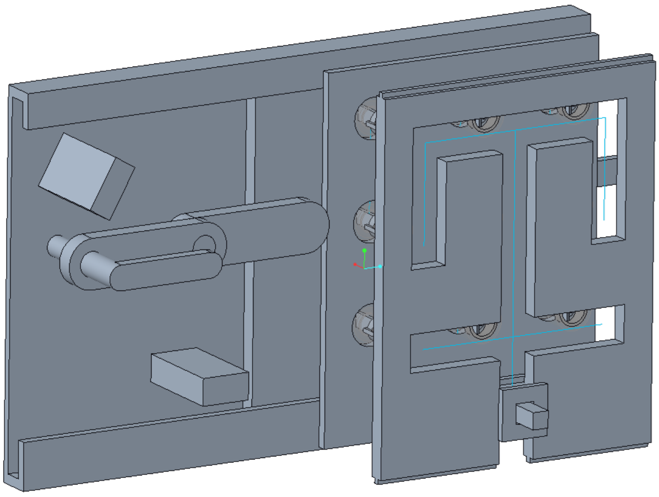


Figura - 3 - Vista frontal del montaje en CAD

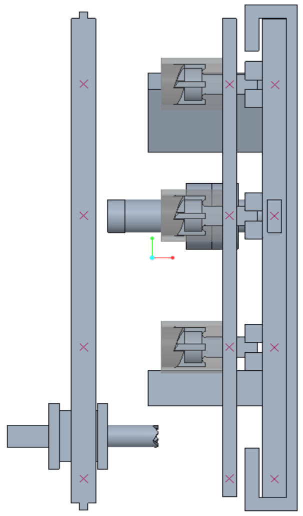


Figura - 4 - Vista lateral del montaje en CAD

Como muestran las figuras, esta iteración consiste en un botón que se desliza por la placa frontal, y que puede presionarse en nueve puntos diferentes, dependiendo de la combinación del dueño. El mecanismo interno de estos nueve puntos es exactamente el mismo. Como muestra la Figura 5, cada uno tiene un émbolo fijo con cuatro dientes y un cuerpo de leva que rota y desliza ligeramente hacia arriba y abajo, siguiendo el desnivel entre los dientes del émbolo. Inicialmente, ambas partes están en contacto y, cuando se pulsa el botón, sus dientes encajan con la parte superior del cuerpo de leva y lo empuja hacia abajo, comprimiendo un muelle ubicado en el pasador que sobresale del cuerpo de leva. Justo cuando el cuerpo de leva pasa el desnivel de un diente a otro del émbolo, el pasador gira.

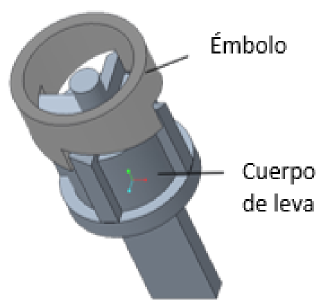


Figura - 5 - Mecanismo interno de PenLock

Por tanto, este mecanismo consigue rotar los pasadores con el fin de que todos estén orientados horizontalmente. Así, cuando la placa que tiene acoplada el cerrojo de seguridad se desliza, todos los pasadores encajan en sus respectivos huecos. Si no están correctamente orientados, es decir, que el patrón es incorrecto, los pasadores impiden el funcionamiento del sistema de bloqueo y desbloqueo.

La limitación de este diseño es que no hay muchas combinaciones posibles lo que hace que sea fácil de descifrar. Como los pasadores son simétricos y solo se necesitan cuatro clics para completar una rotación, únicamente hay dos posiciones distintas: horizontal y vertical.

Con el fin de probar la idea de producto, se imprimieron en 3D las partes y, después de detectar algunos problemas, se volvieron a imprimir con algunas modificaciones, consiguiendo un mejor resultado. Sin embargo, a pesar de los cambios, la rotación seguía sin ser suave, así que se realizó un análisis de 'Diseño de Experimentos' (DOE) para determinar cómo afectaba el diseño del émbolo al funcionamiento del mecanismo.

Durante este estudio, la variable a optimizar fue el tiempo que el cuerpo de leva tarda en completar una rotación. Se ajustaron tres variables: el ángulo de la inclinación de los dientes del émbolo, su diámetro exterior, y su número de dientes. Como cada variable era examinada en dos niveles, alto y bajo, se tuvieron que realizar ocho pruebas diferentes. Finalmente, se llegó al diseño de émbolo que conseguía minimizar el tiempo y, por tanto, el funcionamiento del mecanismo y la experiencia del cliente.

Resultados

Finalmente, tras el análisis DOE y cuatro iteraciones, el diseño del prototipo final fue creado. Aunque se realizaron algunas mejoras y modificaciones en el diseño, el funcionamiento del mecanismo es el mismo que el presentado en la iteración anterior. La Figura 6 ilustra el nuevo diseño en 3D.

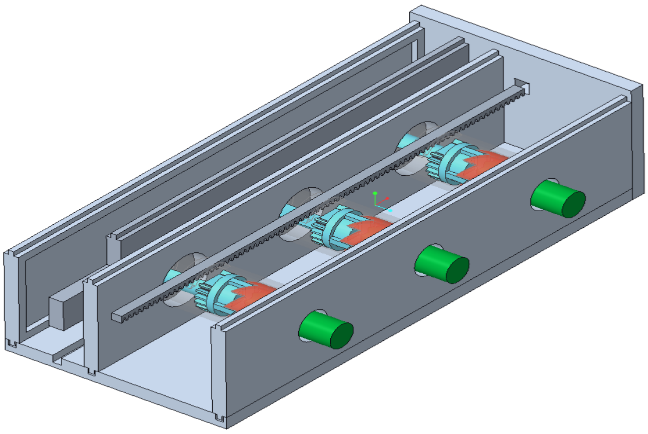


Figura - 6 - Vista detallada del interior del prototipo final

En este nuevo diseño, el botón deslizante de la cuarta iteración fue reemplazado por tres botones individuales. Además, se incorporó un mecanismo de reinicio para poder rotar los pasadores a su orientación original. Consistía en un sistema de piñón y cremallera en el cual el piñón está fijo a la parte superior del pasador. Tal y como muestra la Figura 7, tiene una sección sin dientes para permitir que el pasador deje de girar llegada esa zona del piñón.

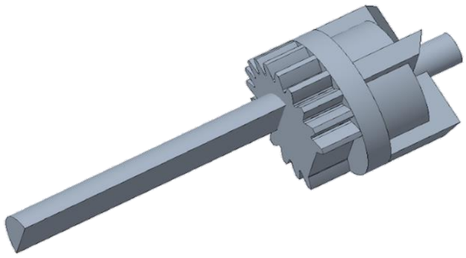


Figura - 7 - Montaje del árbol de leva, el piñón y el pasador

Por otra parte, como se muestra en la figura anterior, la forma rectangular del pasador fue sustituida por una forma semicircular, y, en lugar de ubicarlo en el centro del cuerpo de leva, fue desplazado ligeramente hacia el exterior, permitiendo que la pieza no fuera simétrica. Así, el pasador tendría una orientación completamente diferente para cada rotación,

Asimismo, como ilustra la Figura 8, el diámetro y la inclinación de los dientes del émbolo fueron modificados según los resultados del análisis Además, con el objetivo de garantizar una mayor seguridad, el émbolo con ocho dientes fue considerado el mejor ya que permitía ocho orientaciones diferentes de los pasadores.

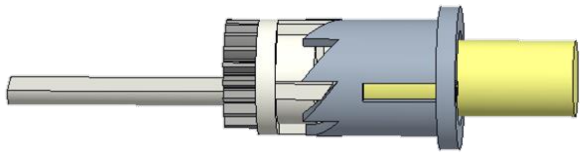


Figura - 8 - Montaje del mecanismo completo

Con respecto al funcionamiento de la cerradura, la Figura 11 ilustra los pasos necesarios para bloquear la puerta con este nuevo diseño. Inicialmente, la puerta está desbloqueada y los pasadores están en sus orientaciones originales. Así, los pasadores están bloqueando la placa que lleva unido el cerrojo, impidiendo que se deslice. Después, la combinación es introducida. Una vez que todos los pasadores han girado de acuerdo con el número de veces que cada botón ha sido presionado, la placa de bloqueo puede deslizar encajando el cerrojo a la puerta ya que los pasadores no interfieren su camino. Finalmente, para asegurarse de que la puerta está adecuadamente cerrada, los pasadores deben reorientarse a sus posiciones originales, bloqueando de nuevo la trayectoria del cerrojo.

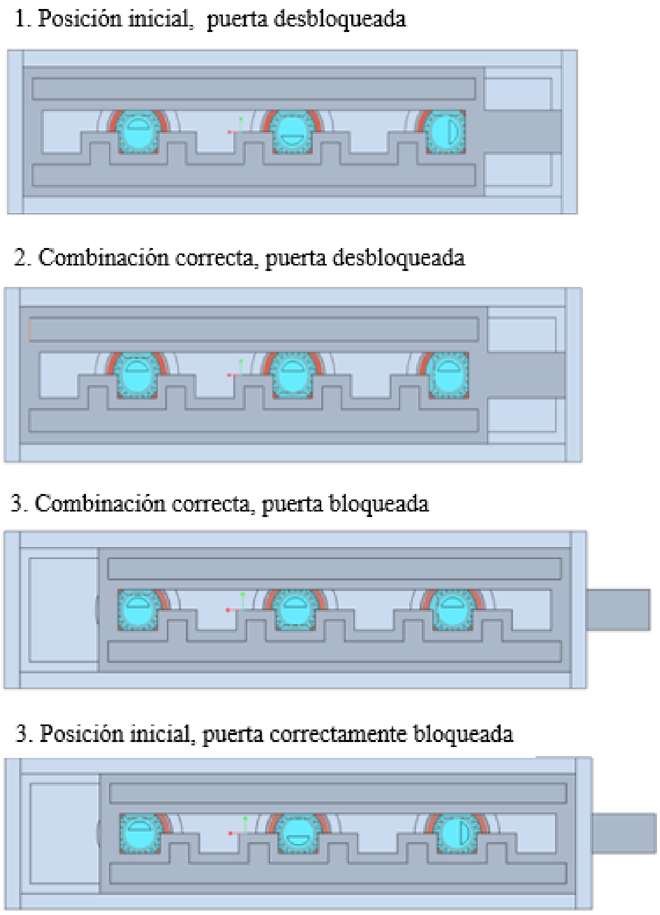


Figura - 9 - Pasos para bloquear la puerta

Con el fin de probar el funcionamiento del diseño, todas las partes que lo forman fueron impresas en 3D y unidas con cinta adhesiva y con pegamento. Dado que el montaje fue un proceso tedioso, se llevó a cabo un análisis de 'Diseño para el ensamblaje' (DFA) para mejorarlo y ahorrar tiempo. Se cronometró el tiempo que empleado en unir todas las piezas y se detectaron algunas dificultades en el proceso. Con este análisis se llegaron a concluir algunas recomendaciones para el futuro del diseño que tenían como fin aumentar la eficiencia del diseño. Sin embargo, debido a la planificación del proyecto, no hubo suficiente tiempo para implementar estas sugerencias.

Conclusión

Con el trascurso del proyecto y tras analizar cuatro iteraciones diferentes con sus puntos fuertes y limitaciones, se consiguió crear al prototipo final. Éste ha cumplido la mayoría de los objetivos establecidos, así como todos los requisitos del proyecto:

- Un diseño mecánico completamente innovador para una cerradura.
- Una cerradura sin llave cómoda de utilizar.
- Difícil de descifrar por el gran número de posibles combinaciones.
- Un patrón personalizable para cada usuario.

DESIGN AND MANUFACTURE OF A PATTERN LOCK

Introduction

The purpose of the present project is to develop a marketable product starting from a simple idea to solve a problem. After the ideation process, it was decided to focus the project on the design and manufacture of an innovative mechanical locking system.

First of all, in order to identify the market need, a background research was performed. Even though many mechanical locking systems exists, they have some limitations that compromise the security and the comfort of the user. The inside mechanisms and the vulnerabilities of existing locks were analyzed, specifically, the pin and tumbler lock, the combination lock, and the directional combination padlock.

The main aim of the product idea is to solve locks' vulnerabilities, which compromise the security and the comfort of the users. The evolution of the project has sought to accomplish the following goals:

- Make it impossible to crack or forge.
- Create a pattern as a key, a key that the user knows.
- Make it easy to install in all kind of doors and replace the current door locks.
- Make it easy to use and customize without the need of professional help.

Methodology

After determining the specifications for the design, the next stage was the prototype development, an iterative process in which an idea was designed, built and then, evaluated.

In order to develop the ideas and build the prototypes, two main resources were used: (i) Creo Parametric 3D Modeling Software to create CAD model of the parts, and (ii) Fused Deposition Modeling printers to 3D print them.

A 'Design of Experiments' test and a 'Design for Assembly' analysis were performed during the final stage of the project. Sais tests made possible to identify the main problems in the design or assembly of the prototype in order to improve them.

Initially the product idea was based on linear directional movements of a key. It was called CrossLock and it was designed with a common front plate where a certain pattern coupled with pushing the key unlocks the door. On the inside, there are different levels with paths for the key to slide, as well as a circular gap in a certain position to push the key to pass through to the next level. After all the levels are passed, user pushes the key and activates the lock and unlock mechanism. As the key is generic for all doors, the security is provided by the movements of the key, the pattern.

Overall, CrossLock combines the personal aspect of a combination lock with the practical safety of a key lock. Figures 1 and 2 show the sketches of the first and second design of this iteration. The first one has only two directional inputs, while the second one incorporates inputs in four directions.

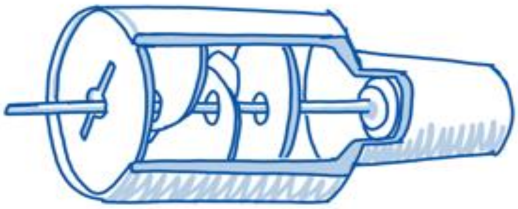


Figure - 1 - First design of CrossLock

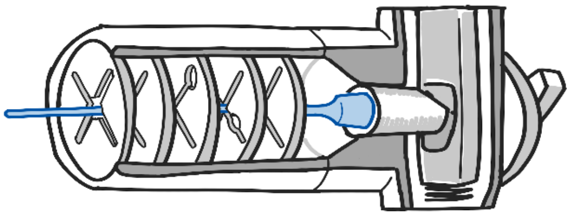


Figure - 2 - Second design of CrossLock

Even though this iteration provides a customizable sequence, it was considered too easy to crack and with a simple inside mechanism. Moreover, this design does not achieve the aim of a keyless lock.

For these reasons, it was decided to develop another idea that ended up becoming the second iteration of the prototype. In this case, the idea was based on rotational combinations instead of directional ones, so the pattern consists in rotating two wheel to certain positions. In this way, this system achieved the aim of design a keyless lock. However, the mechanism was considered similar to the one in combination locks and really difficult to reset.

Therefore, moving on the project, some researches were required to think about new ideas. A mechanism that translates linear motion into rotational motion was the next goal. Thus, retractable pen mechanisms were considered and tested.

The third iteration was designed too simple, only to test the idea of using pen mechanisms for the locking system. In this product idea, the pattern was based on clicking certain pens to release the locking plate and be able to lock or unlock. However, it was noticed that the in and out outputs caused by the inside mechanism of the pens were not a good option for a locking mechanism. Hence, this idea was discarded.

Based on this consideration, retractable pen mechanisms were analyzed in more detail in order to find a way to substitute the in and out outputs with rotational outputs. Then, the fourth iteration, PenLock, was designed. Figures 3 and 4 illustrate its complete CAD assembly.

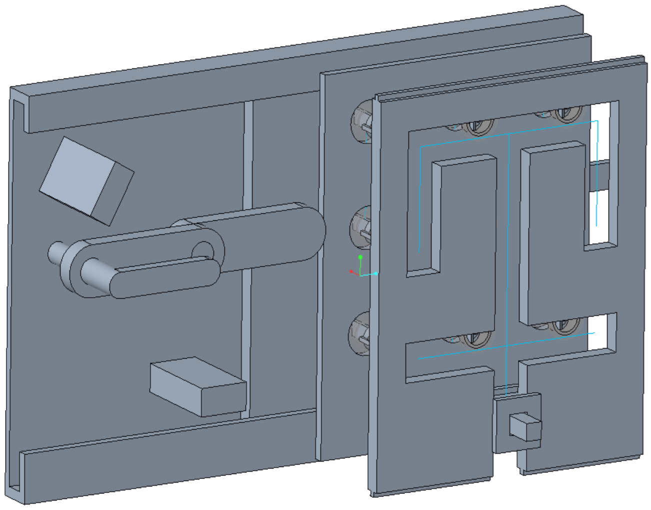


Figure - 3 – Front view of PenLock

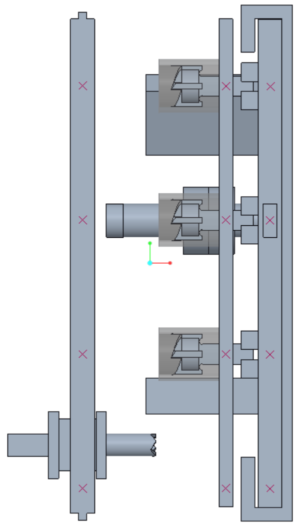


Figure - 4 - Side view of PenLock

As it is shown above, this iteration consists of a button that can be slid through the paths of the faceplate and it can be pressed down in nine different points, depending on the combination of the user. The inside mechanism of this nine points is exactly the same, as Figure 5 shows, each of them has a fixed cam shaft and a cam pin that rotates and slides up and down. In addition, it has a spring placed in the extrusion of the cam pin. Initially, the cam pin and the cam shaft have their surfaces in contact. Then, when the button is pushed the cam pin is pushed downwards as well, compressing the spring. Just in the moment when the ridges of the cam body clear the cam shaft, the slope of the next ridge makes the cam pin to rotate.

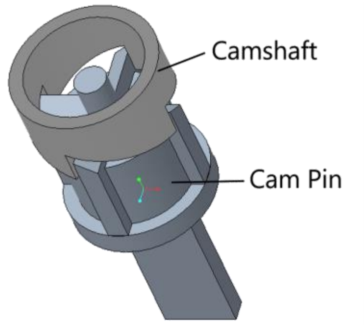


Figure - 5 - Cam mechanism

Therefore, the aim is to rotate the pins in order to have all the pins oriented horizontally. In this way, when the deadbolt plate is slid to lock or unlock, all the pins fit in their respective gaps between the two walls. If they are not properly oriented so the combination is not correct, they interfere with the locking mechanism.

Despite of the complex inside mechanism, there are not many possible combinations. As the pin is symmetric and only four clicks are required to complete a rotation of 360º, there are only two different positions of the pin: horizontal and vertical.

In order to test the idea, the parts were 3D printed and, after analyzing some problems of the design, they were printed again, achieving a better performance. However, the rotation was not smooth as expected and a 'Design of Experiments' test was accomplished in order to analyze the effect of the design of the cam shaft.

During this analysis, the optimized variable was the time that the cam pin takes to make a full rotation. Three variables were adjusted: the angle of the teeth's slope on the cam shaft, its outer diameter, and the number of teeth. Since each variable was examined in two levels, low and high, 8 tests were performed. Finally, the design of the cam shaft that minimizes the time and so that improves the user experience and the operation of the lock, was concluded.´

Results

Finally, after the DOE test and four iterations, the final prototype was developed. Even though some modifications in the design were performed, the operation of the inside mechanism is the same as in the previous iteration. The new CAD model of the prototype is illustrated in Figure 6.

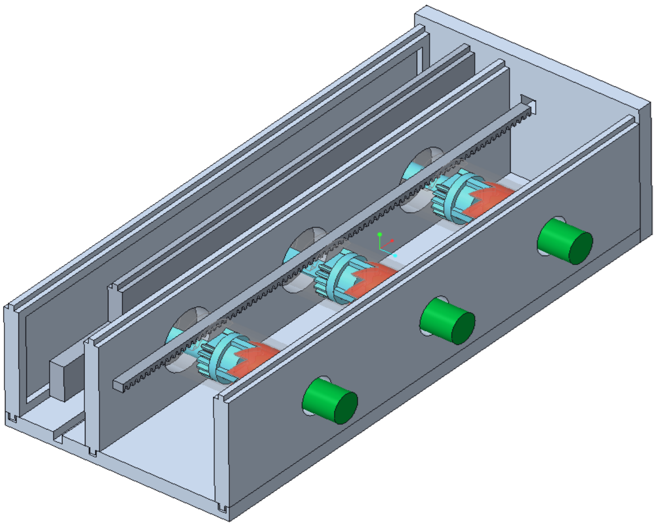


Figure - 6 - Inside view of the final prototype

As it is shown above, the sliding key is replaced with 3 clicking buttons. Moreover, a reset mechanism was incorporate in order to rotate the pins to their original orientation. It is based on a rack and pinion system, in which the pinion is attached to the top of the pin. As Figure 7 illustrates, some teeth of the pinion are removed to allow the pin to stop rotating when it is in the original orientation.

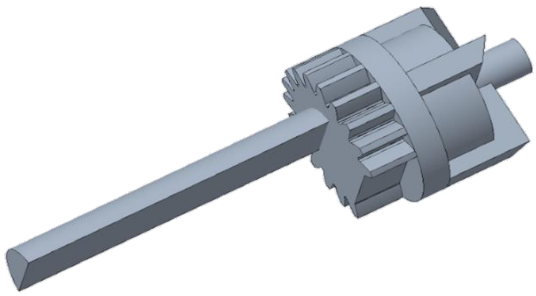


Figure - 7 - Cam pin and pinion assembly

Moreover, shown in the figure above, the rectangular shape of the pin was substituted for a semicircular shape and it was not placed right in the center of the cam body, making the part asymmetric. Thus, this new shape allowed the cam pin to have a completely different orientation for each small rotation.

Additionally, as Figure 8 illustrates, the cam shaft diameter and its teeth's slope were modified based on the DOE results. With the aim of increase the security, the 8 teeth design was selected since this design allowed 8 different orientations for the pins.

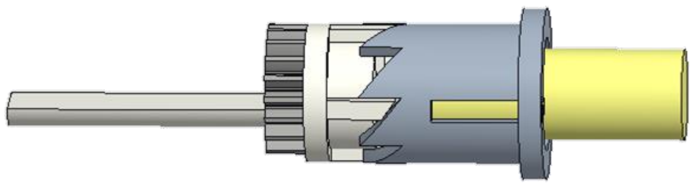


Figure - 8 - Cam mechanism assembly

Regarding the operation of the lock, Figure 9 displays the steps required to lock the door. First, it is unlocked and the cam pins are in their original orientations. Thus, they are blocking the deadbolt plate and it cannot slide. Secondly, the combination has to be entered. Once the pins has rotated according with the number of clicks, the deadbolt plate is able to slide since the pins are not interfering its way. Finally, the pins have to be reset by sliding the rack through the hole of the cam cover until it stops by itself. Since they are in their initial orientations, the deadbolt is blocked and the door is locked properly.

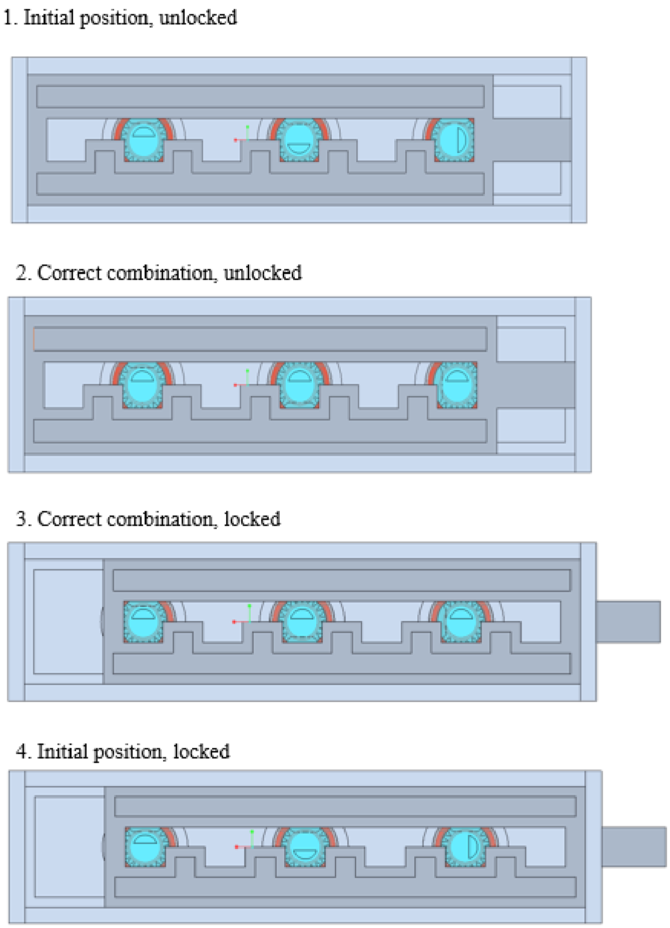


Figure - 9 - Steps to lock the door

All the parts were 3D printed and they were assembled. Since the assembly was a really tedious process, a 'Design for assembly' analysis was performed in order to improve it and save time. The time was measured and some difficulties were noticed. The DFA test allowed to conclude some recommendations for the future of the design in order to increase the design efficiency. However, due to the schedule of the project, there was not enough time to implement these suggestions

Conclusion

As the project moved forward and after analyzing strengths and limitations of four iterations, the final prototype was achieved. It fulfills most of the established requirements as well as all the prerequisites of the project:

- An innovative mechanical design for a lock
- A keyless lock, comfortable to use.
- Difficult to crack due to the wide range of possible combinations.
- A customizable pattern for each user.

INDEX

1. INTRODUCTION

The present project has been focused to develop a novel product idea into a marketable product. Figure 1 illustrates the iterative process that has been followed: first an ideation stage to research and create a rough design of the idea, and then, a prototype development stage in which the design was built and evaluated as many times as needed.

The design required to be new, with two mechanical or moving components, with some assembly needed and one innovative aspect to be iteratively optimized. Due to this prerequisites of the project, during the ideation stage, the design and manufacture of a new locking mechanism was considered the most suitable product idea to be developed.

The project has sought to achieve a lock able to provide a great commitment to safety and comfort, but different from the current ones. Locks allow to be secure and protected, and to keep items safe as well. They consist in a fastening device that is released by a key or by a secret pattern or combination that protect doors, barriers and safes from being opened. Although there have been many improvements since the first mechanical lock was designed years ago in Ancient Egypt, many limitations still exist and many techniques that threaten the security have been discovered.

Therefore, the main purpose of the present project has been to create a new secure and reliable solution. Once the problem was identified, the next stages were: the background research in existing products, the design of a product that solves the weaknesses found in everyday locks, the evaluation of the design and manufacturing trade-offs, the analysis of manufacturing processes; and, finally, the building of a rapid prototype of the design. These stages were repeated until the final prototype of the idea was accomplished, a design that fulfilled the aims of the project.

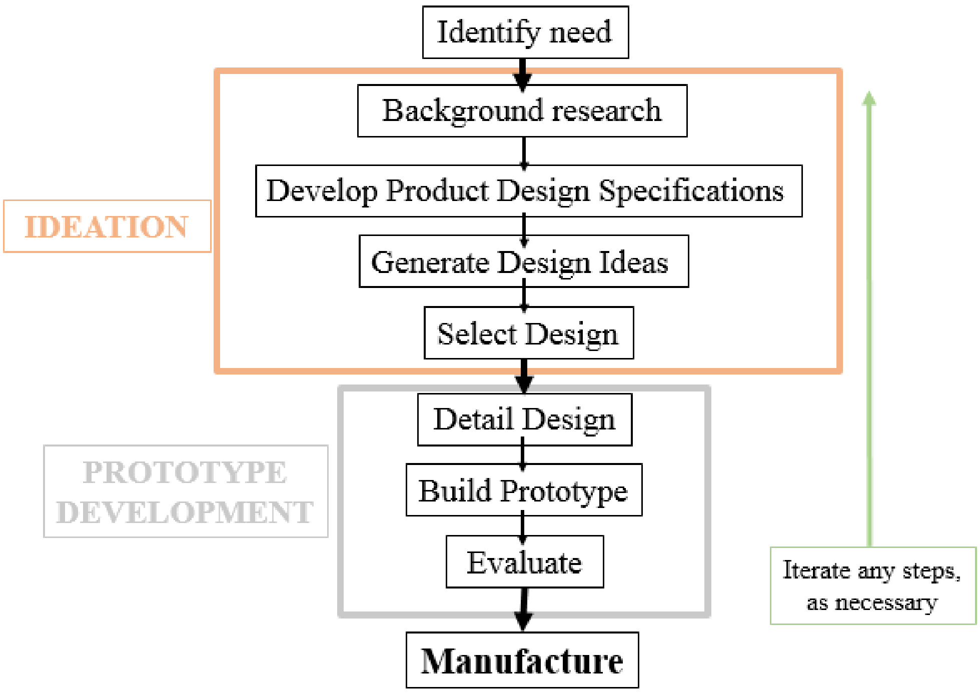


Figure 1. Stages of the design process

2. IDEATION

2.1. BRAINSTORMING

Ideation is the creative and first stage of generating, developing, and communicating new ideas. The beginning stage of the project was the brainstorming, the primary method of ideation. It consists in a free-flowing of ideas to solve a problem by improving an existing product or creating something completely new.

The product idea had to be developed by meeting three requirements: a new design with two mechanical or moving components in it, some assembly needed and one original aspect to be iteratively optimized. During this stage of the projects, four products ideas with its sketches and descriptions were suggested: (i) a banana peeler, (ii) an eraser, (iii) a pattern lock; and (iv) a clothes folder.

(i) Banana Peeler (Figure 2):

- One handed banana peeler.
- Pushing the banana through splits the peel along the wedges.
- The slicer can be driven forward incrementally to slice the banana up.

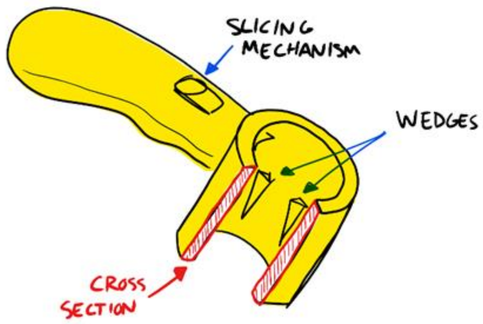


Figure 2. Sketch of the banana peeler

(ii) Eraser (Figure 3):

- A mechanical arm attached to a whiteboard or flat surface.
- A hand crank on the base moves the erasing arm in a repeated motion.
- The whiteboard is cleaned fully with minimal effort by the user.

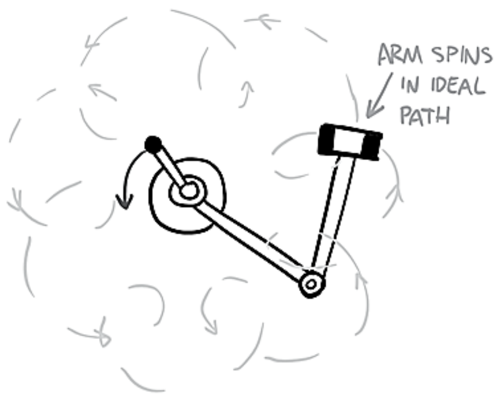


Figure 3. Sketch of the eraser

(iii) CrossLock (Figure 4):

- New mechanical design for a door lock.
- It has a front where a certain pattern coupled with pushing the key unlocks the door.
- Lock has levels corresponding to each motion and push of the key.
- Only a generic and light key is required.
- After all the levels are passed user pushes the key in the center activating the mechanical lock and unlock mechanism.

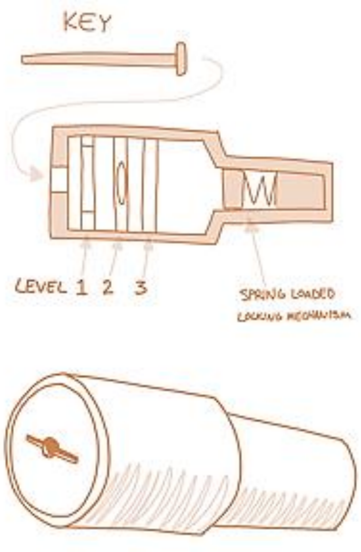


Figure 4. Sketch of the door lock

(iv) Clothes Folder (Figure 5):

- Able to iron and then fold clothes.
- Placed on a table with small holes that expel steam in order to eliminate wrinkles.
- Mechanism that rotates the side plates to fold any kind of clothing

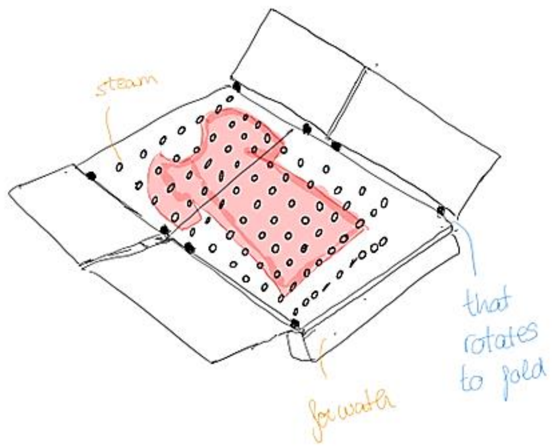


Figure 5. Sketch of the clothes folder

Analyzing the critical aspects and the possibility to improve these ideas, CrossLock was considered the most convenient product idea to develop into a marketable product. Furthermore, it met the initial requirements for the project. The mechanism of the banana peeler was analyzed as too simple, as well as the eraser, and the clothes folder already existed.

a. SWOT ANALYSIS

Strengths, weaknesses, opportunities, and threats analysis allows to examine deeper a product idea in order to evaluate it and develop a plan to improve it. It consists in defining:

- Strengths, the biggest advantages,
- weaknesses, the possible failures,
- opportunities, the problems that it solves,
- and threats, the biggest challenges to overcome.

The SWOT analysis performed on the initial design selected for the project, CrossLock, is listed in Table 1.

Strengths	Weaknesses
- Difficult to forge. - Cheaper than an electric lock. - Light key to carry around.	- Difficult to ensure a maximum thickness to the whole lock. - After many attempts, the pattern could be hacked. - People could lose the lighter key.
Opportunities	**Threats**
- The different levels could be used with different orientations to create a variety of patterns. - It could be normed and reduced threat.	- Making sure the material and size of the key to make it light to carry around, but still sturdy enough to unlock the mechanism. - Size and thickness of the door lock to easily replace a classical lock.

Table 1. SWOT analysis of CrossLock

b. DESIGN TREE ANALYSIS

A design tree analysis of a product idea allows to propose solutions to overcome the problem addressed. The central point of the tree presents the core problem which, in this case, is the impracticality of keys in locking systems as Figure 6 illustrates. On the bottom branches, primary and secondary causes are described. On the top of the tree, the solution to minimize the problem is presented with some specifications and requirements in the sub-brunches.

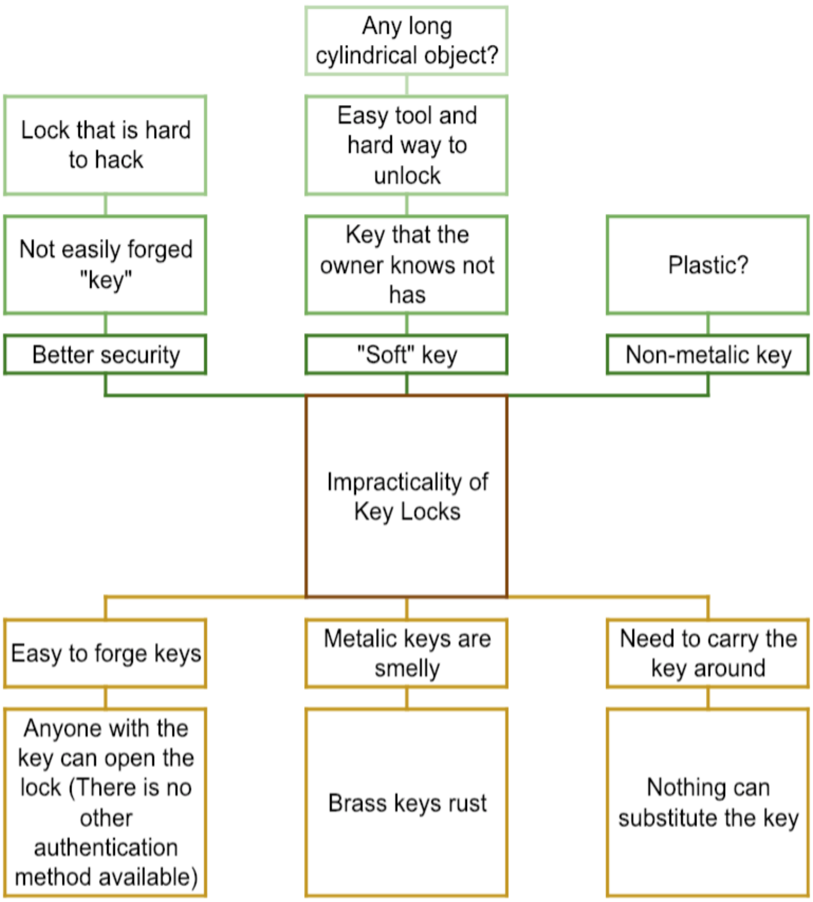


Figure 6. Design tree analysis

2.2. BACKGROUND RESEARCH

To explore the products that have already been developed, a research into existing mechanical locks was accomplished before the new design. Their vulnerabilities allowed to establish the main aims of the project in order to ensure a high degree of quality and security. Since the first lock was designed thousands years ago, many varieties have been created, all focused in the same aim of keeping items safe or restricting access to something by using keys or combinations. The pin tumbler lock, the combination lock and the directional combination padlock were the three products analyzed.

i. Pin tumbler lock

The pin tumbler lock is one of the most common lock mechanisms for doors, in which the security is provided by a unique shape of a key. As Figure 7 illustrates, it is composed of an outside part called the shell and an inside part called the plug which rotates. The plug consists of a straight-shaped slot known keyway at one end, and a cam that retracts the locking bolt to open the door at the other end. There are several vertical shafts that go through the case and the plug, called the pin chambers. They are a set of spring-loaded assemblage with pins of different lengths to prevent the lock from opening without the correct key. Each one consists of two pins that are placed one above the other: the key pin, which touches the key, and the driver pin, which touches the spring. For the plug to turn, the gaps between the key pins and driver pins must align with the shear line.

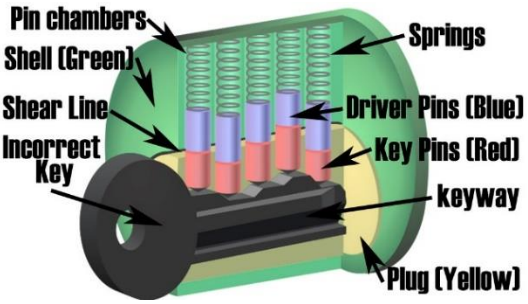


Figure 7. Parts of a pin tumbler lock [Source: https://3dprint.com/76671/3d-printed-pin-tumbler-lock]

The inside mechanism is shown in Figure 8 in three different situations. In the first one, when there is no key in the lock, the driver pins are pushed down into the plug by the springs, preventing the plug from rotating. In the second case in which an incorrect key is inserted, the key pins and driver pins are not aligned with the shear line and therefore, the plug cannot rotate. Finally, the third and fourth pictures illustrate the case in which the correct key is inserted. The gaps between the pins are aligned with the shear line and, consequently, the plug can rotate freely.

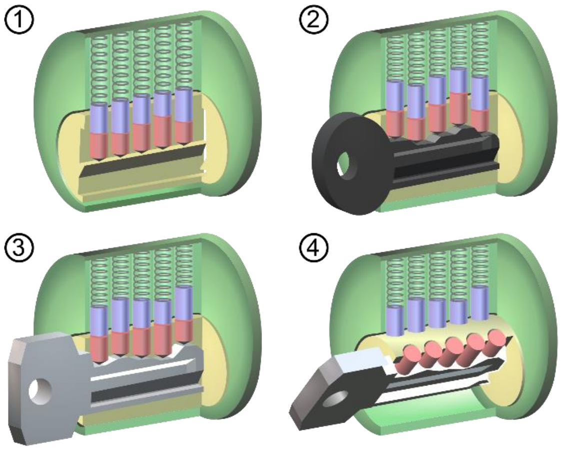


Figure 8. Pin tumbler lock diagram [Source: https://3dprint.com/76671/3d-printed-pin-tumbler-lock]

Generally simpler locks have only one correct key, however, there are master keyed locks which require multi-keyed entry: their own key and the master key. In these cases, an extra pin called spacer pin is incorporated in at least one shaft. It adds a different shear point so that both keys are able to align the pins with a shear line to rotate the plug.

Although pin tumbler pins locks are considered high security mechanisms, there are some techniques that compromise the security by unlocking the door without the correct key and without breaking it. The basic pin tumbler lock is vulnerable to lock picking methods, which manipulate the lock to unlock it. Lock bumping is the most common one. It only requires a bump key of the appropriate size of the door lock. Each ridge of this key is cut to maximum depth so, when it is inserted and bumped with a mallet or a screwdriver, the pins in the lock are forced to the shear line as the key rotates the plug.

Additionally, a snap gun can be used to open a pin tumbler lock without the original key. A steel rod is inserted into the keyway and then, the snap gun fires the rod against all the key pins at the same time, briefly releasing the plug and making possible to turn it with a tension wrench. This technique damage more likely the mechanism.

ii. Combination lock

Combination lock is a locking mechanism in which a sequence of symbols is used to unlock, instead of a key. It can be customized within a very large range of possible combinations. There are two common types: multiple-dial (Figure 9.a) and single-dial locks (Figure 9.b). The first ones are the least secure because they can be quickly opened without the combination. For each symbol, there is a rotating disc with a notch cut into it. The security is guaranteed by a pin with different teeth on it which grab into the discs. When the correct combination is dialed, the teeth of the pins and the notches are aligned and the lock can be opened.

Figure 9.a. Multiple-dial lock [Source: CH-24H Multiple Dial Lock With Combination]

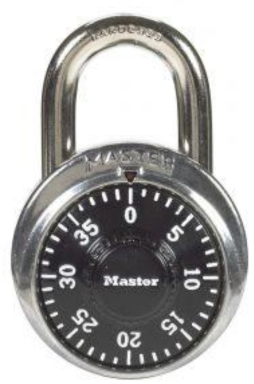


Figure 9.b. Simple-dial lock [Source: Master Lock 1500D Dial Combination Padlock]

However, single-dial locks works in a slightly different way. As Figure 10 shows, a single combination dial is connected to several parallel discs, called cams, through a spindle. The very last wheel is called the drive cam and it has attached a drive pin. When the cam rotates, the drive pin touches a small tab in the next disc, called wheel fly. Therefore, the drive pin turns the first disc until it makes contact with the adjacent wheel and the process is repeated until the combination is finished and all the discs have spun.

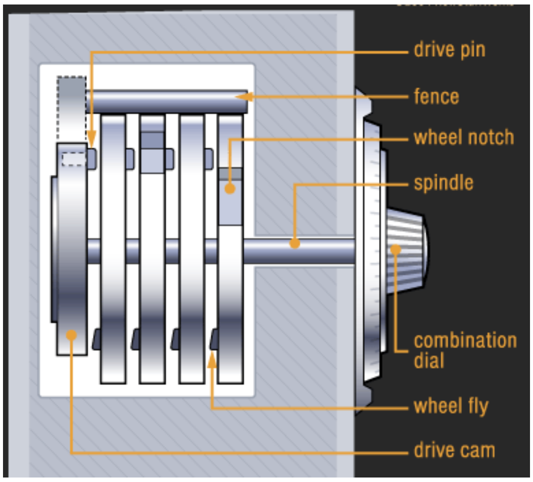


Figure 10. Parts of a single-dial lock [Source: Robert Valdes, https://home.howstuffworks.com/home-improvement/household-safety/combination-lock.htm]

As Figure 11 illustrates and, based on the same idea of multiple-dial locks, each wheel has a notch cut into it and the wheels and the notches are lined up perfectly when the combination is finished, creating a gap. Under the force of its own weight, the fence, a small bar attached to a lever, falls into the gap allowing the lock to be opened. This fence provides the security when the combination has not been dialed or it is not correct, as it rests on the wheels, blocking the path of the bolt.

Figure 11. Inside mechanism of a single-dial lock [Source: Matthias Wandel (20th April 2008), Wooden combination lock (video file)]

The combination lock, commonly in safes or padlocks, are easy to use. It is simple to restart if a wrong input is entered. However, one vulnerability is that they are easy to crack, for example, by listening the inside mechanism while the combination wheel is spinning.

iii. Directional Combination Padlock

Directional Combination Padlock is a portable and speed dial lock, composed of a latch mechanism of metal called shackle, and a locking mechanism. It allows to customize a personal combination based on four directional movements: up, down, right and left. The combination can repeat a movement and it can be of any length. Before opening it, the shackle has to be squeezed toward the lock twice and release. After this, the combination can be entered by sliding the button to each position in the combination pattern and then, the lock can be opened.

Inside the lock, there is a wheel in each direction as it is illustrated in Figure 12. Inputs in any direction will spin the wheel that is in that way. There are cogs between the wheels that rotate counterclockwise and fit into the grooves in the wheels. In addition, the wheels have gaps in a certain point and little paddles on one side of each wheel. The way it works is when the correct combination is dialed and the shackle is pulled up, a connected mechanism slide the four paddles into the gap of each wheel.

Figure 12. Directional Combination Padlock [Source: Master Lock 1500Id Speed Dial™ Combination Padlock]

The main weakness of the directional combination padlock is the comfort and the user experience. It is really hard to restart the unlock sequence over when one wrong input is made or a step of the combination is missed. At the same time, reviews of some customers reveals that the inside mechanism tends to break easily. However, regarding the security, it provides a high security mechanism, an anti-shim technology, a new latch assembly that avoid the shim tool to hit the shackle.

2.3.MANUFACTURING TECHNIQUES

During some practice sessions, three manufacturing techniques were analyzed in order to determine the most suitable one for the iterative process needed to develop the project. 3D printing, injection molding and machining were examined and tested in the laboratory. Their requirements and limitations were important factors in the decision.

a. 3D PRINTING

3D printing is a technique commonly used for rapid prototyping. It allows the quickly fabrication of a scale model of a physical part using a computer-aided design (CAD) file or a digital 3D model. It is an additive manufacturing process in which the part is created by adding successive layers of liquid or powered material. These layers, corresponding to the cross section of the designed model, are glued or fused automatically.

The main advantage of 3D printing is the unrestricted geometry of the design. The orientation of the digital model and the thickness of the layers are important factors, mainly for inclined and curved surfaces, to avoid the stair-case effect and, hence, to achieve a better printed part. Furthermore, it is cheaper compared to labor costs and manufacturing costs in conventional techniques.

In contrast, 3D printing has some disadvantages as well. The support material is one of them. It sustains the part by enabling overhanging geometries to be supported. The problem is that it needs to be removed carefully without damaging the part.

There are four main prototype methods using 3D printers: (i) Fused Deposition Modeling, (ii) Stereolithography, (iii) Selective Laser Sintering; and (iv) Multi-Jet Printing.

i. Fused Deposition Modeling

Fused Deposition Modeling or FDM technique, also called Fused Filament Fabrication, is based on the extrusion of a thermoplastic material layer by layer onto a build platform. Currently, it is the most popular due to its cost-effectiveness and accessibility. A variety of filament materials are extruded, including thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high-impact polystyrene (HIPS) or aliphatic polyamides (nylon). These materials provide stability of the mechanical properties over time, quality and durability of the parts. Therefore, this method is suitable for functional parts and durable manufacturing tools. Moreover, the support material is created where needed and it is built in a water soluble material in order to not endanger the part during the removal process.

However, FDM technique has several disadvantages. It has the lowest dimensional accuracy and resolution compared to other 3D printing technologies, hence, it is not suitable for parts with intricate details.

ii. Stereolithography

Stereolithography or SLA is a 3D printing process that selectively cures a photo-sensitive resin layer-by-layer using an ultraviolet laser beam. It can produce parts with very high dimensional accuracy and with intricate details, and parts with very smooth surface finish. Therefore, it is ideal for visual prototypes and for assemblies requiring precision.

Nevertheless, parts are generally brittle and nonfunctional, the mechanical properties and visual appearance degrade overtime with the sunlight, and the required post-processing is tedious involving manual removal with scalpels and hand sanding. Moreover, regarding the build time, it takes a long time to build in the vertical direction due to curing step, in which the base must move down to allow fresh resin to cover the surface.

iii. Selective Laser Sintering

Selective Laser Sintering or SLS is a process in which a laser selectively sinters the particles of a polymer powder, fusing them together and building a part layer-by-layer. The main difference and advantage of this method is that support structure is not required, therefore, detailed small parts can be made and not damaged in the post-processing. Besides, printed parts have good isotropic mechanical properties, making them convenient for functional prototypes.

Despite these advantages, parts printed with this technique have a grainy surface finish and internal porosity that may require post-processing. In addition, large flat surfaces and small holes are susceptible to warping.

iv. Multi-Jet Printing

Multi-Jet Printing (MJP) is considered a combination of FDM and SLA in one machine. The print head deposits droplets of material which are instantly cured by UV light. It is able to model extremely smooth and precise parts with highly complex geometries at a relatively low printer cost and at a fast build time. However, although it uses water soluble support materials, they do not dissolve easily in an ultrasonic bath and they require to be removed by high-pressure water jets.

b. MACHINING

Machining is a type of material removal process in which a cutting tool discards unwanted material from a workpiece in order to produce the desired shape. It is considered a common and versatile manufacturing process because, although machined parts are typically metal, almost all materials can be machined. However, as a removal process, it is not the most cost-effective technique since material is cut away.

Machining includes a variety of processes. The most common ones are those that remove the material by mechanically using a sharp tool. This process follows three different steps. First, the roughing, which consists in making the general pattern by removing large amounts of material without giving the part too much detail. This step uses tools with larger diameter. Then, the following step is the re-roughing, when smaller features are created within the general pattern. And, finally, the finishing that allows to create better surface finish and exact geometry. A smaller diameter tool is used for re-roughing and finishing.

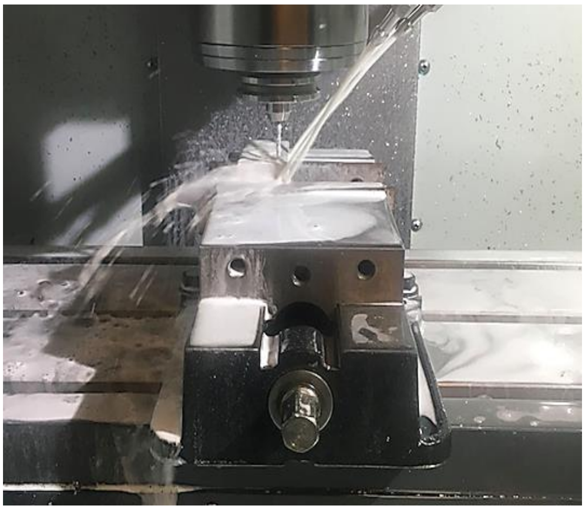


Figure 13. Machining process

Before the machining process starts, the part needs to be designed by using a 3D modeling software. In order to determine what material needs to be removed, it is required to set a workpiece, the blank block, and a reference model, the CAD file. The datum plane which is the plane where the cutting tool returns after completing each step of machining needs to be set as well.

Moreover, the design must be within the mill window which defines the area where the tool will machine. Extended area of the mill window on the gate side ensure that the tool will approach the blank from the side to machine the sprue runner gates.

The code that will guide the CNC (Computer Numerical Control) mill is called G-Code. It consists of a variety of commands that specify the geometric and kinematic properties of the machine and tool path in order to machine the desired part. Computer-Aided Manufacturing (CAM) allows the code to be automatically and rapidly generated based on a few machining parameters that have to be predefined in the software, they are:

- Spindle speed, the angular speed with which the tool rotates about its axis.
- Cut feed, the speed at which the cutter will move horizontally.
- Maximum step depth, the vertical depth of cut for each layer.
- Step over, the offset distance between toolpaths that should be lower than the radius of the tool.
- Clear distance, the distance between the cutter and the top face of the part at the very start of the cutting.
- Tool.

By defining this parameters, an appropriate path is automatically generated by the 3D modeling software and the G-code can be created.

Laboratory test

During a laboratory session, the machining process was tested with a given workpiece. An aluminum rectangular block was machining by using a Tormach 3-axis CNC mill. Table 2 lists the input parameters for each step of the machining process of the part.

	Roughing	Re-Roughing	Finishing
Tool	End Mill Ø 6,35 mm	Ball Mill Ø 3,175 mm	Ball Mill Ø 3,175 mm
Cut Feed (mm/s)	4,23	3,81	6,35
Max Step Depth (mm)	2,286	1,27	-
Step-Over (mm)	2,54	1,27	1,27
Spindle Speed (rpm)	4000	4000	4000

Table 2. Tool path specifications

The designed part was the mold for a simple rectangular plate with a series of rounded extrusions in the center. As Figure 14 illustrates, it looked similar to some sort of LEGO brick.

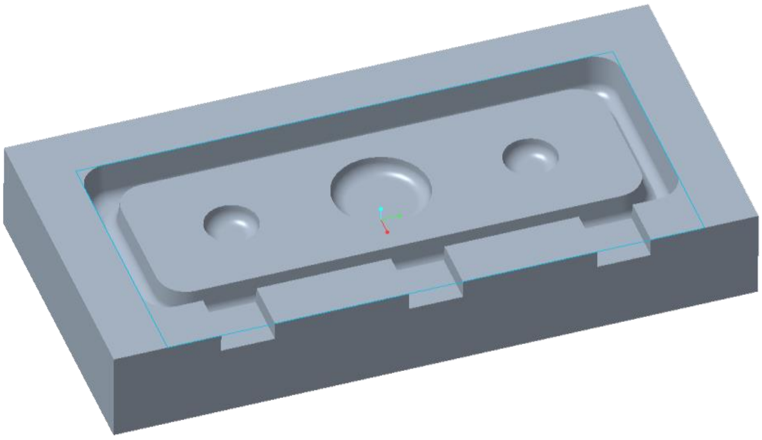


Figure 14. CAD model

The design constraints included:

- No undercuts.
- Side walls with a draft angle greater than or equal to 2°.
- Interior cuts greater than 0,125” (3,175 mm).
- Rounded interior corners with a radius greater than or equal to 0,0625” (1,5875 mm).
- The part mold had to fit within the milling window.

The interior corner constraint forced to change the design from sharp to round corners. In addition, the furthest cut also had to fit within the minimum diameter, therefore, it had to be widened. Each wall was designed to have a draft angle rather than straight walls.

One of the differences between the CAD model and the final part was that the finish on the surface was very rough and had grooves as it is shown in Figures 15, 16, and 17. This happened because a ball mill was used for finishing, thus, it could have been avoided by using an end mill instead.

Figure 15. Picture of milled part

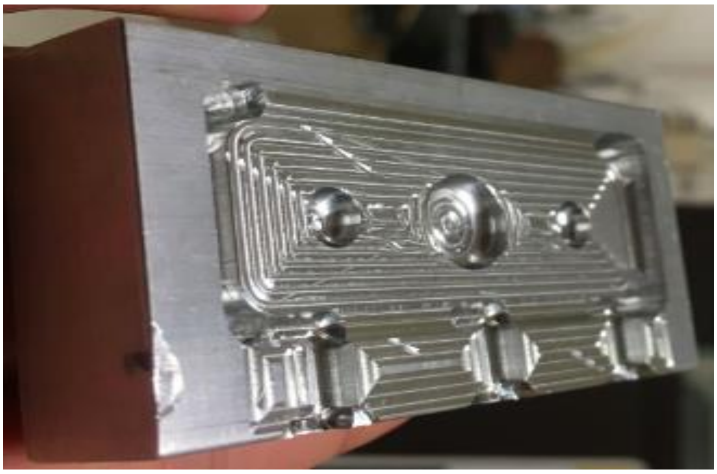


Figure 16. Picture of incomplete channel of the milled part

Figure 17. Picture of milled part

Additionally, the channel in the CAD model did not completely mill out as it is demonstrated comparing Figure 14 and Figure 16. This may have happened because the diameter of the mill was too large for the channel. It was very close to the minimum necessary width of the channel but perhaps because of tolerance issues it was not able to mill it out. If the design had been slightly larger, the channel would have been milled out properly. This also could be avoided by using a slightly smaller tool.

In order to reduce machining time for the design, there are some factors that could be modified. The draft angles could be redesigned as smaller angles so less layer of the model needs to be removed. Less layer also would lead to less machine movement, thus reducing the machining time. However, the draft angle should be greater than the minimum constraint, which was 2 degrees in this case.

Reducing the draft angle below the limit would make the draft angle meaningless as it will be hard to take the part out from the machined mold.

Furthermore, reducing the depth of the different extrusions would decrease the machining time since it would need less layers and thus, less machine movement. Also reducing the difference between the depth of the deepest (6,35 mm) and the highest extrusion of the part (1,778 mm) would lead to a shorter machining time as well.

Another factor that could reduce the machining time is setting the radius of the eight internal corners to be equal. The symmetry of the part could simplify the path of the tool, reducing the machining time without involving negative effects in the design.

In conclusion, when designing a part that is intended to be milled it is important to account for any existing tooling or milling window constraints, along with being aware of the machine's capabilities. With this in mind, the design must be adjusted accordingly in order to avoid unexpected results and long machining time.

c. INJECTION MOLDING

Injection molding is a manufacturing technique in which solid resin, usually plastic in the form of pellets, is fed out the hopper and melted in the injection unit of the injection molding machine. Then, it is forced into the injection mold by a nozzle. While it is in the mold in the cooling stage, the plasticizing unit melts resin to use in the next part. Finally, the part can be carefully ejected from the mold.

Two kind of plastics are used: thermoplastics, soft at high temperatures and harden once cooled even when the process is repeated; and thermosets, with a permanent shape after heat and pressure are applied.

Regarding the design stage of the mold, there are some factors to account for: warping, shrinkage, and residual and concentrated stresses. Shrinkage depends more on the material selected than on the design due to the stability of the plastic after aging. Designing an adequate cooling stage and a proper gate size and location can decrease the probability of shrinkage, ensuring accurate tolerances in the part. Moreover, avoiding sharp corners decreases stress concentrations due to the decrease of the tool wear and the decay of the mechanical properties. Another factor, warping, can be caused by differential shrinkage as well as by differential cooling; while residual stresses are resulted by changes in volume of shape in the designed part, or by non-uniform heating or cooling processes.

Laboratory test

In some laboratory sessions, analytical and experimental perspectives of injection molding were examined. Two parts were tested: a part corresponding to the mold created in advance by machining and a given spiral-shaped part.

MoldFlow simulation software, an Autodesk Mold Adviser, was used to analyze and simulate the injection molding process. It is a tool that provides manufacturability feedback at an early stage of design. This allows to change process parameters as well as mold design, in order to improve the outcome of the final part.

During the test in the Mini-Jector machine (Figure 18), the material used was a low-density polyethylene (LDPE) and the melt temperature and the maximum machine injection pressure were set for each simulation.

Figure 18. Mini-Jector machine

Once the design is in MoldFlow software, it is able to display different simulations:

- Confidence of fill, the region within the cavity that is filled with plastic.
- Quality Prediction, the expected quality of the part's appearance and its mechanical properties.
- Fill Time, the flow path of the plastic.
- Pressure Drop, the drop in pressure from the injection point to a point when it is filled.
- Injection Pressure at the moment the part is filled.
- Flow Front Temperature, the material melt temperature when the part is filled.
- Weld line where the red lines indicate the presence of weld and meld lines in the model.
- Air traps where the blue spheres means regions where the melt stops at a convergence of two flow fronts.

In this laboratory, a spiral mold was simulated and analyzed for nine temperature-pressure combinations: 163ºC (436 K), 177ºC (450 K) and 190ºC (463K); at 31MPa, 39MPa and 47MPa. In addition, the mold created during the machining session was tested at a melt temperature of 463K and a maximum machine injection pressure 31MPa.

i. LEGO mold test and results

The part designed was a simple rectangular plate with a raised border wall, and three rounded extrusions in the center. As Figure 19 illustrates, it looked similar to a LEGO brick.

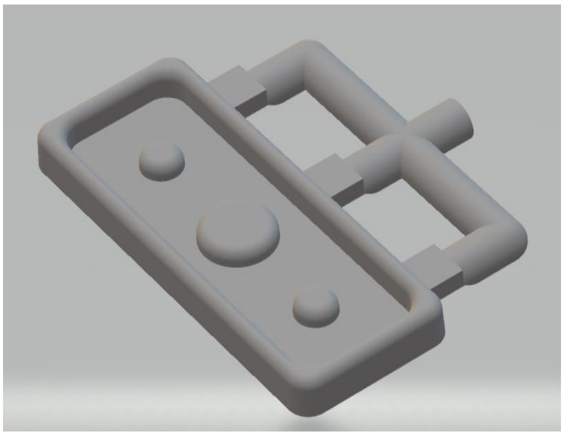


Figure 19. Part design

One initial problem predicted by MoldFlow was weld lines. Comparing Figures 20 and 21, it can be noticed that in the actual part the weld lines turned out to be larger than the predicted ones, going all the way across the height of the machined mold; while in the prediction, there were a few sets of weld lines that were not connected. The temperature at the ends of the predicted weld lines was rather high, at 135.8 degrees, causing the plastic to flow more easily and connecting the weld lines to form one continuous weld line on each side of the part instead of several weld lines.

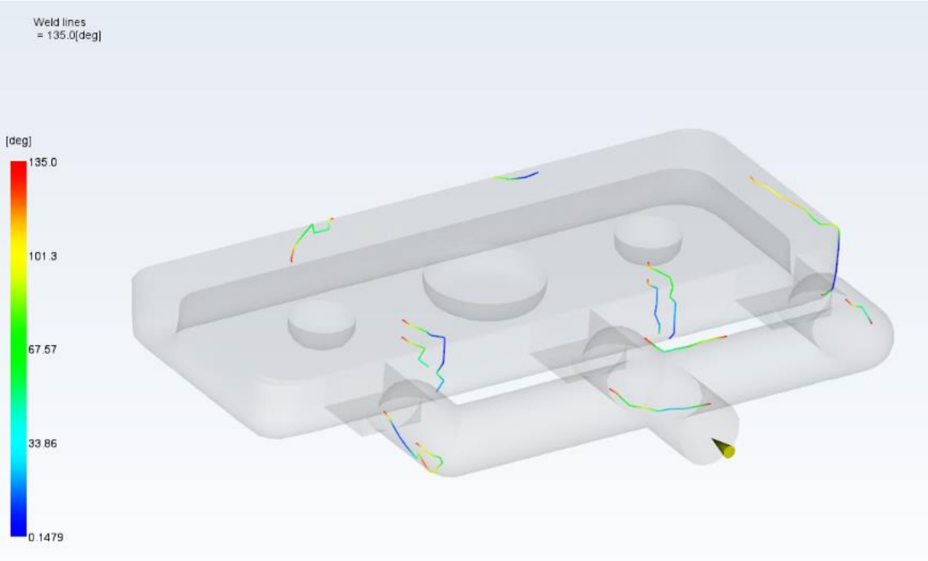


Figure 20. MoldFlow weld lines prediction

Figure 21. Picture of actual part

Weld lines result from two differing flow paths not combining well enough, typically occurring around obstructions such as holes. In this case, the weld lines occurred in between the series of knobs. One way to reduce these weld lines would be spacing the knobs further apart from each other.

Another problem that MoldFlow predicted was air traps. Figure 22 displays several places where small air traps were predicted to occur. However, the final injection molded part contained no air traps, so this issue did not come up. Through the creation of the part, the problem eliminated itself.

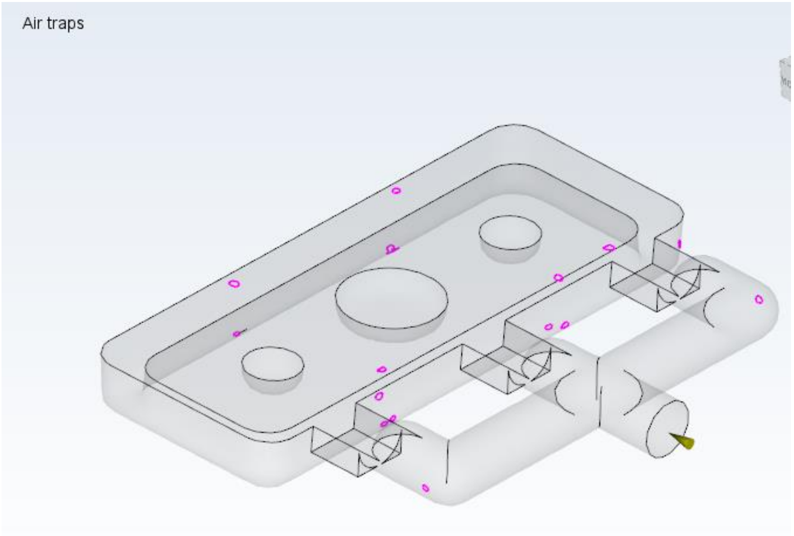


Figure 22. Moldflow air traps prediction

A defect presented in the piece, which MoldFlow did not predict, was a short shot issue where the plastic did not inject entirely into the mold. This defect was most likely caused by the injector not being properly aligned to the sprue or the true temperature not being high enough yet. Taking these factors into account during the second time of injection molding, the part molded fully. This issue could have been prevented by running the machine multiple times to try and get a consistent injecting pattern.

Figure 23. Picture of short shot issue

ii. Spiral mold test and results

The actual spiral mold shown in Figure 24 was injected at three different temperatures (436 K, 450 K and 463 K) and at three different pressures (31MPa, 39MPa and 47MPa).

Figure 24. Spiral mold

Figure 25 illustrates an example of Confidence of fill simulated by MoldFlow, including the high, medium and low percentage of fill. The setting parameters correspondent to this test are 450 K and 47MPa. Therefore, before injecting the mold, it was predicted that the plastic would not fill the entire spiral.

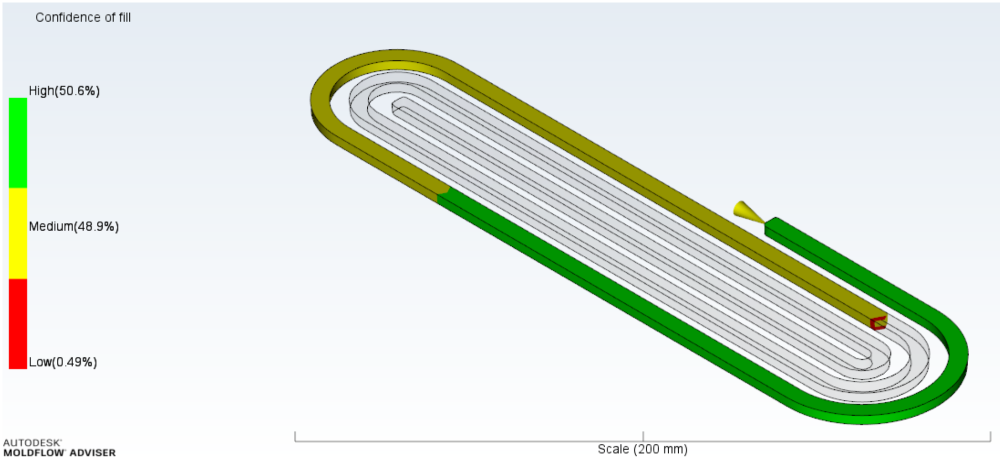


Figure 25. Confidence of Fill of the spiral mold at 450 K and 47 MPa

For each of the simulated cases, MoldFlow displayed the highest, medium and lowest confidence of fill, as well as the total part weight. These data is listed in Table 3.

Temperature (K)	Pressure (MPa)	High (%)	Medium (%)	Low (%)	Total Part Weight (g)
450	**47**	50,60	48,90	0,49	9,0450
463	**39**	51,20	38,50	0,27	8,9310
463	**47**	62,70	36,50	0,82	10,2560
463	**31**	59,90	37,60	2,50	7,5610
436	**31**	62,30	35,90	1,81	5,9900
436	**39**	63,30	35,80	0,91	7,4460
436	**47**	64,50	34,90	0,54	8,1500
450	**31**	60,90	37,30	1,76	6,7910
450	**39**	62,30	37,20	0,46	8,0200

Table 3. MoldFlow data of the spiral mold

With this data, the total filled length was predicted, as well as the length of high, medium and low confidence, by using the following equations:

$$Total\ Filled\ length = \frac{Total\ part\ weight}{Cross - sectional\ Area\ \times density\ of\ LDPE}$$

$$Length\ of\ High\ Confidence\ = Percent\ High\ \times Total\ Filled\ Length$$

$$Length\ of\ Medium\ Confidence = Percent\ Medium\ \times Total\ Filled\ Length$$

$$Length\ of\ Low\ Confidence\ = Percent\ Low\ \times Total\ Filled\ Length$$

The density of LDPE is 0.925 g/cm^3 and the cross-sectional area of the mold was 20.4250 mm^2. The resulted values are recorded in Table 4.

Temperature (K)	Pressure (MPa)	Total Part Length (mm)	Length High Confidence (mm)	Length Medium Confidence (mm)	Length Low Confidence (mm)
450	**47**	478,7456	242,2453	234,1066	2,3459
463	**39**	472,7116	242,0284	181,9940	1,2763
463	**47**	542,8430	340,3625	198,1377	4,4513
463	**31**	400,1985	239,7189	150,4746	10,0050
436	**31**	317,0465	197,5200	113,8197	5,7385
436	**39**	394,1116	249,4727	141,0920	3,5864
436	**47**	431,3738	278,2361	150,5495	2,3294
450	**31**	359,4429	218,9007	134,0722	6,3262
450	**39**	424,4930	264,4592	157,9114	1,9527

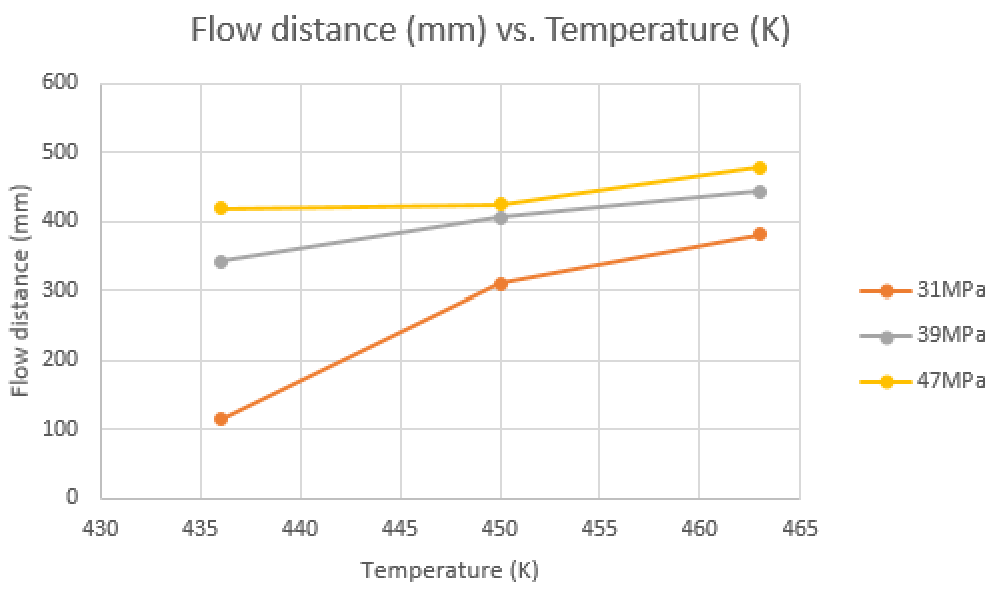
Table 4. Predicted data for the spiral mold

Furthermore, the flow distance was measured in the actual part in order to analyze the influence of the variation of the two parameters in the actual injection molding process. Table 5 displays the experimental length measured for the nine different cases.

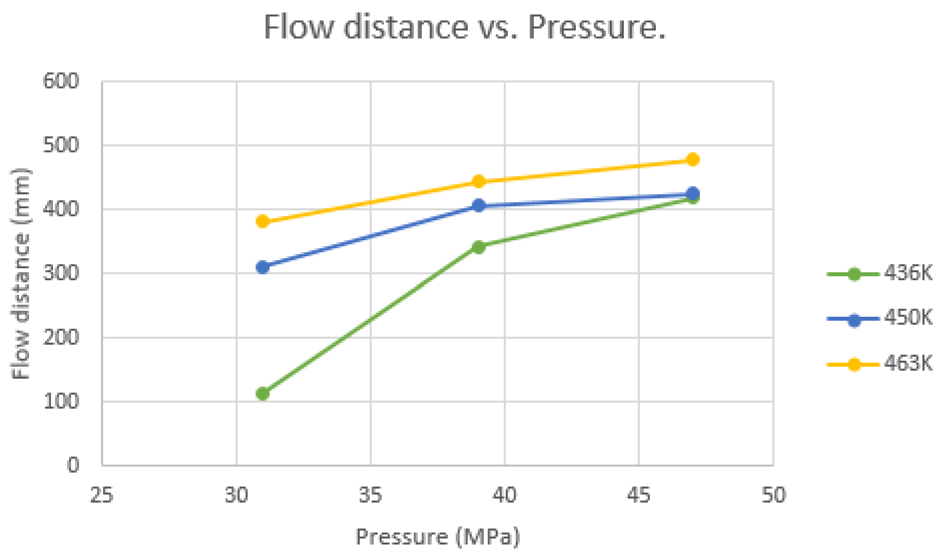
Experimental length (mm)	436K	450K	463K
31 MPa	114,3	311,15	381
39 MPa	342,9	406,4	444,5
47 MPa	419,1	425,45	479,425

Table 5. Experimental length of the part

Based on this experimental data, Plot 1 shows the effect of the temperature on the flow distance, and Plot 2 the effect of the pressure.



Plot 1. Flow distance vs. Temperature for three different pressures



Plot 2. Flow distance vs. Pressure for three different temperatures

Increasing pressure while holding temperature constant and increasing temperature while holding pressure constant yield similar growth in flow distance. For the 3 pressures, increasing the temperature over the entire range yields an average of 92,5% increase in length of the spiral. For the 3 temperatures, increasing the pressure over the entire range yields an average of 109,7%. Plot 2 demonstrates that holding temperature constant and varying pressure has a greater effect on flow distance.

Comparing the column of Length of High Confidence in Table 4 and 5, in most cases, the total experimental length measured in the laboratory is greater than the one predicted by ModFlow. Table 6 displays the percent difference that allows to compare the predicted lengths and the experimental lengths.

Percent Difference (%)	436K	450K	463K
31 MPa	42,13	42,14	58,94
39 MPa	37,45	53,67	83,65
47 MPa	50,63	75,63	40,86

Table 6. Percent difference

The external factors and human errors could be the main reasons of these discrepancies. MoldFlow software assumes a perfect geometry of the spiral that can differ from the mold use in the laboratory. Moreover, if the machine is not calibrate properly, the final result may be different from the one predicted, for example, the actual temperature and pressure of the machine can be quite different from the one set if the temperature is changed and the machine does not have enough time to reach the new parameter.

As it is shown in Table 6, both, pressure and temperature, have the same accuracy at predicting flow lengths, approximately 50% of accuracy in all the cases analyzed.

iii. Conclusion

In conclusion, when injection molding a part, simulations can help predict issues in the piece, but new issues will arise and old issues will disappear. Things that may have been relevant, like air traps, are inconsequential to the final design. Short shot, a machine issue, may arise whether predicted or not.

Temperature from the injection molding process and the pressure of the injection both affect the quality of the outcome by affecting the flow distance of the melt resin. From the released data from the spiral mold, it was evident that the temperature, pressure and flow distance were proportional within the data set range.

2.4. OBJECTIVES

The principal purpose of this project is to solve a product's vulnerability, in this case, locks' vulnerabilities. Even though many mechanical locking systems exists, they have some limitations that compromise the security or the comfort of the user.

As many lock picking techniques have been developed in the recent years, key locks are not considered safe enough. Anyone with the original key or a copy can break in easily. Furthermore, the impracticality of traditional keys is a weakness. The user has to carry around the key, and when it is lost or stolen, the security is threatened.

In consequence, market needs a new locking system that provides, primarily, a high degree of safety and comfort for the user: a mechanism with increased security that guarantees that it is practically impossible to crack, and that works with a ''soft key'', a key that the owner knows, not has. Moreover, customizability is an important factor to improve the user experience.

Based on the problem statement and the market need, the evolution of the project has tried to accomplish the next goals:

- Make it impossible to crack or forge. The main point of this goal is that, differing from the conventional key door locks, with this design the owner knows the key, not has, it is the patterns or combination.

- Make it easy to install in all doors. The dimensions of the outer shell of the door lock should be designed similar to most of the current door locks in order to make easy to replace them with this new design.

- Make it easy to use and customize. The product should be designed to make easy to change the pattern, without the need of professional help.

3. PROTOTYPE DEVELOPMENT

3.1. FIRST ITERATION

The first design of the lock came up during the ideation process. It was based on linear directional combinations and it was called CrossLock.

The lock was designed with a front part, common for all doors, where a certain pattern coupled with pushing the key unlocks the door. The key has two parts: a small cylinder with a larger diameter in order to push and go through the different levels, and a larger cylinder with a smaller diameter where the key is held. The face plate has a circular hole in the center to initially push the key through its largest diameter part. It also has gaps that represent the possible paths of the pattern.

On the inside, lock has levels corresponding to each motion and push of the key. Each level has paths for the key to slide, as well as a circular gap in a certain position in order to push the key there to pass through to the next level. After all the levels are passed, user pushes the key and activates the lock and unlock mechanism, formed by a spring and a hasp.

As the key would be the same for every lock, the security of this product is provided by the pattern, different for each door lock.

Initially, the first design of this iteration was created very simple, with only inputs in two directions, as it is illustrated in Figure 26. It was created to check if the idea worked.

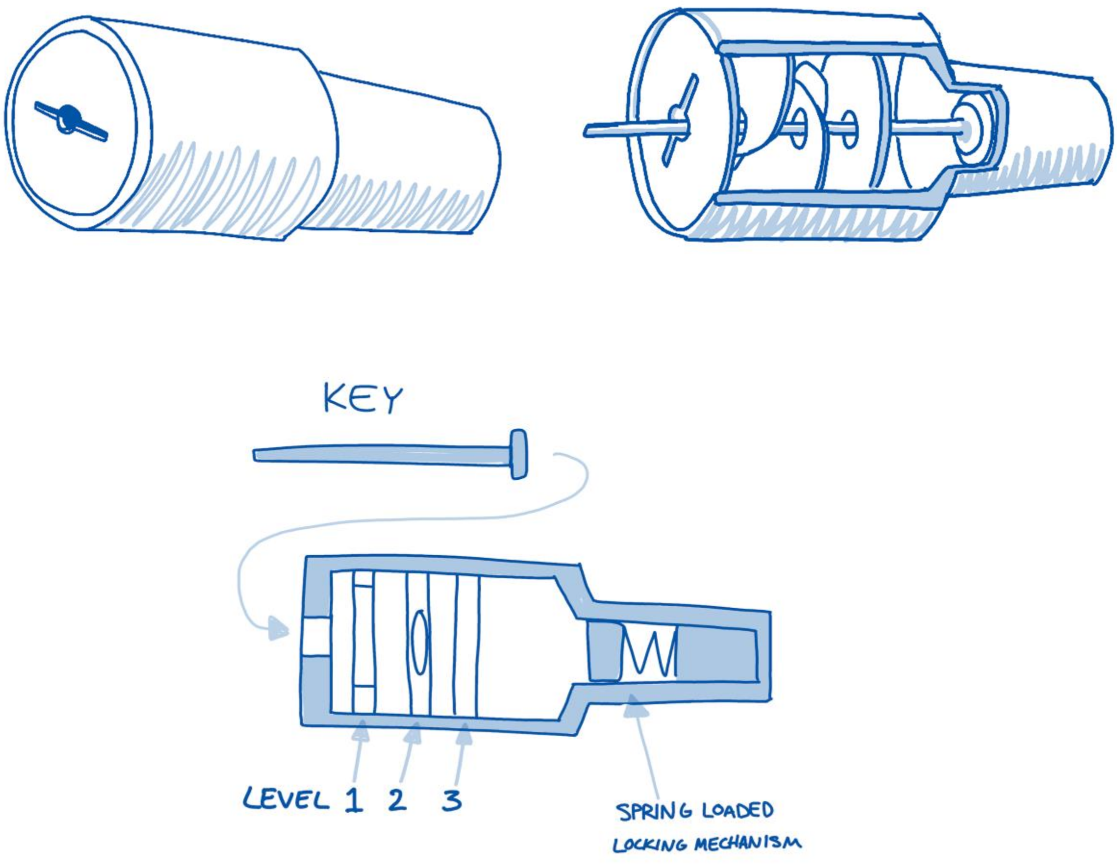


Figure 26. Initial design sketches

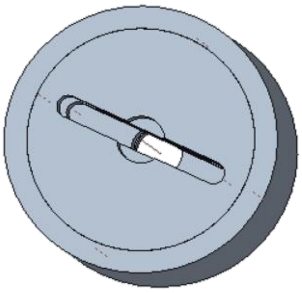


Figure 27. Front CAD first design

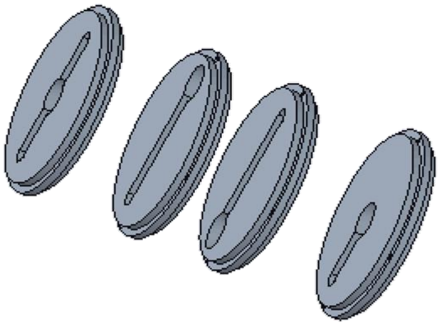


Figure 28. Exploded view of the levels in CAD

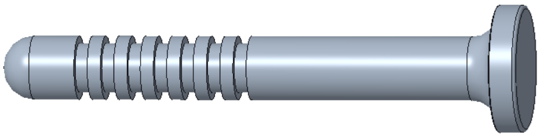


Figure 29. Key CAD design

As it is shown in Figure 28, the correct combination for the printed prototype is: push in the center, up and push, down and push, up to the middle and push.

The second design, illustrated in Figure 30, was based on the same mechanism of the previous one, however, it was designed with inputs in four directions, more levels for the pattern and a clearer lock-unlock mechanism at the end.

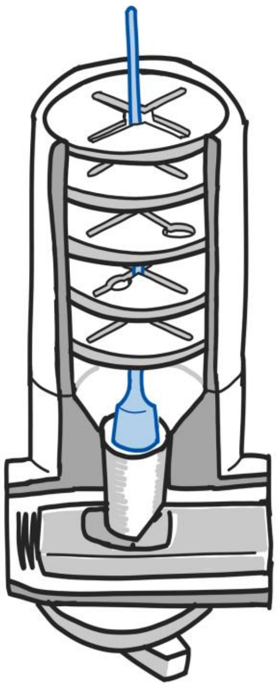


Figure 30. Second design sketch

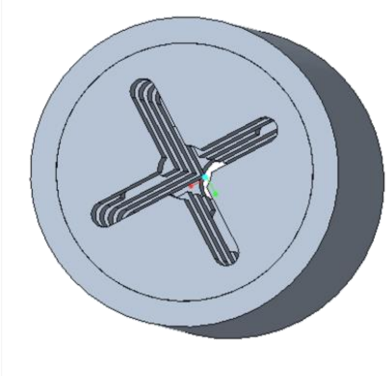


Figure 31. Front CAD second design

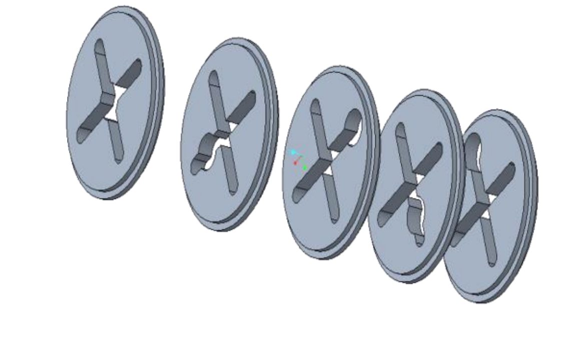


Figure 32. Exploded view of the levels in CAD

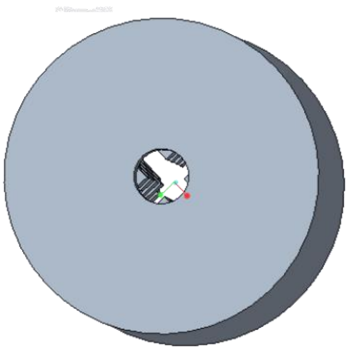


Figure 33. Back view in CAD

The snap-fit, integral attachment feature, was suggested in order to put the different levels inside the outer shell. This assembly method would allow the user to easily change the orientation or even the position of the levels in order to create a different path to follow with the key.

Moreover, multiple and generic keys would be included with every lock, making easy to replace in case of loss. And, as the security of the product comes from a combination of movements of the key that only the owner knows, the security would not be compromised by making copies or losing the key.

Increasing the number of levels, creating false positive paths, changing the cross path to create more possible movements of the key, and adding a mechanism that prevent to unlock the door if the pattern has been done wrong in many attempts, were some ideas to improve the security of this iteration.

Overall, CrossLock combines the personal aspect of a combination lock with the practical safety of a key lock, while being more accessible all around. It provides a generic key, easy to replace, and a customizable sequence, reliable as long as user knows the code.

On the contrary, it was considered too easy to crack and a really simple inside mechanism, making difficult the aim of ensuring a high degree of safety. Additionally, as one of the goals of this project is to achieve a lock that does not require a key, it was decided to move away from this idea.

3D printing test

As this was the first iteration of the prototype, a 3D printing test was performed in order to introduce this technique. The outer surface, the first and second levels, and the key were printed using the CAD designs displayed in Figure 27 and 28. After printing, the support material was removed with pliers, and the surfaces were sanded. The resulting parts are illustrated below, in Figure 34.

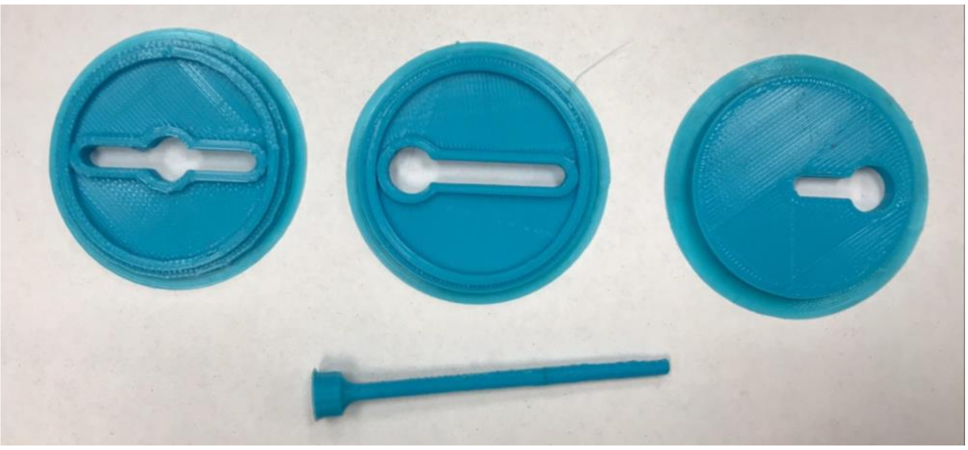


Figure 34. Printed parts for the first iteration

The prototype shown in Figure 35 was made with the 3D printed parts from the CAD files and then attached to the outer shell, made of cardboard, with hot glue gun.

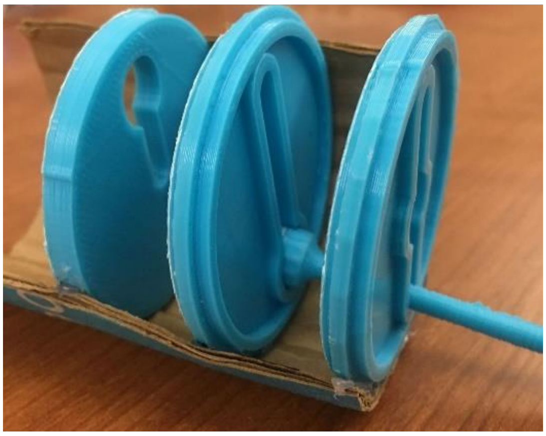


Figure 35. Prototype of first iteration

The CAD models and 3D printed parts were compared in order to analyze the accuracy of this technique.

In the third level, the inside of the holes as well as the outer edges were rounded as it is illustrated in Figure 36. However, in the 3D printed copy, it came out with relatively sharp edges. One likely reason for this difference could be the small radius of the round edges.

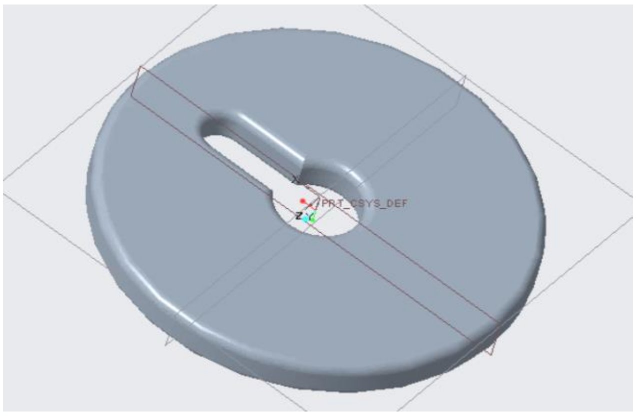


Figure 36. CAD design of the third level

The parts were oriented flat on the printers because laying them upright would lead to the 3D printer having to use lots of support material to balance the parts. Laying them flat was the most suitable orientation for these parts since it did not require any support material beyond the brim. Moreover, it increased the strength of the parts as opposed to orienting the parts vertically.

Figure 37. Printed key fitted into the outer hole

Another difference between the parts was that the holes for the keys were not as large as they were set in the CAD model. This led to the key not fitting into the hole as it is shown in Figure 37. The reason why there was a dimensional error is that the 3D printer that was available does not print the circular design. It is set to print circles as polygons, as Figure 38 shows.

Figure 38. Sanded key inserted in the outer hole

It is possible to eliminate this error by simply reducing the diameter of this part of the key. However, since this specific 3D printer was only used for initial modelling, not to manufacture the final product, the initial dimension of the CAD file were kept in order to be able to easily use the file for other type of manufacturing. Also, despite the fact that the selected orientation led to poor resolution of a circle, this was the best orientation because it minimized the need for support structure and the printing time.

Comparing with other 3D printing techniques, if this part was made with SLS instead of FDM it probably would be warped as it was relatively thin (1 cm). However, due to the fact that the parts would excrete dust after being brushed, sanding process would have been easier so that the key would fit. Additionally, the parts would probably be stronger if they were made by SLS.

In conclusion, the precision of 3D printers was unexpected, they were not accurate at all in the size of the holes they printed. The tolerance was greater than the predicted one, the key had a diameter 2 millimeters smaller than the keyhole in the CAD model, yet the 3D printed parts did not fit. Furthermore, rounded edges would only be visible if the radius were smaller than the layer sizes.

3.2. SECOND ITERATION

Due to the poor security of the first iteration, a second prototype was created. In this new one, rotational combinations were incorporated. It consists of two wheels that the user rotates through extruded shafts in order to enter de combination. The wheels has different shapes on its edges. The mechanism also has trails whereby the wheels are pushed and slid, and a sliding plate which moves the deadbolt in and out of the door. The sliding plate has a hole on it with the shapes of the correct figures.

The mechanism works by spinning the two wheels with the combination. If it is the correct pattern, the figures fit in the holes of the sliding plate while pushing the wheels. In this case, the user would be able to slide it by sliding the wheels, and unlock the door (Figure 39). If it is an incorrect pattern, it is get blocked by stopping walls, so the user would not be able to fit the figure in the plate and consequently, to slide the deadbolt plate to unlock (Figure 40). In the built prototype, the correct shape were two stars.

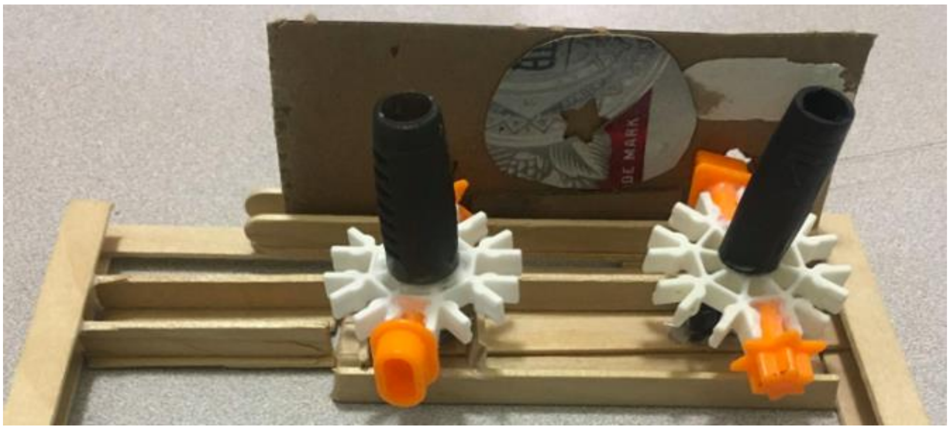


Figure 39. Locked position, incorrect pattern

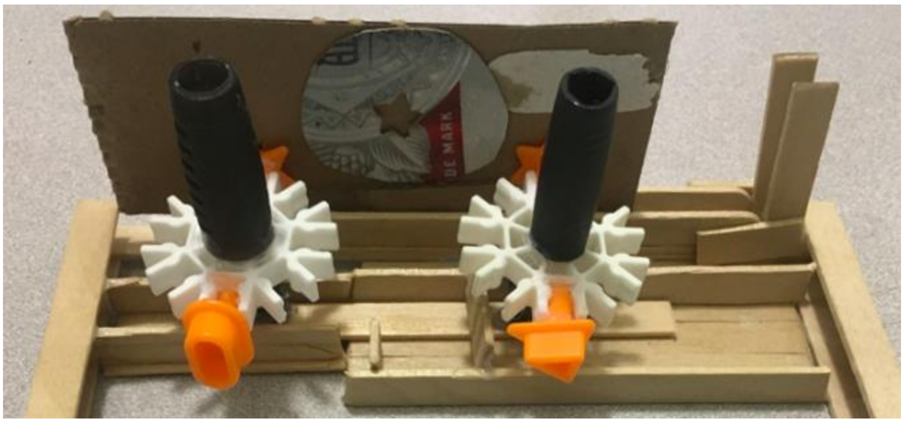


Figure 40. Unlocked position, correct pattern

The real prototype of this idea was thought to use this simple mechanism but incorporating more possible combinations. The idea was to increase the number of false positive figures for each small rotation of the wheel, and to incorporate more wheels.

For this prototype, instead of 3D printing the parts, other simple materials were used. This avoided spending time on designing the CAD models. Since it is a simple iteration, it was just created in order to test the idea of the mechanism, its advantages and weaknesses.

As it is illustrated in the figures above, this testing iteration was built with: cardboard for the sliding plate, little wooden sticks for the guiding rails and the blocking walls, and plastic wheels with different shapes on its edges. In addition, pen barrels were used to allow the user to rotate the wheels. The fixed parts were assembled with hot glue gun.

Regarding the goals of this project, this design worked due to its keyless entry and its difficulty to be cracked. Despite these positive aspects, it was considered too similar to combination lock, and too difficult to reset since the wheels would be rotated and slid.

3.3. THIRD ITERATION

In this iteration, the combination is based on retractable pens. As Figure 41 shows, it is composed of nine clicking pens placed horizontally in three rows of three pens each one, and two plates with nine holes each one. The front plate allows the user to enter the combination by clicking the correct pens, and one sliding plate with the deadbolt attached that allows to lock and unlock by sliding it. Only the correct pens are holding the sliding plate. Therefore, in order to be able to slide it, the user has to click out these correct pens as their combination. In other cases, the plate would not slide due to the pens that still are unclicked.

Figure 41. Third iteration of the prototype

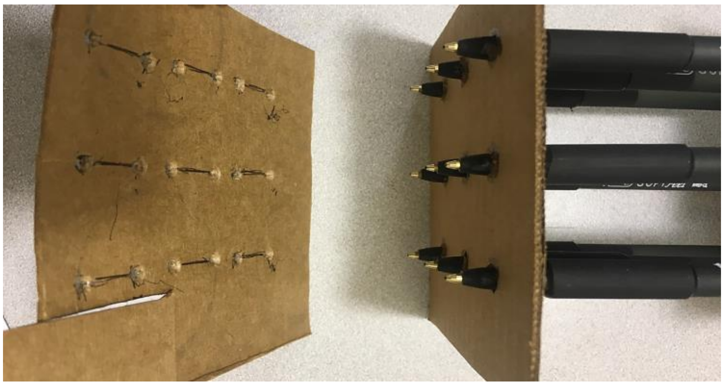


Figure 42. Sliding plate unattached

Similarly to the previous iteration, this was created as a testing prototype. That is why it was not modelled with CAD, and cardboard and actual pens were used instead.

Despite of its keyless entry and its large number of possible combinations, the locking mechanism was considered not strong enough due to in and out outputs. In addition, the difficulty to reset continued being a problem. As a consequence of this negative considerations, the clicking mechanism of the pens was discarded.

3.4. FOURTH ITERATION

The fourth iteration of the prototype, called PenLock, was based on the inside pen mechanism used indirectly in the previous iteration. In order to understand better how they work, many pens were disassembled and analyzed.

The inside mechanism of a retractable pen translates linear motion into rotational motion, causing a rotation between the extended, writing position, and the retracted or non-writing position. The three parts that describe the pen click are illustrated in the bottom of Figure 43, as well as other additional parts. The cam body, the plunger and the stop members are inside of the plastic tube. The cam body is fixed to the ink cartridge and it is the only part that rotates and slides up and down. Then, the plunger only slides, and the stop members are fixed to the outer tube. In addition, two springs are needed, one at the top between the plunger lip and the outer tube of the pen, and one at the bottom between the ink cartridge and the ballpoint.

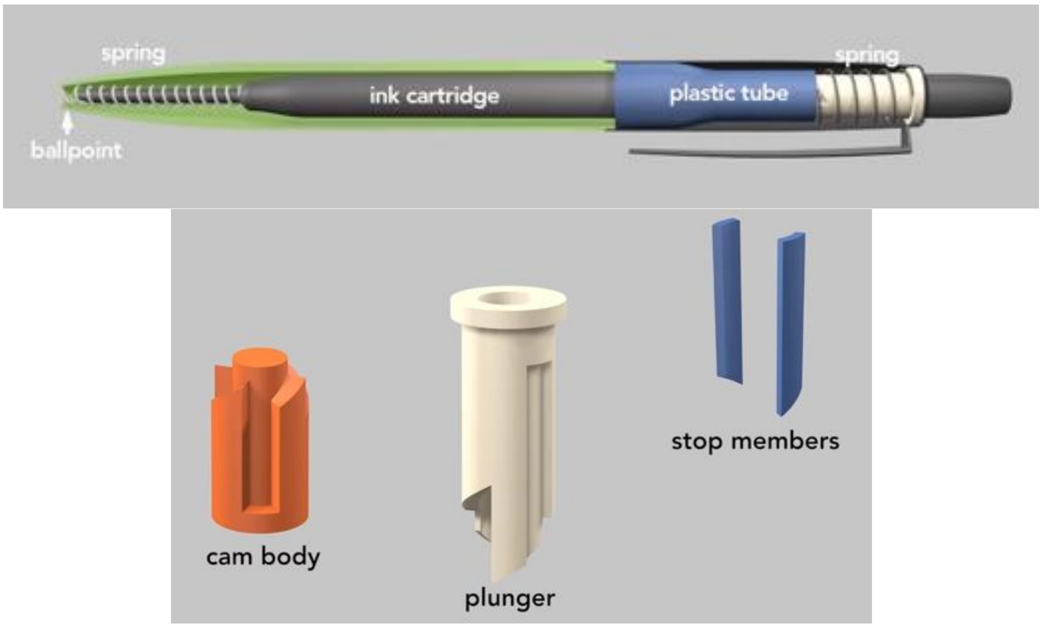


Figure 43. Parts of retractable pen mechanism [Source: William S. Hammack (22nd September, 2015), How a retractable ballpoint pen works (video file)]

Figure 44 illustrates how this mechanism works in five steps. First, when the button is pushed, the plunger and the cam body slides downwards until the top of the cam body drops below the fixed stop members (Step 1). In this position, the bottom spring pushes the cam body up, keeping it in contact with the plunger, and its axial force rotates the cam body because it mates with the plunger at an angle. It rotates 45 degrees until it strikes the flat surface of the plunger (Step 2). Then, the button is released and the top spring that was compressed, come to its equilibrium position. While this happens, the plunger slides upwards until its tips clear the cam body (Step 3). At that instant, the cam body rotates again 45 degrees due to the slope, until it strikes the stop members (Step 4). Finally, the button is completely released and the cam body remains locked in place, in the writing position (Step 5).

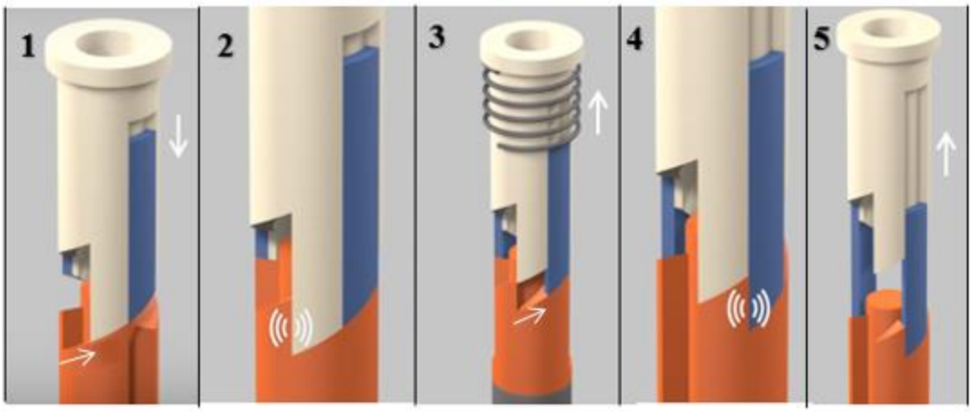
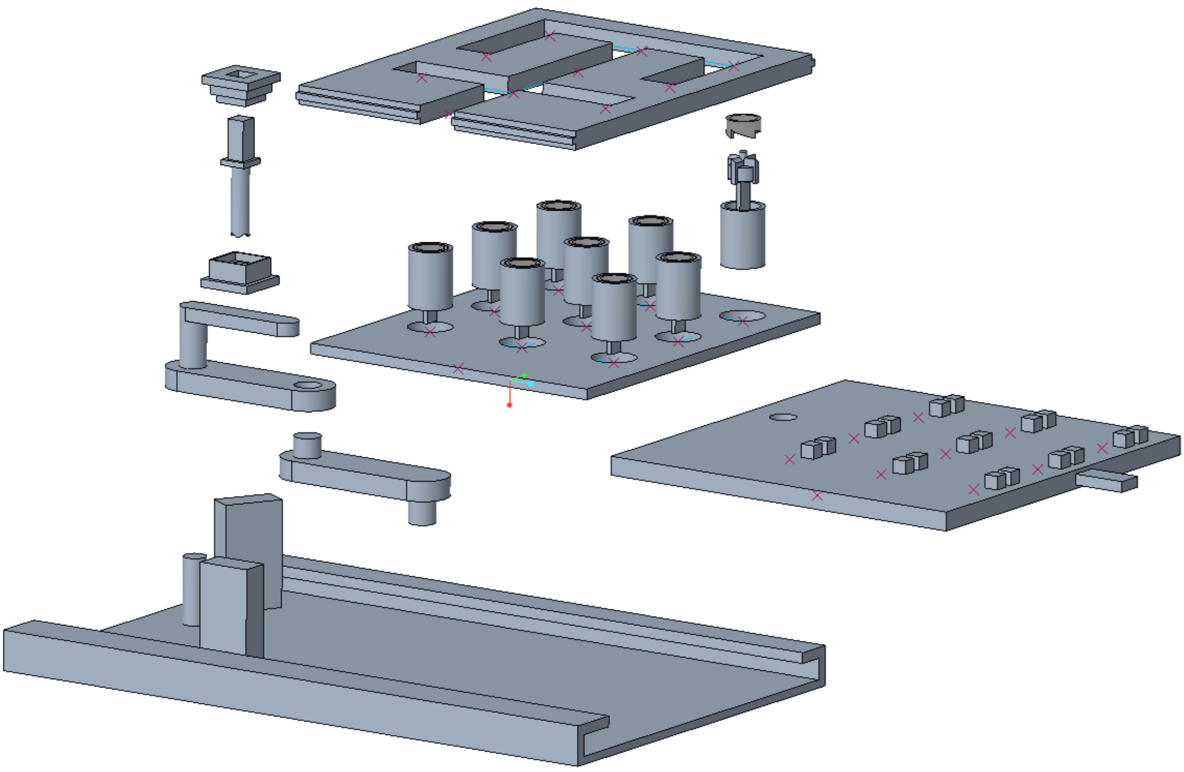


Figure 44. Retractable pen mechanism steps [Source: William S. Hammack (22nd September, 2015), How a retractable ballpoint pen works (video file)]

Based on the idea of transforming linear motion into rotational motion while clicking the button, this iteration was developed. In the new design of the mechanism, the cam body is attached to a pin and, depending on the position of the pins, the deadbolt can be slid in and out of the door or not. Basically, it works by sliding and clicking a key in the right points in order to rotate the pins to their correct orientation.

a. FIRST DESIGN

CAD software was an essential tool to design the different parts of the new iteration. Figure 45 illustrates the disassembled prototype and Figures 46 and 47 illustrate the CAD assembly.



c

Figure 45. CAD disassembly

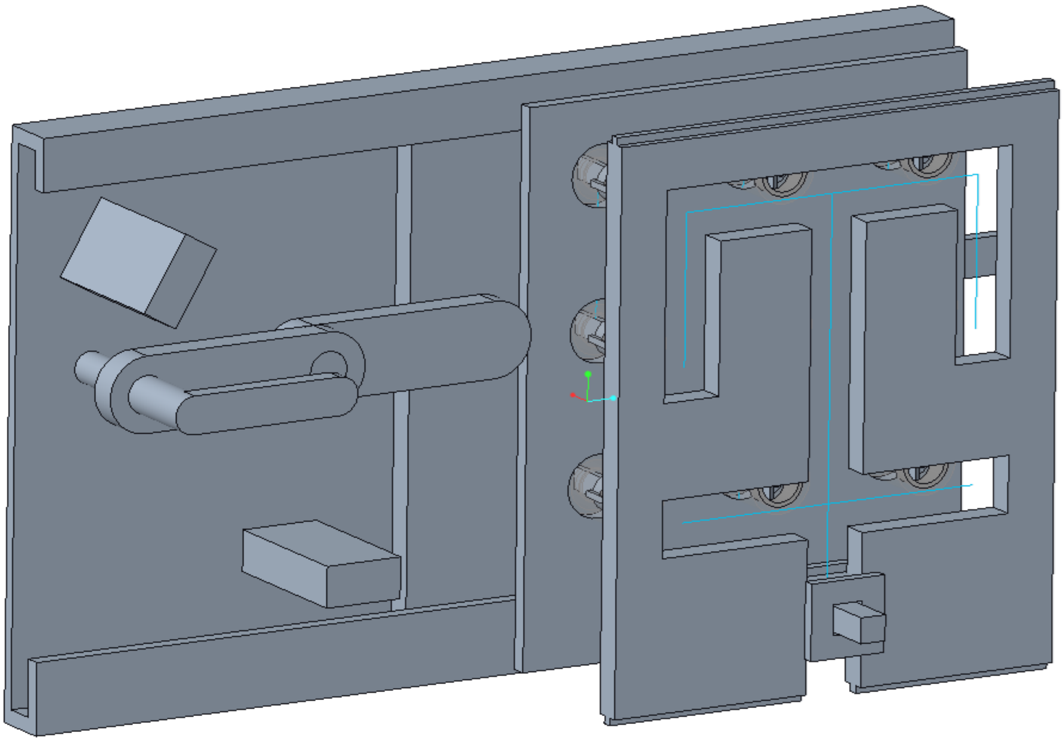


Figure 46. CAD assembly, front view

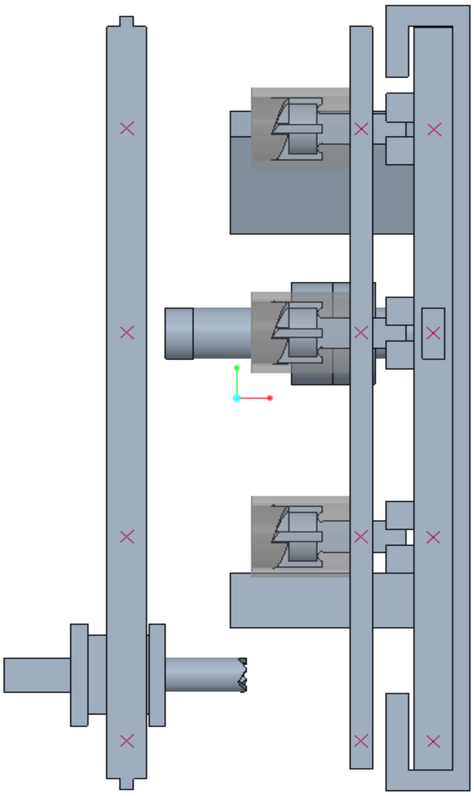


Figure 47. CAD assembly, side view

As it is shown in the figures above, the first design of this iteration consists of many different parts which are:

- A faceplate with a rail to allow the key to slide (Figure 48). The blue line represents the possible paths of the key and the nine circles indicates the nine possible positions where the key can be pushed.

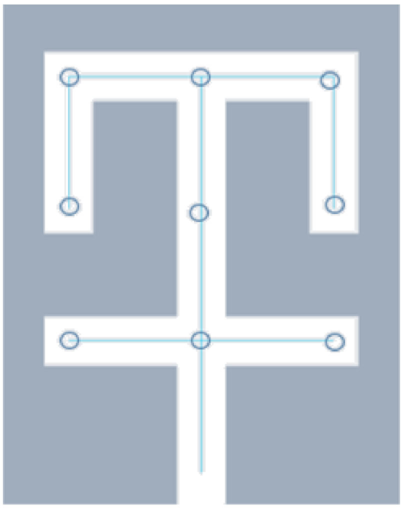


Figure 48. Faceplate CAD model

- A sliding clicking key (Figure 49). It is composed of three parts. The part in the middle has a rectangular tube where user slides and pushes the key, and a cylindrical tube with four tips at its bottom. The tips fit with the cam body while the key is pressed. The top and the bottom part shown in the Figure are needed to assembly the key in the faceplate, allowing the user to slide it to enter the combination. The tube is able to slide up and down inside the rectangular box, when the user clicks the key.

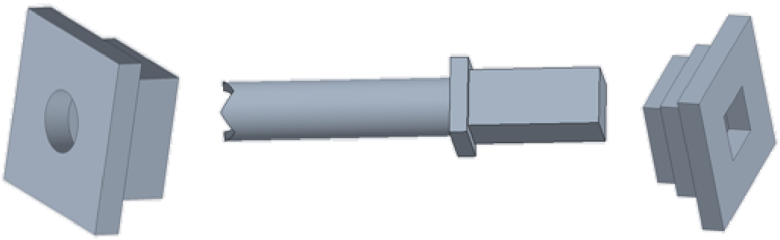


Figure 49. Sliding key CAD model

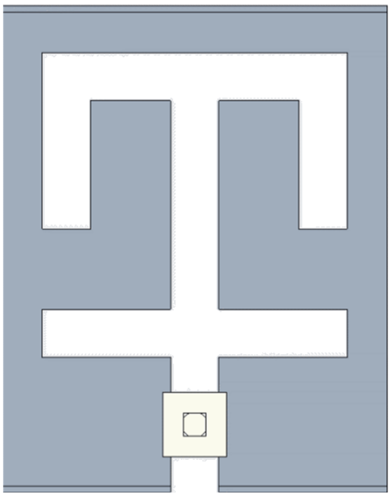


Figure 50. Sling key and faceplate CAD assembly

- Nine rotating mechanisms, based on the clicking mechanism of a retractable pen. Each mechanism consists of:
    - A cam shaft (Figure 51). It is a cylindrical hollow with four ridges with slope, equivalent to the plunger in the retractable pen. This part is fixed, it does not rotate or slide.

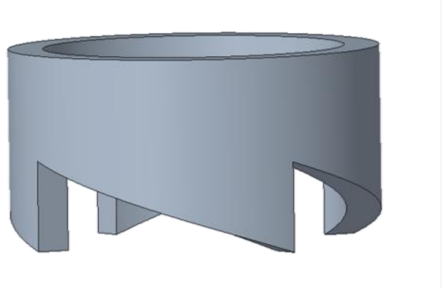


Figure 51. Cam shaft CAD model

    - A cam pin (Figure 52). The top part is equivalent to the cam body of a clicking pen, with four ridges and the same slope as the cam shaft in order to fit together. It has a wall extruded out called pin that rotates when the key is pressed. Moreover, at the bottom part of each ridge, there is a gap that allows the spring to be inserted and not move in the horizontal direction.

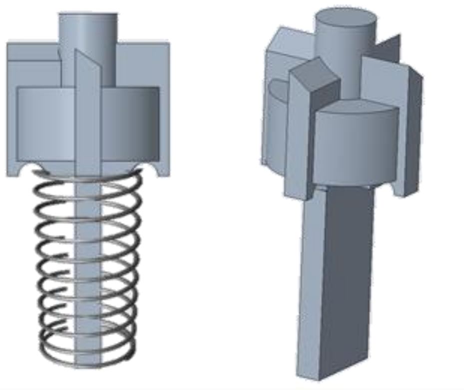


Figure 52. Cam pin CAD model

Initially, the cam pin and the cam shaft have their surfaces in contact. When the user presses the key and so, its bottom teeth pushes the cam pin downwards and the spring is compressed, the cam pin rotates. The mechanism is the same as the plunger and the cam body in a clicking pen. In the moment that the ridges of the cam body clear the cam shaft, the slope of the next ridge makes the cam pin rotate 90 degrees. The pin at its bottom part rotates as well, therefore, its position depends on the number of clicks.

    - A cam cover, a cylindrical hollow where the cam shaft is fixed. It does not move or rotate. It was designed to ease the assembly and ensure that the cam shaft does not move

- A cam plate (Figure 53), where the cam covers are assembled and fixed. It is a plate with nine holes, one for each cam cover. It is placed right after the faceplate.

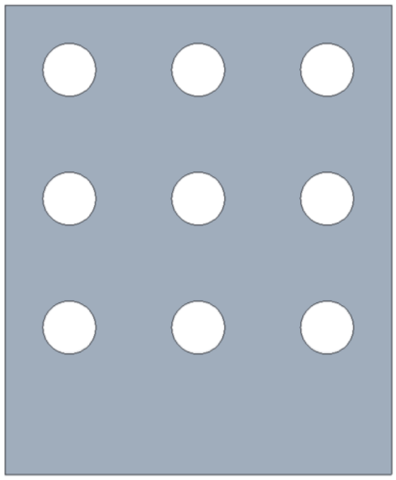


Figure 53. Cam plate CAD model

- A deadbolt plate (Figure 54). This plate is actually the locking plate. It has attached the deadbolt that moves in and out of the door when the plate is slid. The white squares are small extrusions, two per pin, and they are placed in each clicking point. When the nine pins are in the horizontal position, the plate is able to slide since the pins fit properly between the two walls. However, if one or more pins are in a wrong orientation, they would crash the walls without fitting between them, and therefore, they would avoid to lock or unlock. The hole in the left side allows to pin the mechanism that connect the user handle and this plate.

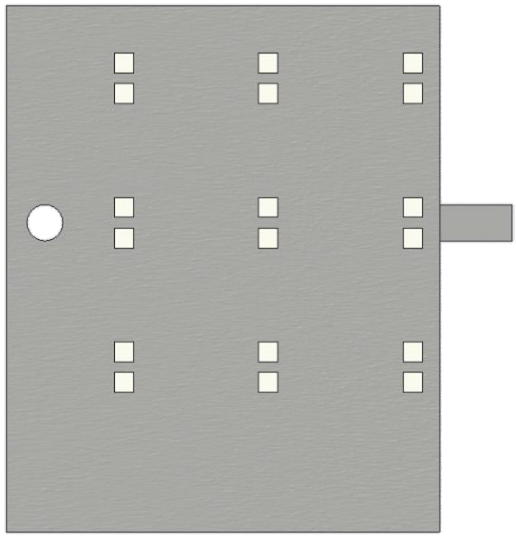


Figure 54. Deadbolt plate CAD model

- A handle ((Figure 55) attached to an A-arm of two equal arms (Figure 56). The first arm is fixed to the handle on its left hole, however, it is pinned to the second arm on its right hole, allowing the rotation of one arm respect to the other. The second arm is pinned on its right hole to the deadbolt plate. When the correct combination is entered and the user turns the handle, the first arm turns as well, and the second arm slides the deadbolt plate. This movement allows the deadbolt to move in and out of the door.

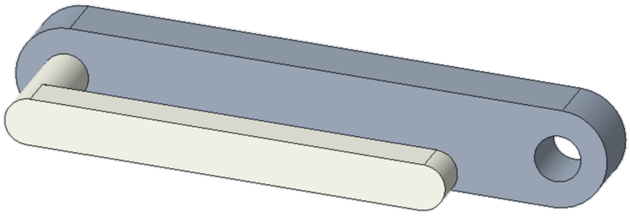


Figure 55. Handle CAD model

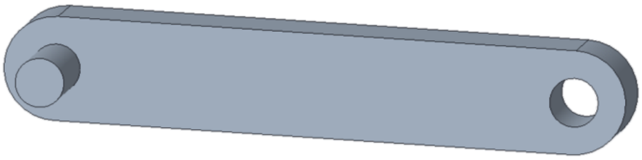


Figure 56. Arm CAD model

- A D-plate (Figure 57). The two gaps placed on its top and bottom parts allow the deadbolt plate to slide. They are the rails to prevent the deadbolt plate to move in other direction different to the horizontal one. Moreover, it has a cylinder to attach the handle, and two walls to stop the A-arm to move more than this angle.

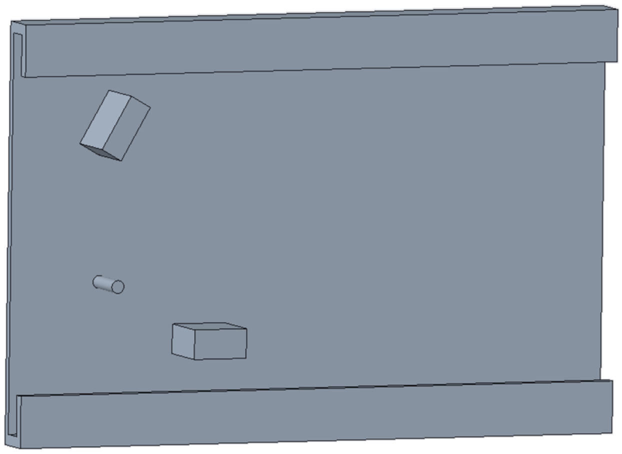


Figure 57. D-plate CAD model

In essence, in order to unlock the door, the sliding key is moved through the faceplate and it is pressed down on some of the nine different points, depending on the combination of the user. If it is correct and so all the pins are properly oriented, when the user rotates the handle, the A arm slides the plate to unlock the door because the pins fits between the walls. If the combination is not correct, the pins will interfere with the walls, making impossible to unlock it.

With the aim of testing this idea, some scaled parts were 3D printed, in particular, the faceplate (Figure 58), the deadbolt plate (Figure 59) and the cam mechanism (Figure 60).

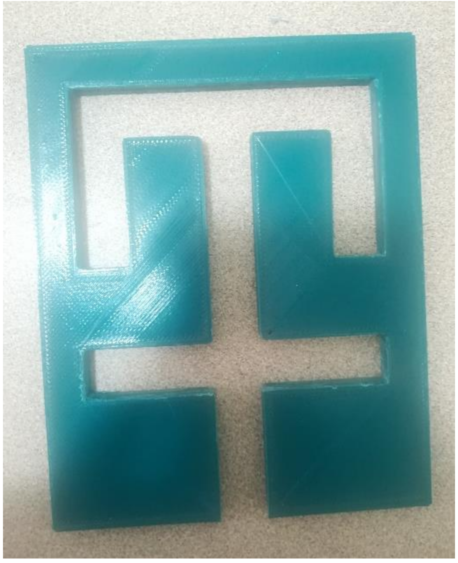


Figure 58. Faceplate, 3D printed

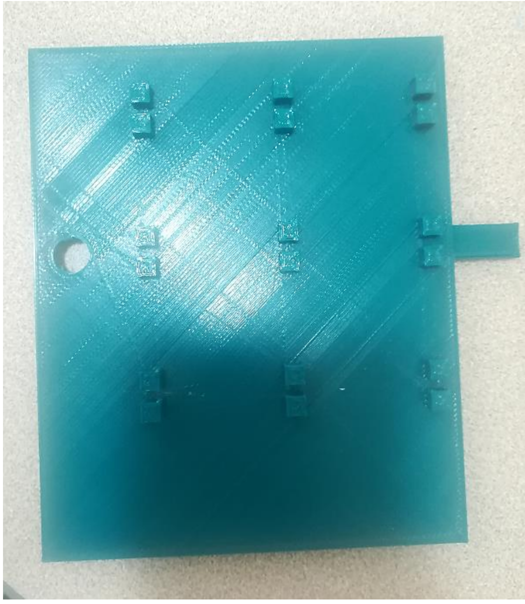


Figure 59. Deadbolt plate, 3D printed

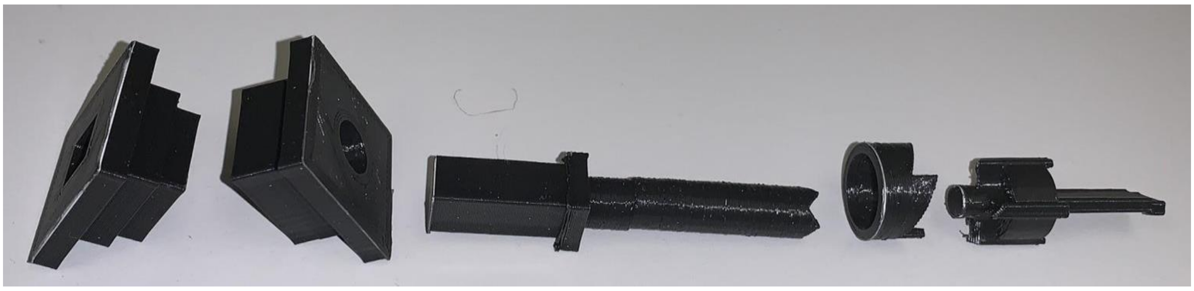


Figure 60. Cam mechanism, 3D printed

As in the third iteration, this locking system does not require a key. However, by adapting the pen mechanism, the in and out outputs that weakened the lock were substituted for rotating outputs. This improvement made able to deem the future of it.

Nonetheless, this design is not difficult to crack after many attempts. Since the pin has a symmetric shape, only two of the four possible orientations are different. It is the same clicking once than three times, or twice rather than four times. In addition, even though the key is slid through the rails to enter the combinations, the sequence or order of the clicks does not affect. Due to these two vulnerabilities, there are not many possible combinations and so, guessing the pattern could be really easy.

Furthermore, a reset mechanism was not accomplished for this iteration. Resetting the pins is essential in order to provide security. When the correct combination is entered and the door is locked, the pins should come back to its original position, so the door cannot be unlocked until the combination is entered again.

Regarding the CAD model and 3D printed parts, the ridges of the cam pin shown in Figure 60 were slightly offset, leading them to slide out from the cam shaft. The main reasons of this inaccuracy were the design error and the tolerance of the 3D printers.

b. SECOND DESIGN

Based on the same pen mechanism, this design was an improved version of the previous one so that the ridges did not slide out from the cam shaft, they stay in place during the rotary motion. The CAD design was modified as well as the scale in order to have a better quality and be able to test its operation.

Moreover, another reason for the rough rotation was detected. The top end spring was getting caught on the ridges of the cam pin as Figure 61 shows. It had to be cut in order to fit.

Figure 61. Spring catching the ridge of the cam pin

Another change in the design was performed, the gaps placed at the bottom part of each ridges were removed as they were considered unnecessary. The spring did not fit in well and, without these gap, it worked properly.

The new design is illustrated in Figure 62, the CAD assembly of the sliding key, the cam shaft and the cam pin. The sliding key was slightly modified in order to simplify the printing process and assembly. It was redesigned as a complete cylinder, and two small extrusions on both sides were created as well, in order to assembly it better.

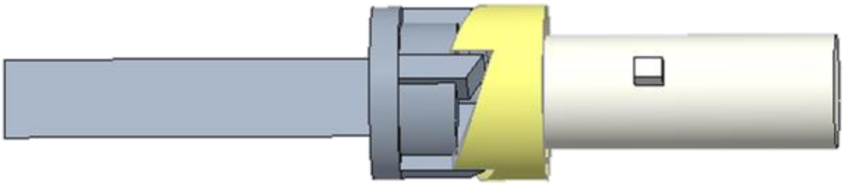


Figure 62. New CAD assembly

Figure 63. Second design of cam mechanism, 3D printed

Despite of this progress, the rotary motion of the cam pin around the cam shaft ridges was not smooth due to the angle of the teeth, the number of ridges and the 3D printers. In order to solve it, a 'Design of Experiments' analysis was performed. Moreover, the reset mechanism was still a problem to overcome.

3.5. DOE EXPERIMENTATION AND OPTIMIZATION

Since some vulnerabilities in the design were noticed, a 'Design of Experiments' test was performed. As the effects of the cam shaft design on the mechanism were unknown, it was decided to utilize DOE in order to identify its most suitable model. In this case, the optimized variable was the amount of time that it takes the cam pin to rotate around the cam shaft because it was not operating as smoothly as it was expected. Figure 64 shows how both parts are in contact.

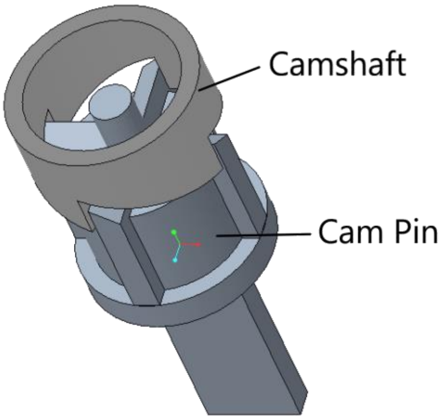


Figure 64. Cam shaft and cam pin

This mechanism is critical to the user experience and, overall, to the operation of the lock. In order to decrease the amount of time taken for this component to rotate, three variables were adjusted in the CAD model: the angle of the teeth's slope on the cam shaft, its outer diameter, and the number of teeth.

For this process, it was decided that a 2^3 factorial design would be performed. Consequently, the three variables were examined on two levers each, a low lever (-1) and a high level (+1). These levels created a range which encompasses the operating conditions of interest. The outer diameter varied from 12,3 mm to 23,37 mm. This is because to build the rest of the rotating component, two different sized springs had been already purchased. The number of teeth varied from 4 to 8. The four teeth cam shaft was created for the original design, which incorporated 90 degrees turns of the cam pin to lock the bolt in place. Using 8 teeth allowed to still use 90 degrees turns, they just required two presses to turn that angle rather than one. Finally, the angle of the teeth varied from 52,2 degrees, the initial design which slope was considered not steep enough, and 72,7 degrees, which made a harsher slope for the camshaft piece. Table 7 presents the variables description as well as their low and high-level values, and Figures 65, 66, 67 and 68 illustrate the different CAD models.

Variable	Variable Description	Low (-1)	High (+1)
x1	Camshaft Outer Diameter (mm)	12,3	23,37
x2	Number of Teeth	4	8
x3	Angle of Teeth (degrees)	52,1755	72,748

Table 7. Variable levels

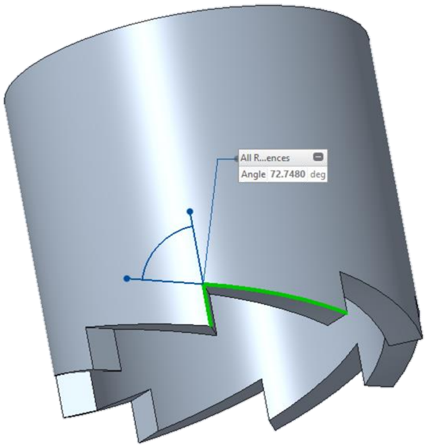


Figure 65. Cam shaft model with 8 teeth and steepest angle

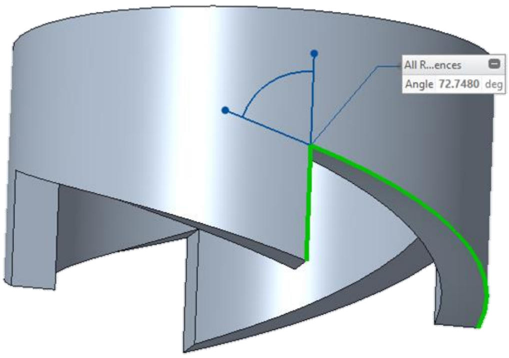


Figure 66. Cam shaft model with 4 teeth and steepest angle

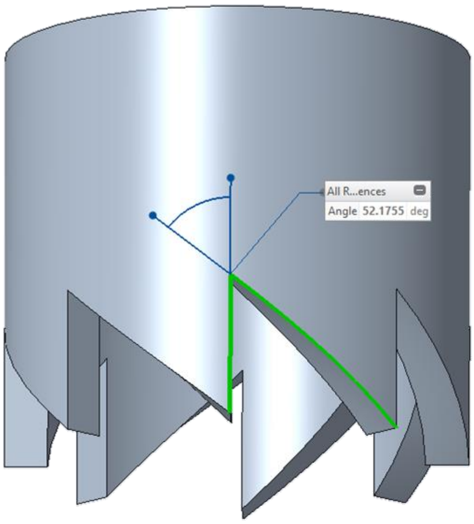


Figure 67. Cam shaft model with 8 teeth and lowest angle

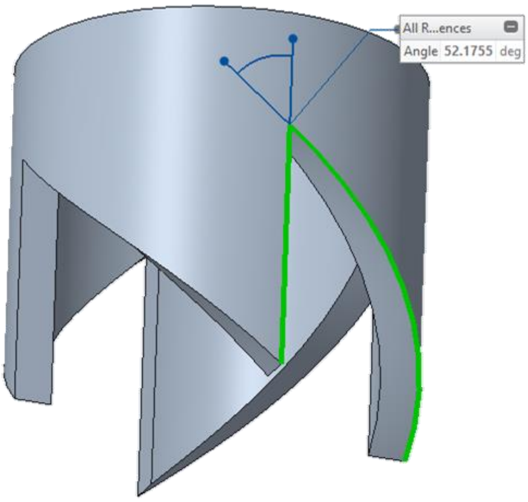


Figure 68. Cam shaft model with 4 teeth and lowest angle

The complete factorial design contains 8 unique test conditions, so, in order to perform the test, the 8 possible cam shafts were printed, as well as two different sizes for the cam pin, cam cover and the sliding key. All the 3D printed parts needed are shown in Figure 69.

Figure 69. Printed parts used for the test

For the resultant value, the amount of improvement was gauged by timing how long it took the part to make one full 360 degree rotation. For the pieces with 4 teeth, this would be 4 successful button presses and rotations. For the pieces with 8 teeth, it requires 8 successful presses. It was considered that the speed one could rotate the cam pin piece was representative of how fast someone who knows the code could unlock the lock. Therefore, the lower the end time value, the better the result.

The test was ran three trials for all 8 arrangements of the variables. The results are displayed in Table 8 and all the calculations were performed with Excel.

Test	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	y_1	y_2	y_3
1	-1	-1	-1	1	1	1	-1	16,446	13,062	9,96
2	-1	-1	1	1	-1	-1	1	14,553	16,359	16,705
3	-1	1	-1	-1	1	-1	1	8,865	10,951	15,43
4	-1	1	1	-1	-1	1	-1	18,235	17,29	12,035
5	1	-1	-1	-1	-1	1	1	4,05	4,132	3,953
6	1	-1	1	-1	1	-1	-1	6,439	6,713	6,137
7	1	1	-1	1	-1	-1	-1	10,643	13,017	9,761
8	1	1	1	1	1	1	1	7,714	10,006	9,695

Table 8. Design matrix

First of all, the values for time average and variance were calculated for each experiment that make up the DOE. The system average standard deviation and variance were determined as well, as Table 9 displays.

Test	$y_{average}$	Variance	
1	13,2	10,5	**System std. deviation**
2	15,9	1,3	2,20
3	11,7	11,3	
4	15,9	11,2	**Ave. System Variance.**
5	4,0	0,0	4,84
6	6,4	0,1	
7	11,1	2,8	**2 σ**
8	9,1	1,5	**4,40**

Table 9. Variance Results

Comparing the average time of each test, it was clear that the cam shaft with the larger outer diameter would rotate faster since less time was required for the last four tests. Moreover, tests 5 and 6, the one with 4 teeth and bigger diameter, were highlighted as the best performance.

There are two methods to determine which effects are statistically significant. The first one uses a confidence interval to judge the statistical significance of variable effect, whereas, the second one uses a normal probability plot of the effects to isolate the important effects.

With the time average values as the output variable, the average effect of each variable was analyzed by calculating its main effect value, E. The sign of a main effect allows to know if the variable causes an increase or decrease in the output, in this case, in the time of rotation. In addition, its magnitude indicates the strength of the effect. Table 10 shows the main effects (E_1, E_2, E_3), as well as the interaction effects (E_{12}, E_{13}, E_{23}, E_{123}).

E_1	E_2	E_3	E_{12}	E_{13}	E_{23}	E_{123}
-6,47	2,09	1,80	2,81	-1,61	-0,75	-1,44

Table 10. Main effects Results

In order to judge the statistical significance of variable effects, these values were compared with the 2-sigma system standard deviation value of 4,40. It marks the effect magnitude value threshold for significance, therefore, any effect larger in magnitude than this value is deemed statistically significant for the process. In this case, the significant contributor was x_1, which means the effect of the outer diameter.

So as to improve the results, the graphical method was performed as well. Listed below in Table 11 are the effects ranked from lowest to highest and the standard deviation of cumulative probability. The equation used to calculate it for the seven ordered effects is:

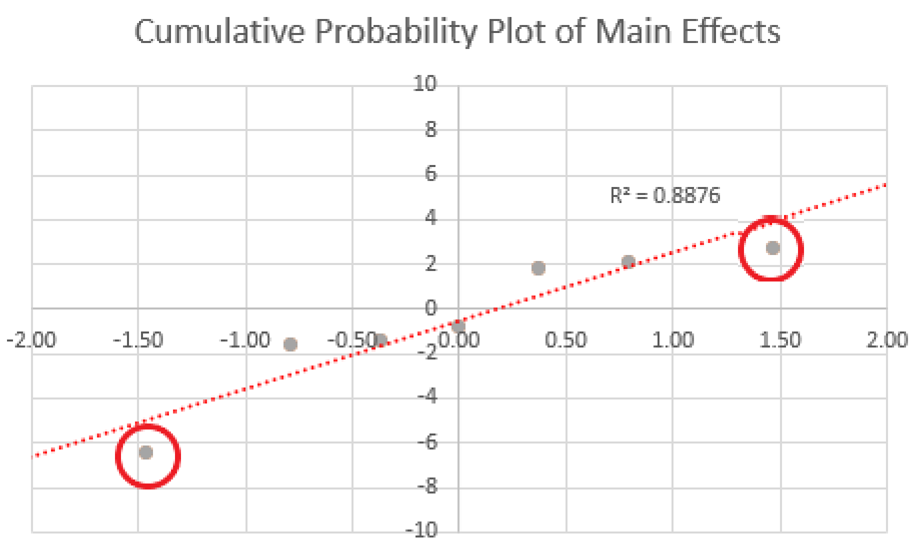
$$P_i = \left(\frac{100 * (i - 0.5)}{2^n - x}\right)$$

, where 'i' means the rank, 'n' the total number of variables , 3 in this case, and (2^n-x) indicates the number divisions out of 100%, 7 in this case to account for all the effect values.

Rank	*Main effect value (y-axis)*	*Probability*	*Standard Dev. (x-axis)*	*Effect*
1	-6,46925	0,07	-1,47	E_1
2	-1,60958	0,21	-0,79	E_{13}
3	-1,44375	0,36	-0,37	E_{123}
4	-0,74958	0,50	0,00	E_{23}
5	1,80	0,64	0,37	E_3
6	2,09	0,79	0,79	E_2
7	2,807583	0,93	1,47	E_{12}

Table 11. Ranked Main Effects

Using this data, main effects versus cumulative probability is displayed on Plot 3. The graphically significant effects are circled, these are the effects that fall farther from the trendline than the other effects. All the data points that appear on or near the line are considered insignificant effects.



Plot 3. Main Effect values vs. Standard Deviation

As it is shown in the graph above, two main effect are deemed as significant, adding new data to the test. This analysis method incorporates the interaction between the diameter and the angle of the teeth, x_{12}, to x_1 as the most significant variables effects. Therefore, the reduced characteristic equation to predict output value, for any set of inputs, is:

$$\hat{y} = y_{ave} + \frac{E_1}{2}x_1 + \frac{E_{12}}{2}x_{12} = 10.92 - 3.23x_1 + 1.4x_{12}$$

, where $\hat{y}$ is the predicted time response. So, in order to optimize the time, the most suitable setup would be maximize x_1 and minimize x_{12}, therefore, minimize x_2.

However, another analysis was performed in order to minimize the variability of the process. With the variance as the output variable, the noise effects were calculated. These results are displayed in Table 12.

E_1	E_2	E_3	E_{12}	E_{13}	E_{23}	E_{123}
-7,45	3,71	-2,62	-1,57	2,02	1,93	-2,61

Table 12. Noise effects Results

Following the same procedure used for main effect, the noise effects were analyzed. The highlighted one in the table above was detected statistically significant since it is out of the confidence interval. Therefore, the significant variable is x_1. With these results, the predicting equation for system variance for any set of inputs, is:

$$\hat{d} = 4.84 - 3.72x_1$$

, where $\hat{d}$ is the predicted variance.

This equation was useful to select process setting that minimize the output variability of the process. Based on the results, the variable x_1, negatively correlated, should be maximize in order to reduce the noise, which means that the best cam shaft would be the one with a bigger diameter.

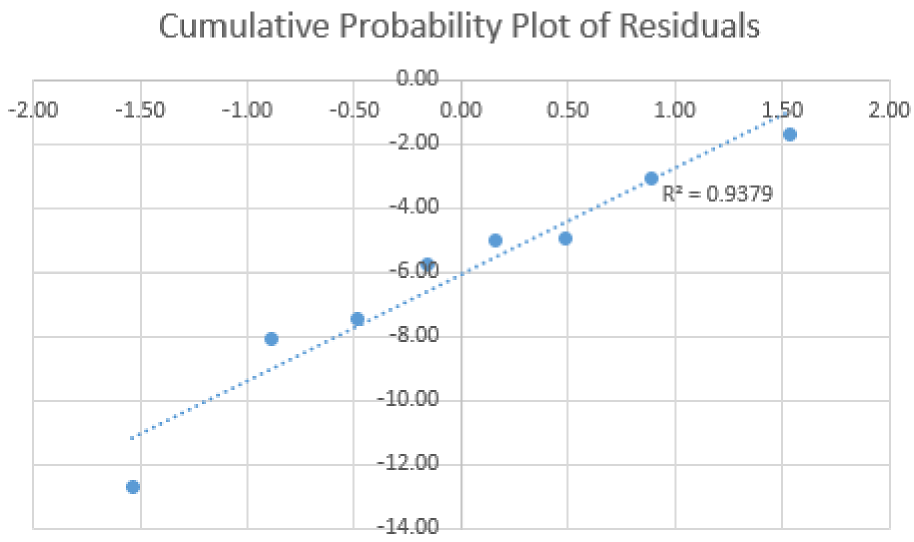
Therefore, with both analysis results and the target of minimizing time of a full rotation and noise, there ideal setting for input variables would be: high x_1 and low x_2, which means a large outer dimeter and 4 teeth, regardless the teeth's slope. By using the characteristic equation, both arrangements would take 6,29 seconds to perform a full rotation of the cam pin.

Finally, the residuals were plotted. This step of the DOE allows to determine how well the model fits the data, and thus the credibility of the proposed characteristic equation. Residuals are simply the difference between measured and expected time of the experiment, as Table 13 displays.

Test	Average time	Predicted time	Residual
1	13,2	12,21	-1,69
2	15,9	14,01	-12,68
3	11,7	14,30	-3,05
4	15,9	16,11	-4,95
5	4,0	5,74	-5,73
6	6,4	7,54	-7,46
7	11,1	7,84	-5,00
8	9,1	9,64	-8,09

Table 13. Predicted values and residuals

A test based on this data was necessary to check de adequacy of the model, by verifying that the residuals form a purely normal distribution around zero. Plot 4 displays the residuals vs their standard deviations.



Plot 4. Graph of residuals

As the points are placed approximately as a straight line, the model was considered good. Furthermore, this line of best fit has an R^2 of 0,9379 that means an adequate fit since it is close to 1. Due to how well the trend line fits, the results given by the characteristic equation were considered valid. At this point, the model was verified and, in consequence, it could be used to make predictions.

In conclusion, the DOE testing confirmed the original hypothesis that larger diameter would lead to smoother operation. The effect of increasing the diameter caused a drastic difference in the amount of time it took to make a full rotation. The measurement methods worked well and the time needed for each of the configurations of the camshaft was measured accurately by using a stopwatch. However, one thing that could improve the data further is a more exact way to time the rotations. There were some delay between the test was done and the timer stopped.

Optimizing the input variables made a large difference and improved the efficiency of the product. Before testing and optimization, the product did not always turn exactly when the key was pressed and it sometimes had to be turned manually. Nevertheless, after testing the 8 different configurations and analyzing the results, the most reliable and efficient design was found.

Therefore, the information collected in this test has been essential make progress and achieve the final prototype. With regard to the future, the next DOE should vary the size of the teeth, angle, and location of the resetting mechanism. This will contribute to the mechanism working quickly and regularly, but it is considered that it will not change major components of the design.

3.6. FINAL PROTOTYPE

The final design builds upon and combines the best aspects of each of the iterations. Despite of some improvements and changes in the design, the operation of the inside mechanism is exactly the same as in the previous iteration.

Since in the preceding iteration the order of clicks did not affect the combination, in this prototype the sliding key is substituted for three clicking buttons. The three of them are exactly the same as it is illustrated in Figures 70, 71 and 72.

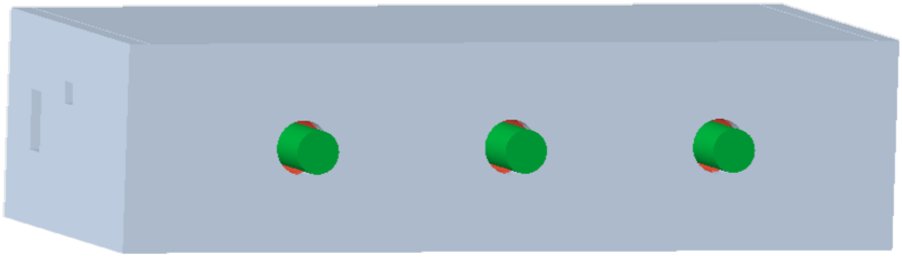


Figure 70. Complete CAD assembly

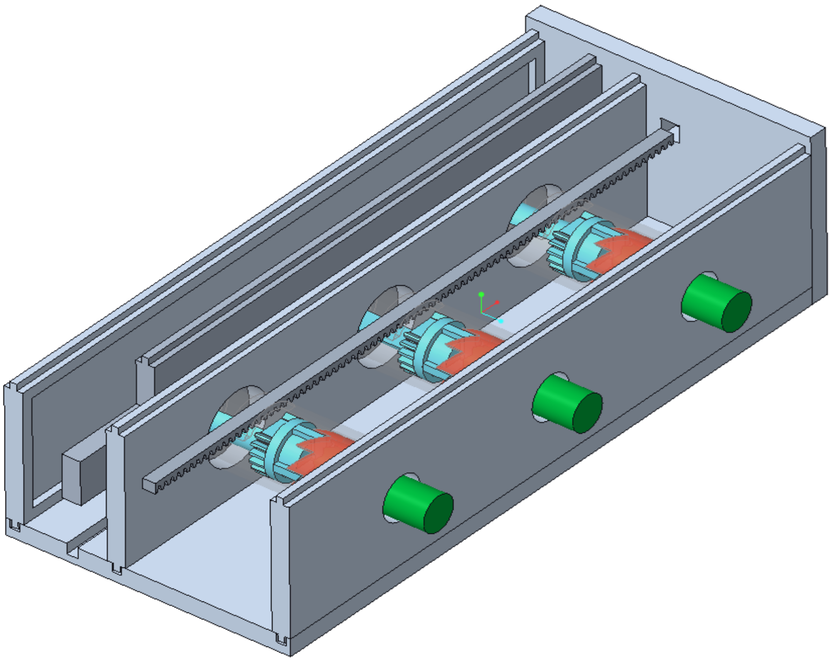


Figure 71. Inside view of the final CAD assembly

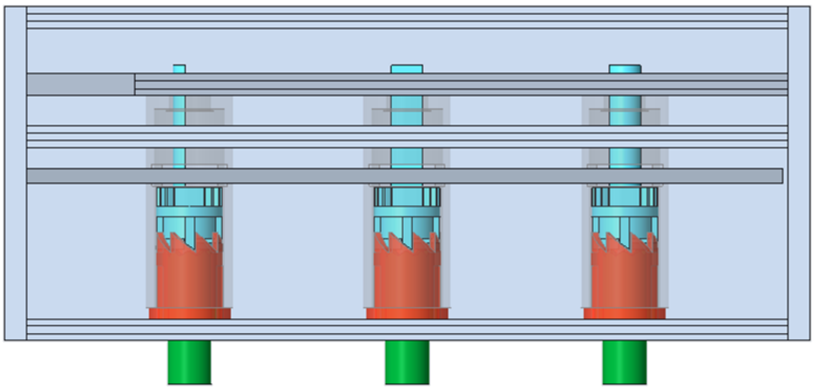


Figure 72. Top view of the final CAD assembly

First of all, the rectangular shape of the pin was modified to a rounded and flatted shape and it was moved from the center of the cam body to the outside to make sure that the part is not asymmetric. This new design allows to make sure that the pin has a completely different orientation for each small rotation, which means more possible combinations and so, more difficult to hack. The new design is illustrated in Figure 73.

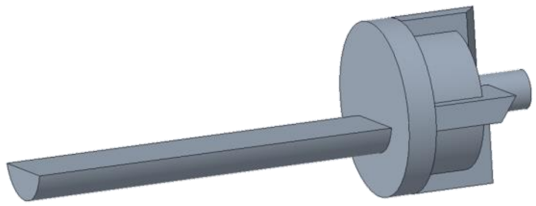


Figure 73. Final design of the cam pin

After the DOE test was performed, the best designs of the cam shaft were concluded. For this iteration, it was considered the cam shaft with the bigger diameter of 23.37mm and the slope of 72.748º, as the best option. However, the cam shaft used in this prototype, shown in Figure 74, has 8 teeth. The main reason was the increase of the security, since 8 teeth would allow 8 different orientations of the new pin, instead of 4 that would allow the 4 teeth cam shaft.

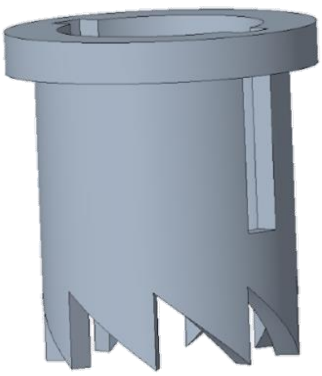


Figure 74. Final design of the cam shaft

Moreover, in order to ensure that the button pushes properly the new cam pin, the number of ridges at its end were increased from 4 to 8 as it is shown in Figure 75. Regarding the assembly of the button and the cam shaft, the push button was designed with two small extrusions on the sides, and the cam shaft was designed with two rectangular gaps to allow the push button to slide in and out of it.

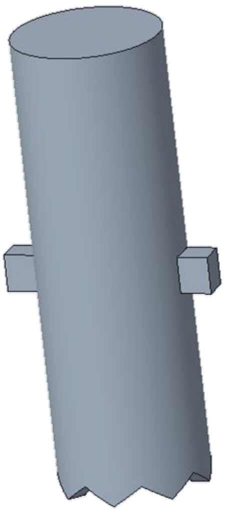


Figure 75. Final design of the push button

The best accomplishment of this prototype is the resetting mechanism. It is essential in order to return the pins to their starting positions and to make sure that the door is locked properly. The designed idea is based on a rack and pinion mechanism. It consists on a circular gear, the pinion that engages a linear gear, the rack, in order to translate linear motion into rotational motion. The pinion, shown in Figure 76, was designed with twenty teeth and the same outer diameter of the cam pin. The rack, shown in Figure 77, was designed with the suitable length in order to be able to rotate the three buttons at the same time.

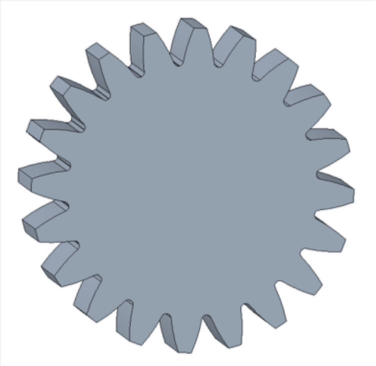


Figure 76. Design of the entire pinion

Figure 77. Design of the rack

As Figure 78 illustrates, the pinion is fixed to the cam pin, in the top part of its pin. Thus, the cam pins rotates by sliding the rack engaged to the pinions. In order to ensure that they rotate and stop in their original position, 4 teeth of the pinion were removed. Therefore the cam pin will rotate until the rack touches this section of the pinion, when the pin will stop rotating.

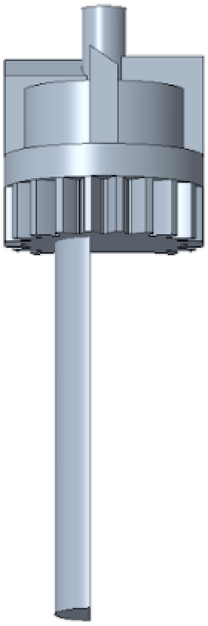


Figure 78. Cam pin and pinion assembly

Figure 79. Cam mechanism assembled

The teeth were removed in a particular position for each pinion in order to set different original positions. Figures 80, 81 and 82 show the designs of three examples of cam pins and their initial orientations as well. In their original positions, the section of the pinion without teeth is in the top part. So, the first pin will be placed horizontally, with the circular part on the top; the second pin, horizontally as well, but with the circular part at the bottom; and the third pin will be vertically, with the circular part on the right.

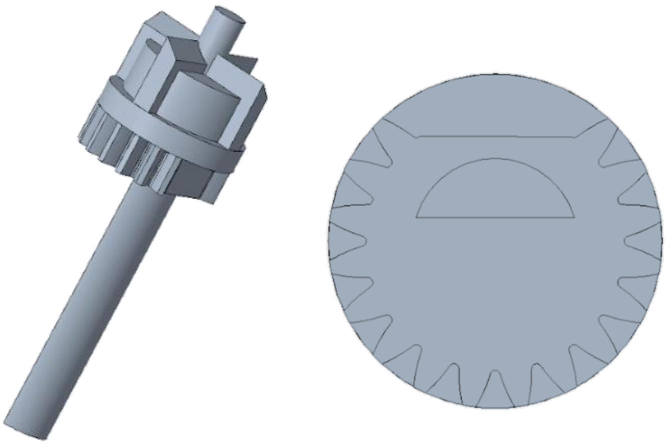


Figure 80. Pin 1

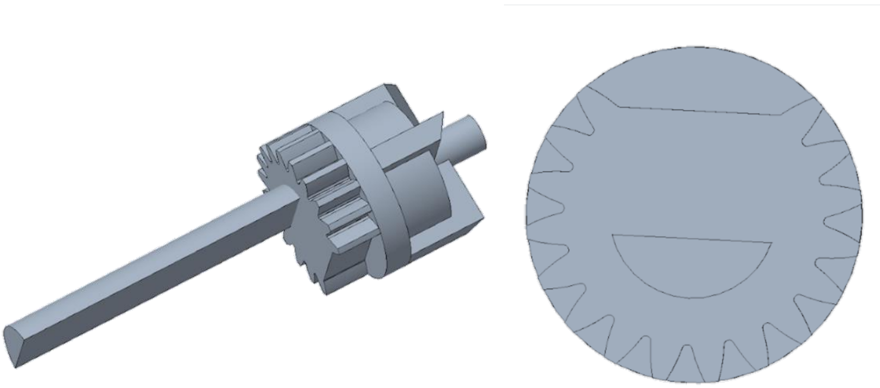


Figure 81. Pin 2

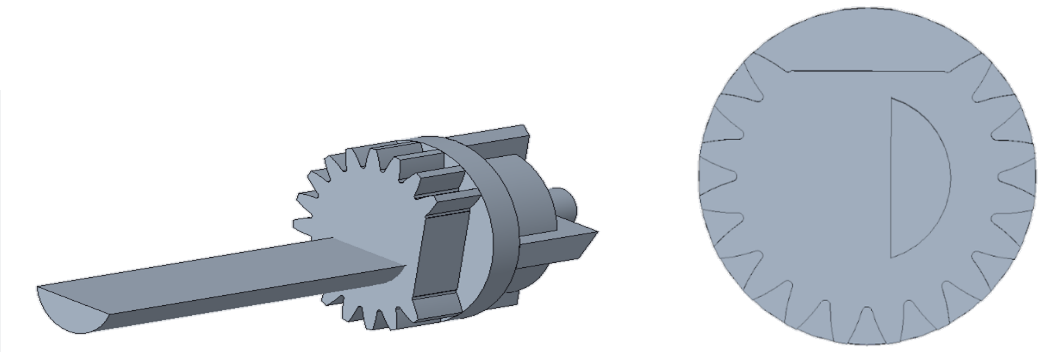


Figure 82. Pin 3

Concerning the design of the cam cover, it had to be modified in order to allow the rack to engage the pinion. As it is shown in Figure 83, the new design is essentially the same but with a gap that coincide with approximately 4 teeth of the pinion.

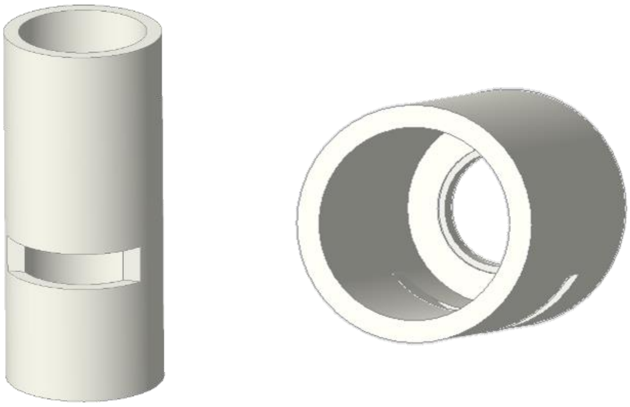


Figure 83. Final design of the cam cover

Regarding the assembly of all the parts, some plates were required to hide the secret orientations of the pins. They are:

- In the first level, a front plate (Figure 84) with three holes for the three push buttons.

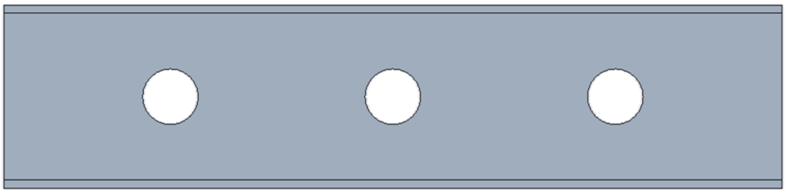


Figure 84. Front plate

- In the second level, a cam plate (Figure 85), with three holes. It was designed to fix the three cam covers.

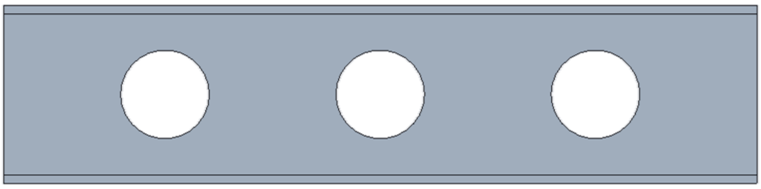


Figure 85. Cam plate

- In the third level, a sliding deadbolt plate (Figure 86). The new design is slightly different from the one of the previous iteration, but based on the same idea. If the correct combination is not entered, the extruded rectangles will interfere with the pins, blocking the movement of the plate. However, with the correct combination and so the correct orientation of the pins, the plate can slide. In this case, the pins are placed at the top of the rectangles.

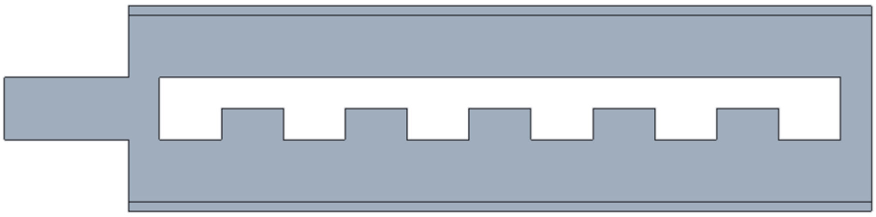


Figure 86. Deadbolt plate

- In the last level, a back plate (Figure 87).

Figure 87. Back plate

- A top and bottom plate (Figure 88). Both are exactly the same and they have some longitudinal gaps in order to fit the different plates.

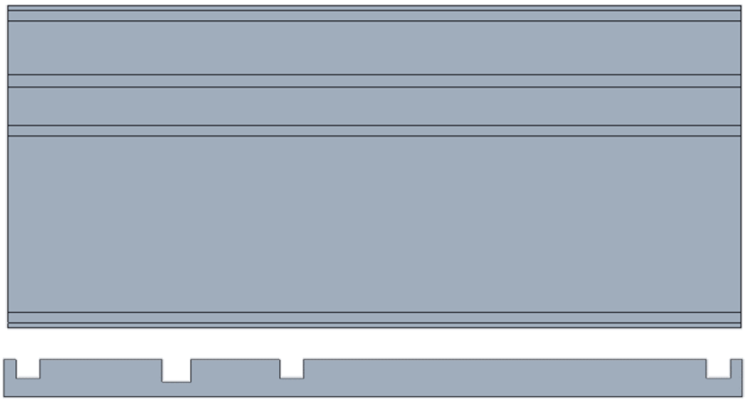


Figure 88. Top and bottom plate

- Two side plates (Figures 89 and 90). Both have a gap for the rack, and the left plate has an additional gap for the deadbolt to slide in and out of the door.

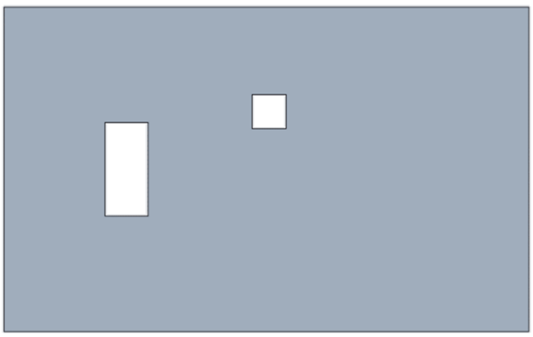


Figure 89. Left plate

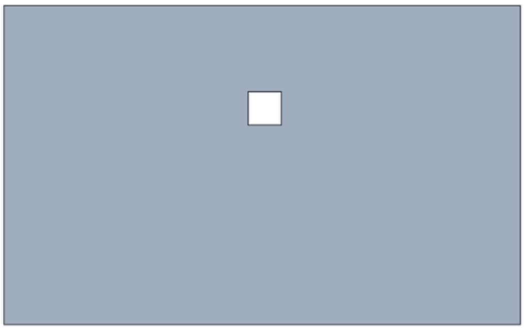


Figure 90. Right plate

Figure 91 illustrates the CAD assembly of the final prototype without the front and left plates. Figure 92 shows a side view of the prototype in which the cam cover is shown transparent to be able to appreciate the inside mechanism.

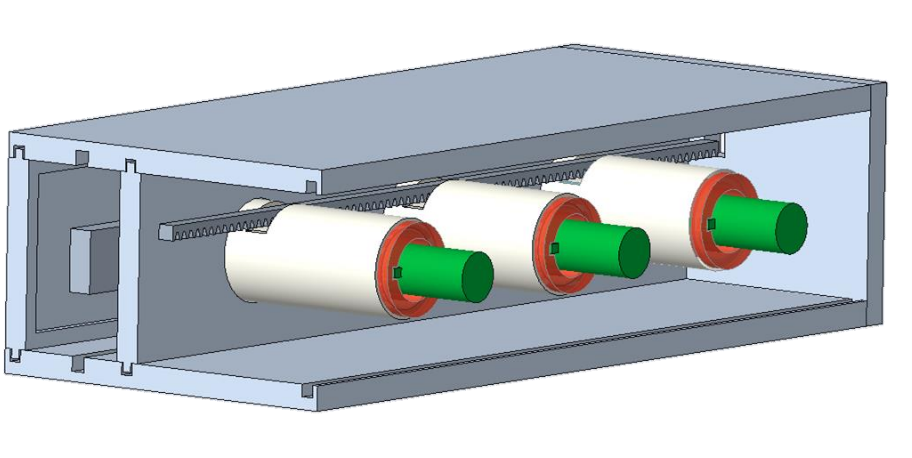


Figure 91. Final CAD assembly without front and left plates

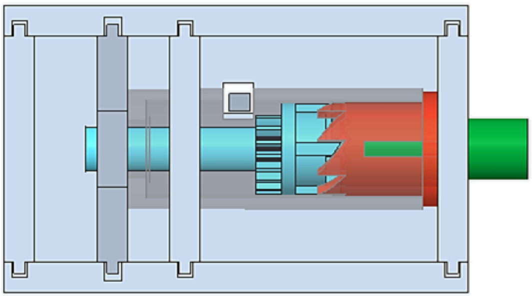


Figure 92. Side view of the final CAD assembly

Regarding the operation of the lock, Figure 93 illustrates the steps required to lock the door.

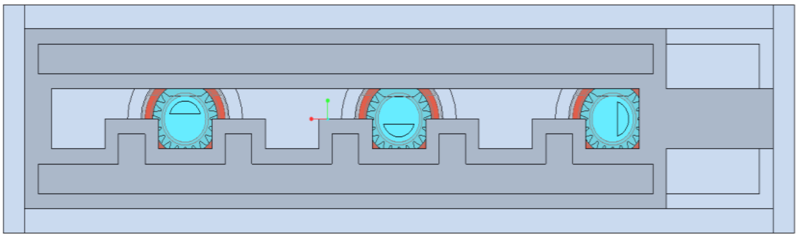
First, the door is unlocked and the deadbolt is inside the locking system. The cam pins are oriented in their original positions, which means with the flat part of the pinion on the top. In these positions, the cam pins are blocking the deadbolt plate and so, it cannot be slid.

Secondly, the combination has to be entered. In this example, the combination consists of: no clicks in the left button, 4 clicks in the middle one, and two clicks in the right one. Once the pins has rotated according with the number of clicks, their flat part should be at the bottom and the circular part at the top.

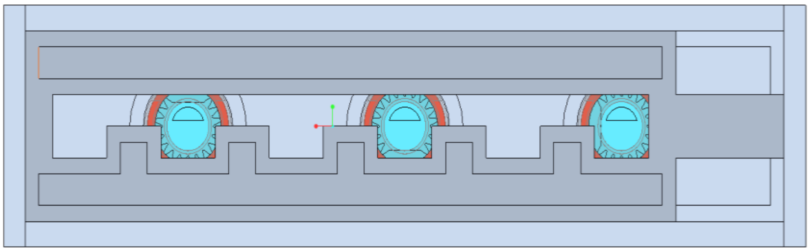
Thus, the deadbolt plate is able to slide since the pins are not interfering its way. By sliding the plate, the deadbolt enters in the door.

Finally, the pins have to be reset by sliding the rack through the hole until it stops by itself. Since they are in their initial orientations, the deadbolt is blocked and the door is locked properly.

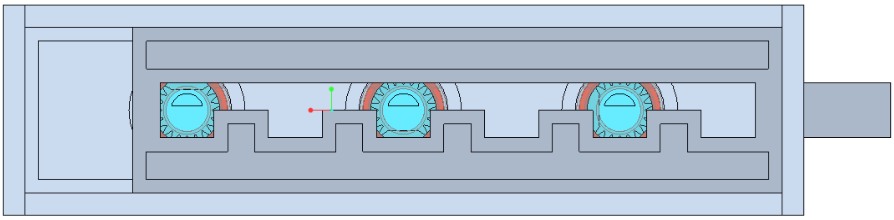
1. Initial position, unlocked



2. Correct combination, unlocked



3. Correct combination, locked



4. Initial position, locked

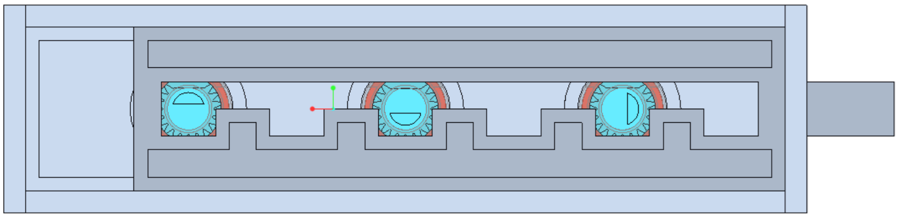


Figure 93. Steps to lock the door

The parts designed were 3D printed and assembled as it shown in Figures 94, 95 and 96.

Figure 94. Cam mechanism 3D printed

Figure 95. Final prototype without top and sides plates

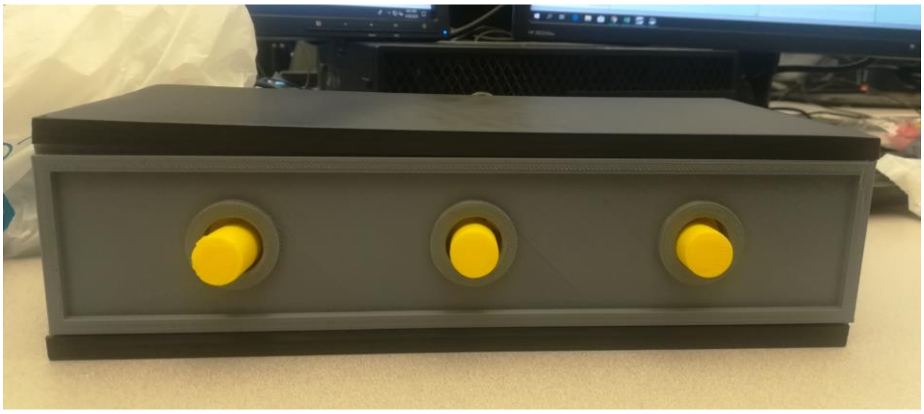


Figure 96. Final prototype

This final prototype achieved the goals of designing a keyless lock, very difficult to hack and easy to use. However, some features of the design could be improved. Regarding the assembly of all the parts, a 'Design for Assembly' test was accomplished to realize the vulnerabilities and possible development of the prototype.

3.7. 'DESIGN FOR ASSEMBLY' TEST

A 'Design for assembly' (DFA) analysis of the final prototype was performed in order to improve the assembly design and save time assembly. Since this process typically occupies between 40% and 60% of the total production period, the results of this test were essential to decrease the time required as much as possible.

DFA consists in the assembly of all the printed parts, measuring the time and considering the difficulties during the process. Table 14 includes a list of all the parts of the final prototype, divided in three groups, alpha and beta, and descriptions of handling, alignment and securing difficulties. In total, the theoretical assembly time sums to 56,7 s.

Alpha symmetry indicates the rotational symmetry about an axis perpendicular to the axis of insertion, and beta symmetry indicates the rotational symmetry about the axis of insertion. Insertion and secure times depends respectively upon difficulties and method, while handling and alignment times depends upon grasping method, presentation, size and part symmetry.

Group	Part	Alpha (deg)	Beta (deg)	Handling and Alignment	Insert and Secure	Time (sec)
Cam	Cam pin (x3)	360	0			2
	Cam shaft (x3)	360	0		Not easy to see inside	2,4
	Cam cover (x3)	360	360		Need to press down on the spring during assembly	3,4
	Slider key pin (x3)	360	0			2
	Spring (x3)	180	0	Part supplied as standard in box (tangle)		1,9
Plate	Front plate	360	180			2,3
	Cam plate	360	180		Need two hands	2,7
	Mid plate	360	180		Need two hands	2,7
	Base plate (x2)	360	180		Need two hands	2,7
	Left plate	360	360		Need two hands	2,7
	Right plate	360	360		Need two hands	3,2
Rack	Rack	360	180			2.6

Table 14. DFA table for final prototype

After the DFA analysis was performed, some considerations for the future assembly were concluded. Snap-fit or Integral Attachment Feature, that consists in assembling the parts by pushing the parts' interlocking components together, could be incorporated into the overall assembly to greatly decrease assembly time. When the plates were attached one to another, a combination of hot glue and duct tape was used. This proved to be a time consuming and painful way to assemble. So, incorporating snap-fit into the design of the plates, assembly would be as easy as lining up the pieces and clicking them together.

Besides, some the parts in the plate group could be combined as one piece, for instance the front plate and the base plate. This combined piece could be manufactured by V-bending the sheet metal that includes both pieces' features. This improvement would eliminate the need of two hands for assembly since the piece itself could stand by itself in a very stable manner.

The cam cover can also be integrated into the middle plate to reduce the number of parts and assembly time. This will reduce assembly time significantly since the cam cover has to be at a very specific location in respect to the mid plate and be held with the mid plate while assembling the front plate. This process is not only difficult but also require more than two hands. Consequently, combining the cover and the mid plate will eliminate such difficulties.

Figure 97. Camshaft cover disassembly

Overall, DFA analysis allows to estimate the design efficiency in order to make modifications on the design to improve it. The equation to calculate DFA efficiency is:

$$Efficiency = \frac{3 * theoretical \min number\ of\ parts}{total\ assembly\ time}$$

The current product has 23 minimum parts and approximately an hour is required to assembly the parts using glue and duct tape. This leads to a DFA efficiency of 1,9%. Nonetheless, after incorporating the DFA suggestions, the improved product would have only 18 minimum parts, and an assembly time of 56,7 seconds using snap-fit and bolts. These modifications would allow to reduce the manufacturing cost and time, increasing the DFA efficiency to 95%.

The schedule of the project did not allow time to implement these suggestions, however, the final assembly of the parts would look very similar before and after implementing these DFA suggestions. Figures 98 and 99 illustrates the final assembly.

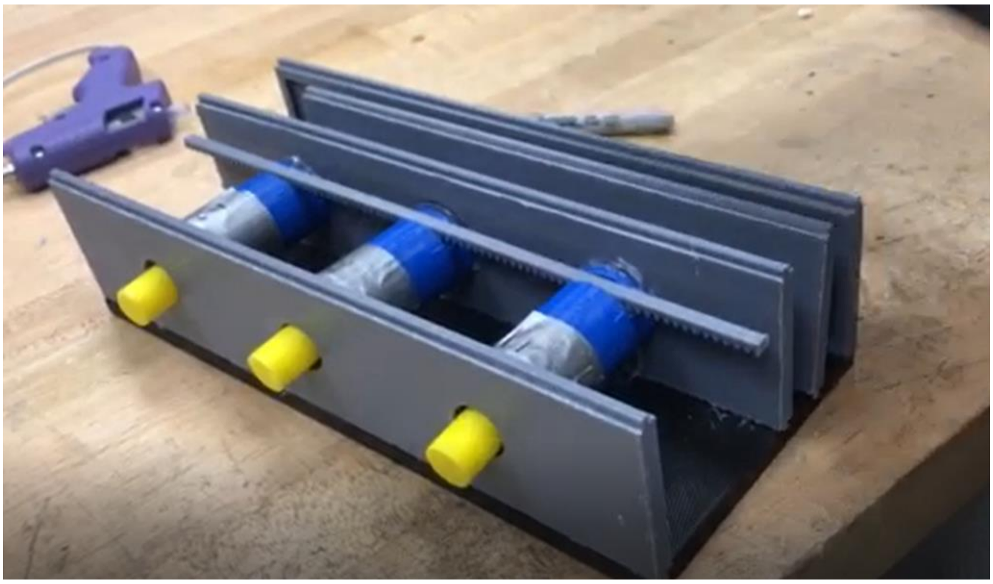


Figure 98. Final assembly without top plate

Figure 99. Final assembly

3.8. FUTURE STEPS

Despite of all the improvements since the first iteration of the prototype, there are some aspects of the design that could be improve in order to provide a higher degree of security and quality. Due to lack of time, they could not be performed, as happened with the results of the 'Design for Assembly' suggestions.

Although the printed prototype has 3 push buttons, the original idea was a 9 buttons lock (Figure 100). With exactly the same mechanism for each button, more possible combinations would be able, making the lock harder or even impossible to hack.

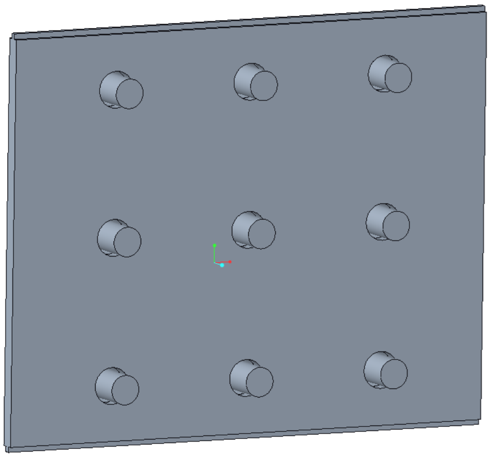


Figure 100. 9buttons lock

Since there are many possible patterns of any length, perhaps it could be difficult to remember it. In order to solve this, a possible solution could be to incorporate in each button a group of letters, for example ABCDEFGH in the first button. Thus, depending on the number of clicks in the button, it would correspond to a specific letter. In this way, the user could create its combination as a word and so, remember it easily.

Another aspects of the design that was not created due to the lack of time, were the mechanisms that connect movements of the user to the lock, such as the slip of the deadbolt plate or the reset. A handle attached to an A-arm, as in the fourth iteration of the prototype, would be an idea in order to slide the deadbolt in and out of the door. For the reset mechanism, pressing a button could slide the rack through one way in order to rotate the pins, and then the rack would come back forward to be ready for the next reset.

Furthermore, regarding the operation of the cam mechanisms, some progress could be accomplished. Changing the material of the cam shaft and cam pin could lead to a smoother rotation, making easier to translate the click in the button into a small rotation of the pin. Moreover, a spring with a lower stiffness constant could allow that less force would be required for each click.

Finally, the scale of the prototype would be required in order to be able to install the lock in all doors, replacing the current locks without many changes.

The prototype was printed only with 3 buttons and in a big scale just in order to test the operation of the mechanism. The product idea would become a marketable product if the improvements described above were performed.

4. PROTOTYPING RESOURCES

Fused Deposition Modeling has been used to 3D print the project since it is a very convenient mean of developing rapid and low cost prototypes, and an iteratively prototyping process was required before the final design.

In order to 3D print, the parts were designed by using Creo Parametric 3D Modeling Software, a computer-aided design (CAD) program. The printer used to model the prototypes is called Lulzbot TAZ 6 and it is shown in Figure 101. It is considered the most reliable and accessible printer, and it has a print area of: 0,28 m x 0,28 m x 0,25 m. The thermoplastic material used to print was polylactic acid, the PLA. It has minimal warping and shrinking, therefore, it is convenient featuring flat surfaces and hard angles, or high tolerances for fit. The unit cost of FDM printed parts is USD 0,03 per gram (0,026 €/g).

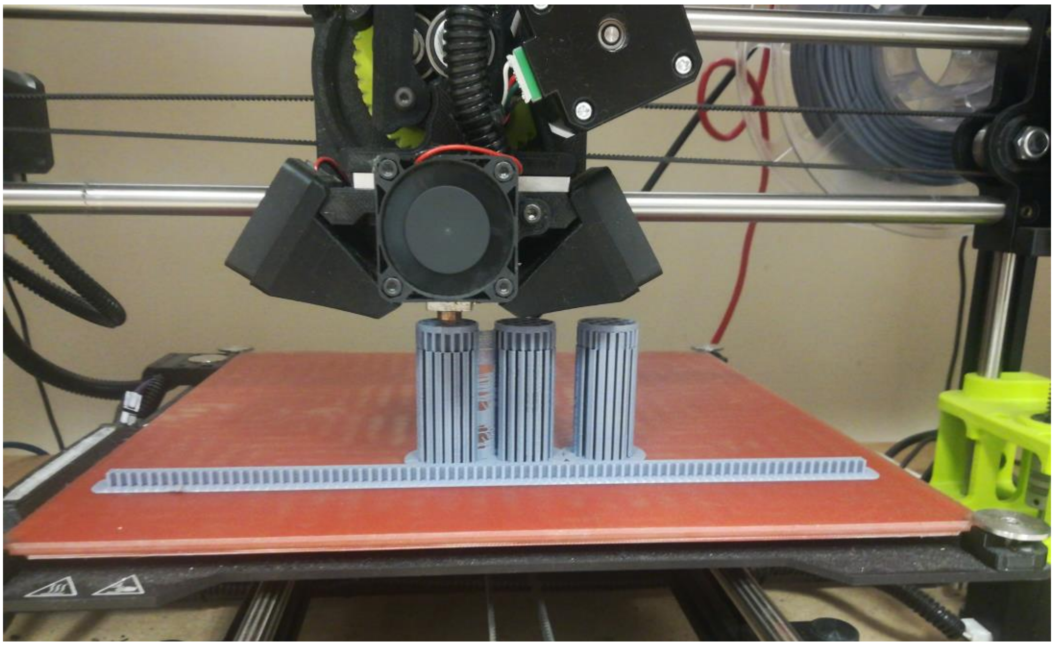


Figure 101. Lulzbot TAZ 6 printer

Additionally, other materials such as cardboard, pens, plastic figures and small wooden sticks, were used to model some of the iterations for the prototype. This avoided the need of modeling all the parts in CAD and the 3D printing as well, therefore, it allowed to save time and money during the prototype development. Hot glue gun and tack tape were used to assemble the different parts of each iteration.

Other computer software, like Excel and Matlab were used to do the calculations required.

Moreover, online orders of specific compression springs were needed during the latest iterations. Different lengths, stiffness, and outer diameters were bought through McMaster-Carr.

Overall, the total budget allocated for this project was USD 150 (132 €), from which, only USD 56 (49,3 €) were spent over the prototype development. The prototype waterfall budget in Figure 102 summarizes the money spent on each material or part, as well as the money remaining.

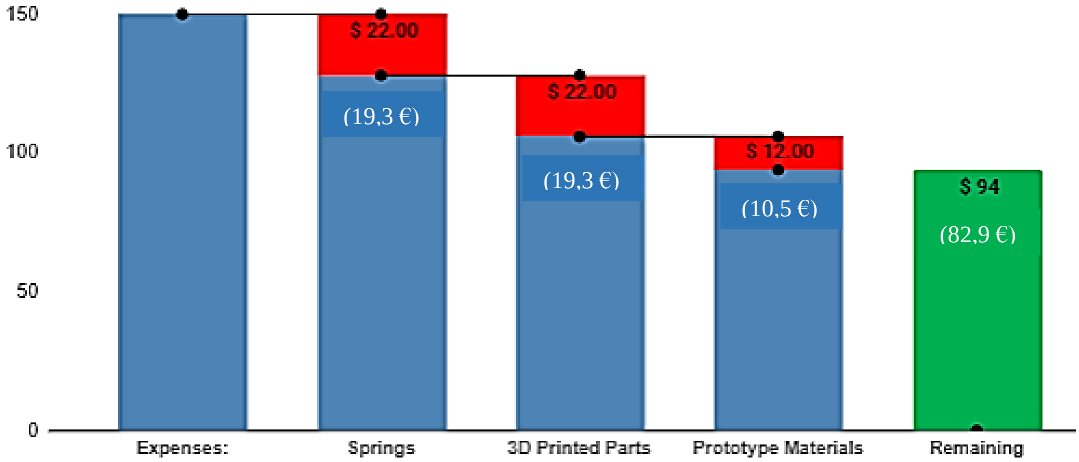


Figure 102. Prototype Waterfall Budget

5. MANUFACTURING COST

In order to estimate the manufacturing cost of the product idea, a software called A priori was used. From the CAD model of each part of the prototype and a few inputs, A priori is able to perform a simulation-driven costing. The material, the manufacturing process, the production volume, and product life, are some of the inputs required.

Standard key locks are made of various strong metals. Its internal mechanisms are generally made of brass or die-cast zinc, the deadbolt is usually made of steel or stainless steel; and the outer casing may be made of brass, chrome, steel, nickel or any other durable metal or alloy. Most of them are manufactured with die-casting and further machining. However, standard combination locks are usually made of zamak, a zinc alloy, by injection molding. Also, stainless steel or cold-rolled steel are used for the outer components.

Based on the manufacturing information of the current locks, the materials and processes for each part of the product was decided. Table 15 displays the information provided by A priori: the piece part cost and the total capital investment depending on the CAD model, the material and the process selected. The cost was estimated for an annual production of 16,000 locks and a product life of 10 years.

Part	Number of parts per product	Process	Material Composition	Total Capital Investments (USD)	Piece Part Cost (USD)
Front plate	1	Sheet Metal	Steel, AISI 1035	0	0,74 (0,65 €)
Cam pin	3	Plastic Molding	Acetal, Copolymer	13.037,66 (11.477,32 €)	0,47 (0,41 €)
Cam shaft	3	Plastic Molding	Acetal, Copolymer	8.692,69 (7.652,35 €)	0,13 (0,11 €)
Push button	3	Plastic Molding	Acetal, Copolymer	8.336,39 (7.338,70 €)	0,43 (0,38 €)
Cam cover	3	Plastic Molding	Acetal, Copolymer	11.643,11 (10.249,66 €)	0,2 (0,18 €)
Base plate	3	Sheet Metal	Steel, AISI 1035	23.500,32 (20.687,81 €)	1,45 (1,28 €)
Cam plate	1	Plastic Molding	Acetal, Copolymer	9.711,46 (8.549,20 €)	0,32 (0,28 €)
Bolt plate	1	Sheet Metal	Steel, AISI 1035	23.010,90 (20.256,97 €)	0,81 (0,71 €)
Rack	1	Plastic Molding	Acetal, Copolymer	9.427,45 (8.299,18 €)	0,12 (0,11 €)
Spring	3	Purchased	Zinc	0	1,14 (1 €)

Table 15. A priori data of manufacturing cost

Therefore, considering the designed 3-buttons lock, the total cost of the product would be USD 13,45 (11,84 €).

On one hand, regarding the materials selected, acetal or polyoxymethylene (POM) is a very high tensile strength plastic with significant creep resistant properties. It has a particularly low coefficient of friction which combined with its high resistance to heat, water and chemical compounds, makes it very useful for applications that utilize gears. Due to this characteristics it was considered the best option for the inside mechanism of the lock, which parts have to rotate smoothly without friction. Therefore, the cam pin with the pinion assembled, the rack, the cam shaft, the push button, the cam cover and the cam plate, would be made of acetal by plastic molding. Moreover, this material is a cheap plastic that helps to reduce the manufacturing cost. This material cost about 3,52 USD per kilogram (3,1 €/kg).

On the other hand, the outer surfaces does not move and they should be hard in order to achieve maximum safety. For this reason, carbon steel 1035 was considered the best raw material for the different plates, especially for the front one. It is a water resistant steel with high wear resistance and hardenability, as well as one of the cheapest, it costs approximately 3,426 USD per kilogram (3,02€/kg). For these parts, as they are plates, the manufacturing process selected was sheet metal.

6. MANAGEMENT PLAN

Over the semester, there have been different milestones to ensure the progress of the project. The key milestones and deliverables for the project are listed in Table 16.

Deliverable	Date
Project Proposal	21 January 2019
Design Review	18 February 2019
Prototype Review	1 April 2019
Design of Experiment Test	15 April 2019
Design for Assembly Test	22 April 2019
Final Prototype Review	29 April 2019

Table 16. Project milestones

In order to schedule the semester and ensure the achievement of the milestones, a Gantt chart was created and updated over the course of the project. It is a project management tool that includes the action item list and its deadlines. The final Gantt chart of the project is displayed in Table 17 and it is organized week by week from 21st January to 29th April.

	January		February				Mars				April				
	21	28	4	11	18	25	4	11	18	25	1	8	15	22	29
Inspiration															
Brainstorming															
Background research															
Initial design sketches															
Project Proposal															
Research market need															
SWOT analysis/ Design tree analysis															
CAD of the first iteration															
3D printing of the first iteration															
First prototype assembly															
Lock/Unlock mechanism ideation															
CAD of the second design															
Design Review															
Brainstorm to improve security															
Second iteration design															
Third iteration design															
Research on retractable mechanisms															
Fourth iteration design															
CAD of the fourth iteration															
3D printing of the fourth iteration															
Improvements in the CAD models															
3D printing of the modified parts															
Fourth iteration assembly															
Prototype Review															
CAD of 6 different cam mechanisms															
3D printing of the parts															
Design of Experiments test															
Final prototype design															
CAD of the final prototype															
3D printing of the final prototype															
Final prototype assembly															
Design for Assembly test															
Final Prototype Review															

Table 17. Final Gantt chart