# GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

# GRAPHICAL METHOD FOR MECHANISM SYNTHESIS USING VIDEO SEQUENCES FOR INPUT DATA

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Madrid

Junio de 2019

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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

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**GRAPHICAL METHOD FOR MECHANISM SYNTHESIS USING VIDEO SEQUENCES FOR INPUT DATA**

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Madrid

Junio de 2019

# MÉTODO GRÁFICO PARA SÍNTESIS DE MECANISMOS EMPLEANDO SECUENCIAS DE VÍDEO

**Autor: Lorenzo García, Cristina de.**

Director: Gutiérrez Wing, Enrique.

Entidad Colaboradora: BU - Boston University.

## RESUMEN DEL PROYECTO:

*Introducción:*

Los mecanismos son una de las formas más fiables, eficientes y económicas de reproducir un movimiento. Además, dependiendo de los materiales seleccionados, pueden elaborarse mecanismos relativamente compactos y ligeros, lo que resulta muy beneficioso para ciertas aplicaciones, por ejemplo, el mecanismo de apertura y cierre del compartimiento de equipaje de mano en un avión.

Uno de los mecanismos más importantes son los **mecanismos de cuatro barras**. Son una combinación de elementos rígidos unidos mediante articulaciones formando una cadena cinemática cerrada. En concreto, están constituidos por tres barras móviles unidas mediante nudos articulados, y unidas a su vez a una cuarta barra fija mediante pivotes. La barra conectada a un punto fijo mediante un pivote recibe el nombre de *manivela*, y generalmente proporciona el movimiento al mecanismo. La segunda barra conectada a un punto fijo se denomina *balancín*, es la barra que recibe el movimiento. Dependiendo del diseño del mecanismo y las dimensiones de las barras, la biela y el balancín pueden girar 360º o tener una rotación limitada. La barra que conecta la manivela y el balancín se denomina *acoplador*, y contiene el punto cuyo movimiento resulta de interés. Los mecanismos de cuatro barras describen un movimiento plano pues todos sus elementos se mueven permanentemente paralelos a un plano fijo. Por otro lado, los mecanismos de cuatro barras tienen un grado de libertad, es decir, con definir el movimiento de una barra, normalmente el de la manivela, queda definido el movimiento de todo el mecanismo. Es posible transformar la rotación de la manivela en movimientos más complejos y generar

curvas muy diferentes. Además, estos mecanismos se pueden combinar para generar movimientos más elaborados y precisos.

El diseño de mecanismos es fundamental a la hora de encontrar la solución óptima para describir un movimiento deseado. El diseño de mecanismos consta de dos partes: la síntesis y el análisis.

La **síntesis** de mecanismos es el proceso iterativo, creativo e intuitivo para el diseño de mecanismos que describan un movimiento deseado. Consiste en seleccionar el tipo de mecanismo más adecuado y una vez seleccionado, encontrar el número de eslabones necesarios, sus tamaños, puntos fijos, la disposición de piezas y los materiales a emplear, a fin de que el mecanismo resultante desempeñe la función determinada. Este proyecto se centra en simplificar y resolver los problemas relacionados con la **síntesis cinemática**. Se centra en el estudio del movimiento de los mecanismos (establecer las dimensiones de las barras que forman el mecanismo, el tipo de unión entre ellas, el movimiento de entrada…). No considera la estática (el estudio de fuerzas y momentos) ni la dinámica (el estudio de la acción de las fuerzas) de la mecánica de sólidos.

El **análisis** de mecanismos es el proceso posterior a la síntesis. Trata de estudiar que el mecanismo diseñado describa el movimiento deseado analizando la trayectoria, velocidad y aceleración de los puntos que lo constituyen y comprobando que todos los esfuerzos que aparecen son menores que los esfuerzos que las piezas pueden soportar.

La síntesis de mecanismos es un paso clave a la hora de realizar un buen diseño para generar unos movimientos determinados. No se puede realizar ningún análisis a un mecanismo si no se ha sintetizado previamente. Este proyecto se centra en esta primera parte del diseño de mecanismos y trata de encontrar una solución válida a los problemas más comunes asociados con la síntesis: la generación de trayectorias y el guiado de sólidos.

La **generación de trayectorias** pretende controlar la posición de un punto del plano dispuesto a seguir una trayectoria determinada. Si el acoplador tiene forma triangular, dependiendo de su tamaño, con el giro de la manivela el vértice de dicho triángulo traza una curva llamada *coupler curve* o curva pareada.

El **guiado de sólidos** trata de controlar el movimiento de uno de los sólidos de manera que pase por una serie de posiciones determinadas.

Actualmente se han desarrollado distintos procedimientos para automatizar el proceso de la síntesis de mecanismos y permitir el diseño de mecanismos sin necesidad de tener amplios conocimientos acerca de la síntesis de mecanismos. Algunos de estos métodos se desarrollan por medio de programas de ordenador de uso frecuentes como son Matlab o Mathematica. Otros métodos utilizan procesos más complejos que implican varias iteraciones, programas de simulación o métodos numéricos.

La empresa de animación **Disney** ha desarrollado una metodología para permitir a usuarios no expertos diseñar y fabricar personajes animados mediante sistemas mecánicos formados por mecanismos y engranajes. El objetivo de esta nueva metodología es mejorar la técnica para animar los robots que aparecen en sus películas, atracciones o espectáculos, que imitan el movimiento de humanos o animales, de manera que sean cada vez más cercanos a la realidad. Su metodología se basa en el uso de una base de datos que contiene información estándar de trayectorias y de los mecanismos asociados que las generan.

Con este trabajo se pretende simplificar el proceso de diseño de mecanismos de cuatro barras con el desarrollo de un método para diseñar un mecanismo capaz de reproducir un movimiento captado en una secuencia vídeo. Se pretende que este método sea sencillo de tal manera que pueda ser aplicado sin necesidad de amplios conocimientos de la síntesis de mecanismos, pero a su vez, basado en sus principios fundamentales.

*Metodología:*

El método desarrollado en este proyecto simplifica el proceso de síntesis de mecanismos siguiendo la idea propuesta por Disney. Se basa también en diseñar un mecanismo a partir de una curva que se pretenda generar. Sin embargo, no requiere el uso de bases de datos y la curva que se utiliza como punto de partida se obtiene del vídeo que muestra el movimiento que se pretende reproducir.

Este método se pone en práctica mediante un ejemplo de aplicación. En concreto, se trata de diseñar un mecanismo que imite el movimiento de los pies subiendo las escaleras para facilitar la carga de cajas o carritos de la compra por las escaleras.

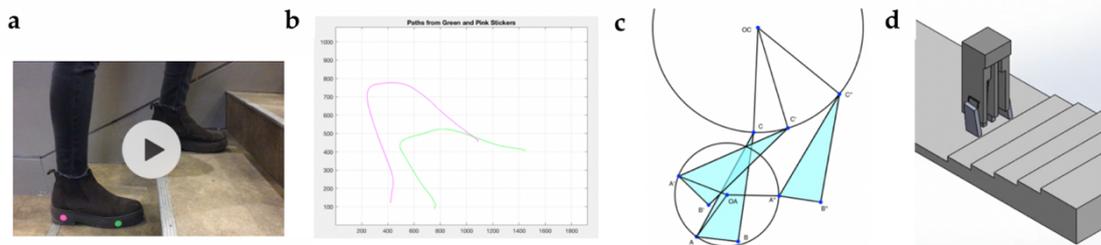Este método se puede dividir en las siguientes etapas:



*Figura 1: Revisión de las principales etapas de la síntesis de mecanismos: a) Secuencia de vídeo inicial; b) Trayectorias descritas por las etiquetas; c) Diseño de un mecanismo mediante el método de las tres posiciones; d) Simulación del resultado final.*

a. **Secuencia de vídeo del movimiento deseado.** Es el punto de partida para resolver el problema. Para lograr un buen resultado, el vídeo debe tener una configuración particular. Los puntos de interés en el vídeo deben resaltarse con etiquetas de colores claramente diferentes en comparación con el fondo. Además, la cámara no debe moverse durante la grabación del vídeo y debe estar grabado desde un plano paralelo al movimiento sin ningún tipo de distorsión.



*Figura 2: Posición inicial, intermedia y final de la secuencia de vídeo que representa un pie subiendo las escaleras.*

b. **Detección de posición en el vídeo usando Matlab.** Mediante un programa desarrollado en Matlab, se obtienen las trayectorias que describen las etiquetas durante la secuencia de vídeo. Este programa se basa en localizar la posición de las etiquetas en cada marco detectando la posición de los píxeles cuyos valores presentan una gran diferencia en comparación con el resto. El resultado obtenido del análisis del vídeo se utiliza como punto de partida para la síntesis. La idea es

diseñar un mecanismo que repita sucesivamente el movimiento captado en la secuencia de vídeo.
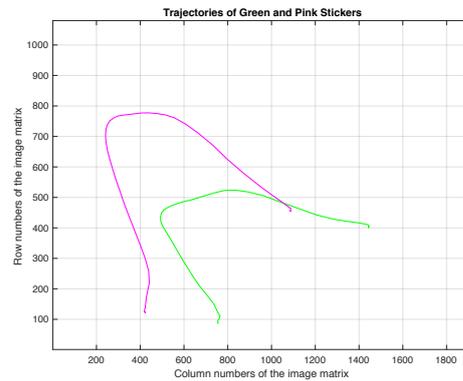


*Figura 3: Trayectorias descritas por las etiquetas a lo largo de la secuencia de vídeo.*

c. **Síntesis de mecanismos con el uso de Math Illustrations.** Se consideran dos métodos gráficos diferentes para la síntesis de mecanismos que resuelven los problemas de guiado de sólidos y de generación de trayectorias: el método de las tres posiciones y el método de las *coupler curves*. Ambos métodos se desarrollan con el uso del programa Math Illustrations que mediante una sencilla interfaz de usuario permite resolver problemas básicos de dibujo técnico.

- El **método de las tres posiciones** trata de resolver el problema de guiado de sólidos. Permite definir tres posiciones de un sólido y diseñar un mecanismo que siga dichas posiciones. Estas posiciones se obtienen del vídeo analizado con Matlab. Asimismo, se definen una serie de reglas para evitar encontrar entre dichas posiciones un punto que interrumpa el movimiento.
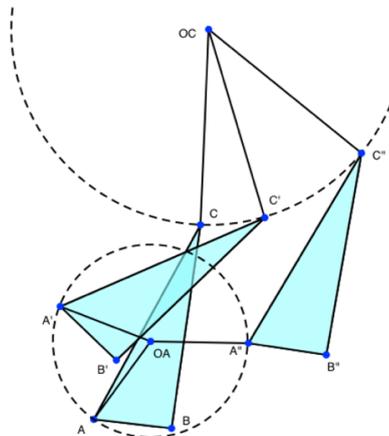


*Figura 4: Movimiento completo del mecanismo diseñado mediante el método de las tres posiciones.*

- El **método de las *coupler curves*** trata de resolver el problema de generación de trayectorias. Permite diseñar un mecanismo de cuatro barras con un acoplador triangular que, con el giro de la manivela, el vértice de dicho triángulo genera la trayectoria deseada. La trayectoria que se pretende conseguir se obtiene del vídeo analizado con Matlab.
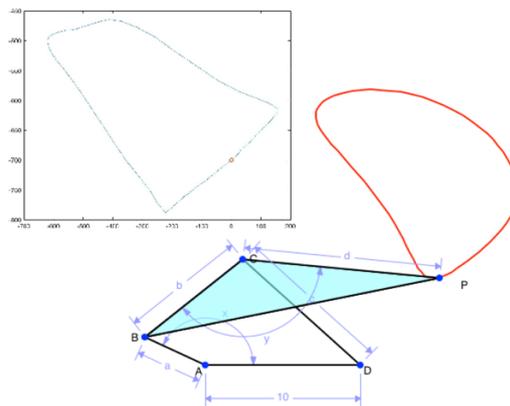


*Figura 5: Movimiento completo del mecanismo diseñado mediante el método de las coupler curves.*

d. **Verificación del movimiento generado con SolidWorks.** Se verifica el correcto funcionamiento de los mecanismos diseñados mediante una simulación en SolidWorks lo más cercana posible a la realidad. Esto permite detectar y corregir posibles fallos antes de iniciar el proceso de construcción.
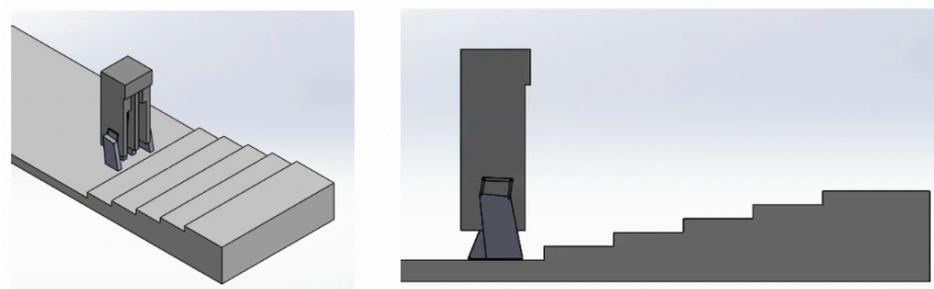


*Figura 6: Simulación final*

<u>*Resultados*</u>:

La metodología desarrollada en este proyecto pretende ser un primer acercamiento a la síntesis de mecanismos. Elimina las partes más complejas del proceso, como el uso expresiones matemáticas como dato de entrada, reemplazadas por un vídeo, o la

necesidad de usar un software o una base de datos para hacer la síntesis, reemplazada por métodos gráficos sencillos.

El **código** implementado en Matlab es muy eficiente incluso con colores de fondo diferentes al del ejemplo de aplicación, siempre que sean claramente diferentes de los colores de las etiquetas. Los **métodos gráficos** introducidos para realizar la síntesis de mecanismos son fáciles de entender, pero también proporcionan los conocimientos básicos para métodos más avanzados de síntesis de mecanismos. Sin embargo, aún requieren un mayor desarrollo y optimización, ya que dependen en gran medida de los criterios del diseñador. Ambos métodos considerados presentan algunas limitaciones. El método de tres posiciones sólo puede definir un máximo de tres posiciones del movimiento que se desea reproducir y el método de las *coupler curves* solo es válido para generar una curva cerrada. Finalmente, la **simulación** proporciona una primera impresión realista de cómo funcionará el mecanismo en la realidad.

En relación con el ejemplo de aplicación, resulta ser un movimiento más complejo de lo esperado. El dispositivo final que se propone en este proyecto puede considerarse como un primer prototipo de un aparato para incorporar en cajas o incluso en sillas de ruedas, con las modificaciones de tamaño apropiadas, para hacer que suban las escaleras sin la necesidad de intervención humana.

*Conclusiones:*

Los resultados obtenidos de aplicar el método desarrollado en este proyecto son mecanismos que cumplen su función, reproducen un movimiento especificado como objetivo de manera continua. Sin embargo, la transmisión del movimiento no es óptima, sino que requiere de futuras mejoras. Por ello, los mecanismos obtenidos por este método se podrían utilizar como punto de partida para los métodos numéricos de síntesis de mecanismos. Se pueden considerar como un prototipo inicial del mecanismo final que tras la aplicación de otras técnicas más complejas y precisas, sería posible obtener una solución optimizada.

# GRAPHICAL METHOD FOR MECHANISM SYNTHESIS USING VIDEO SEQUENCES FOR INPUT DATA

## *Introduction:*

Mechanisms are one of the most reliable, efficient and cost-effective ways to generate a desired motion. Furthermore, with appropriate materials selection, mechanisms can become lightweight and space-saving, resulting in very useful devices for certain applications such as the opening and closing mechanism for a luggage door compartment in an airplane.

One of the most important mechanisms is the **four-bar planar linkage**. It consists of three moveable bars or links connected by one-degree-of-freedom joints and linked in turn to a fourth fixed bar by pivots forming a closed kinetic chain. The link connected to the ground by a hinged joint, which usually acts as the input, is called *crank*. The other link connected to the ground is called *rocker*. Depending on the dimensions, the crank and rocker can rotate 360º or can have a limited rotation. The link that connects the crank and the rocker is called *extension bar* or *coupler*, it contains the point which generates the motion of interest. All these links that make up a four-bar move in parallel planes. Besides, this type of mechanism has a one degree of freedom, meaning that by defining the motion of one link, usually the crank, the motion of the entire mechanism is defined. It is possible to transform the rotation of the crank to very different movements and to generate very different curves. Moreover, these mechanisms can be combined together to generate more complex motions. For all these reasons, this type of mechanisms is one of the simplest and easier to design and manufacture.

The design of mechanisms is fundamental to create the optimal device with particular motion characteristics. It consists of two different parts: synthesis and analysis.

The **synthesis** of mechanisms is the iterative, creative and intuitive process for the design of mechanisms to describe a desired motion. It consists of choosing the most appropriate type of mechanism and once selected, find the number of necessary links, their dimensions, fixed points, the disposition of the parts and the materials to be used, so that the resulting mechanism generate the determined motion. This project focuses on

simplifying and solving **kinematic synthesis** problems. It focuses on the study of the relative motion of the linkage without considering statics (the study of forces and moments) and kinetics (the study of action of forces) of solid mechanics.

The **analysis** of mechanisms is the process that come after the synthesis. It attempts to study that the designed mechanism complies with the requirements previously specified by analyzing the trajectory, speed and acceleration of different points that constitute it, verifying at the same time that all the stresses that appear are smaller than the stresses that the parts can handle.

The synthesis of mechanisms is a key step to create potential linkage design solutions for different kinematic applications. Anything can be analyzed until it has been previously synthesized into existence. This project focuses on this first process of the design of mechanisms and tries to address a solution for the most common problems associated with the synthesis: path generation and motion generation problems.

The **path generation** problem aims to control the position of a point in the plane so that it follows some prescribed path or curve. The controlled points in a four-bar linkage are usually in the coupler bar. Depending on the shape of the coupler and the position of its selected point, different motions are produced generating the so-called coupler curves.

The **motion generation** problem attempts to control the motion of one of the solids in the plane so that it sequentially passes through some specific positions.

At this time, simple interactive systems have been developed to try to automate the synthesis process and to enable non-expert users to design their own mechanisms. From systems based on common numerical computer environments such as Matlab or Mathematica, to more complex methodologies that involve iteration processes, computational software or numerical techniques.

In particular, **Entertainment Disney company** developed a methodology to facilitate non-expert users to design and manufacture complex animated mechanical characters whose working principle is based on mechanisms and gears. The purpose of this new system is the simulation of human or animal movements, as less identifiable by eye as possible, to animate the robots that appear in their movies, attractions or spectacles. Their

methodology is based on the use of a database with parametrized mechanisms assembly types and the motion generated by each of them.

This project aims to simplify the four-bar linkages synthesis process from the development of a methodology that allows designing four-bar mechanisms which reproduce the motion of a rigid body captured in a video sequence. This methodology allows non-experts to design four-bar linkages without the need for extensive knowledge about the synthesis of mechanisms but at the same time, it allows them to learn the basic steps of the synthesis process.

## *Methodology*:

The method implemented in this project simplifies the synthesis of four-bar planar linkages following the idea initiated by Disney. It is also based on designing a mechanism containing one point that generates the same path or curve specified as input. However, it does not require a database and the path or curve used as input is obtained from a video sequence.

This method is developed from the design of a mechanism for a practical application. In particular, from the design of a mechanism that that reproduces the movement of human's feet climbing stairs captured in a video sequence, to facilitate the lifting of loads through the stairs.

This method can be divided in the following main steps:
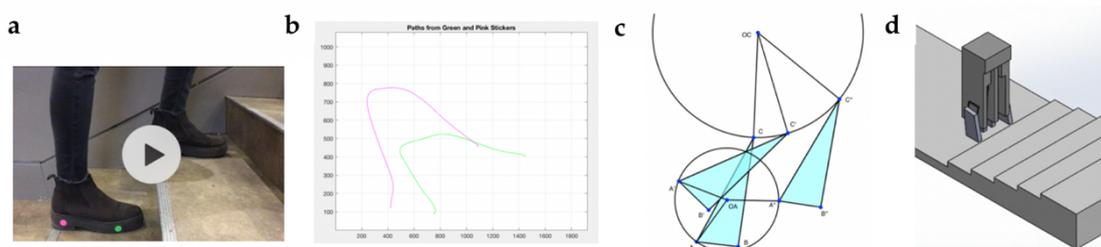


*Figure 1: Overview of the main stages of the synthesis process: a) Video sequence used as input; b) Trajectories described by each sticker; c) Synthesis of the mechanism by three-positions method; d) Simulation of the designed mechanism.*

a. **Video sequence of the desired motion.** It is the input for the problem to solve. In order to achieve a clear result, the video must have a particular setup. The points of interest in the video must be highlighted with stickers of clearly differentiated colors compared to the background. Besides, the camera must not move during the video recording and the plane on which the camera is focused must film the desired motion without any distortion.



*Figure 2: Initial, intermediate and final position of the foot climbing stairs in the video sequence.*

b. **Position detection from the video using Matlab.** With the implementation of a code in Matlab, it is obtained the path described by each sticker during the video sequence. This code is based on the detection of the position of the stickers in each frame by addressing the position of the pixels with clearly different values. The main output of this first step is used as input for the synthesis problem. The idea is designing a mechanism that will repeat sequentially the motion captured in the video sequence.
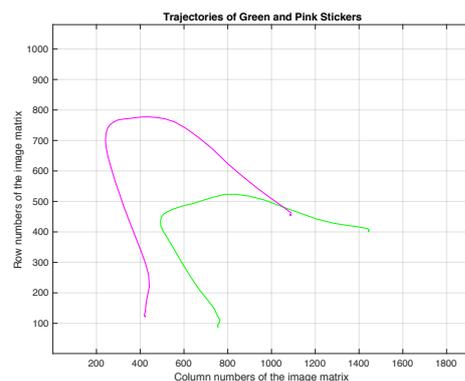


*Figure 3: Path generated by the stickers during the video sequence.*

c. **Mechanism synthesis using Math Illustrations.** Two different graphical methods are considered for the synthesis of mechanisms to solve both motion and path generation problems: Three-Positions Synthesis Method and Coupler Curves Method. Both of these methods are implemented using the program Math Illustrations, an easy and simple software for technical drawing.

- The **Three-Positions Synthesis Method** solves the *motion generation* problem. It allows to specify three positions of a solid and design a four-bar linkage that passes through those positions. These positions are obtained from the video sequence analyzed in Matlab. Some rules are also identified to avoid finding a toggle point between the three positions specified that would prevent the continuous motion of the linkage.
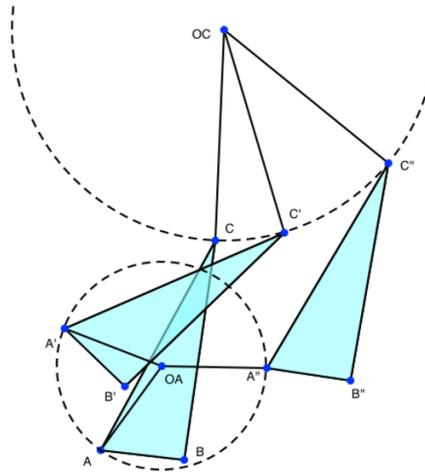


*Figure 4: Complete motion of the mechanism designed by Three-Positions Synthesis Method.*

- The **Coupler Curves Method** solves the *path generation* problem. It focuses on the coupler of the linkage. It allows to design a four-bar linkage with a triangular coupler link controlling for a point in the coupler such that it generates a desired path. This desired path is obtained from the video sequence analyzed in Matlab.
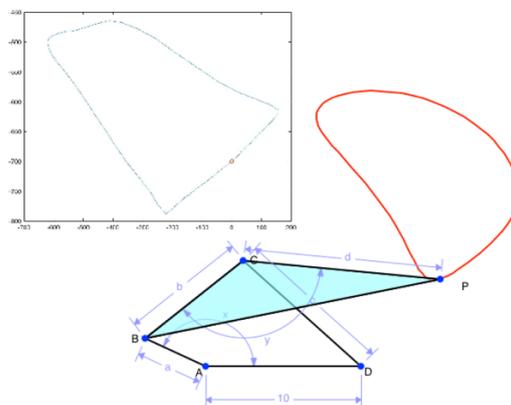


*Figure 5: Complete motion of the mechanism designed by Coupler Curves Method.*

d. **Verification of its functionality with a simulation in SolidWorks.** With the use of SolidWorks, the functionality of the mechanisms that have been designed can be verified with a simulation as close as possible to reality. It allows to detect and correct possible failures before starting the manufacturing process.
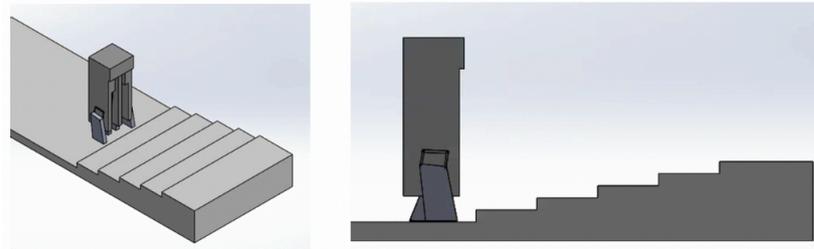


*Figure 6: Final simulation.*

## Results:

The methodology that has been developed in this project pretends to be a first approach to the synthesis of mechanisms. It eliminates the most complex parts of the process such as the mathematical expressions for the input, replaced by a video, or the need of using a software or database to do the synthesis, replaced by simple graphical methods.

The **code** implemented in Matlab turns out to be very efficient even with different background colors, provided that they are clearly different from the stickers' colors. The **graphical methods** introduced to do the synthesis of mechanisms are easy enough to be understood quickly by non-expert users but also provide basic knowledge for more complex methods for the synthesis of mechanisms. However, they still require further develop and optimization as they depend highly on the designer's criteria and provide designs resulted from a trial and error process. Both methods considered present some limitations. The Three-Position Synthesis Method can only specify a maximum of three positions of the motion desired to be represented and the Coupler Curves Method is only valid to generate a closed path curve. Finally, the **simulation** provides a first good impression of how the final mechanism is going to work.

Regarding to the case example studied in particular, it resulted to be more complex than expected. The final device proposed in this project can be considered as the first prototype of a device that could be incorporated in trolleys or even in wheelchairs, with

the appropriate size modifications, to make them move upstairs without human intervention.

## *Conclusions:*

The results of this methodology are mechanisms which fulfill their purpose, they imitate a previous specified motion without encountering a limiting position. However, the transmission of motion is usually not optimized. Therefore, the mechanisms obtained from this methodology can be used as an initial guess for numerical techniques. They provide an initial approach to the final mechanism and after the application of these more complex and precise procedures, an optimal solution for the initial problem can be obtained.

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# ABSTRACT

Mechanisms are one of the most reliable, efficient and cost-effective ways to generate the desired motion. Furthermore, with appropriate materials selection, mechanisms can become lightweight and space-saving, resulting in very useful devices for certain applications such as the opening and closing mechanism for a luggage door compartment in an airplane.

Therefore, the aim of this project is to develop a simple and intuitive methodology to allow non-experts to design four-bar linkages without the need for extensive knowledge about the synthesis of mechanisms. In particular, it is intended to facilitate the first contact with the synthesis of mechanisms for engineering students, so that they can design four-bar planar linkages to move rigid bodies in trajectories that require simultaneously translation and rotation.

This methodology consists of three steps. First, this method eliminates the complexity in the synthesis process of finding the mathematical expression for the path generated by a particular point in the mechanism. Instead, it replaces the input data with a video sequence of the motion desired to reproduce. With the use of Matlab, the necessary parameters are extracted from this video to proceed with the synthesis. Second, it simplifies the design process by using simple graphics methods to get the qualitative synthesis of a linkage, eliminating the need for using complex databases or mathematical processes. With the use of the program Math Illustrations, the user can manually vary the links dimensions and the position of the fixed points to see the consequences in the path generated by the point of interest. Finally, with the use of SolidWorks, the mechanism can be designed, and its motion can be simulated to verify it, leaving the parts ready to 3D print and to assemble to test its working in the real world.

The validity of this method is shown by the design and analysis of a mechanism for a particular motion: the imitation of human's feet climbing stairs. The purpose of this mechanism is to be incorporated in packages or containers to make the climbing stairs while carrying loads easier. This can be very useful for old people who live in buildings which does not have elevator.

# 1. INTRODUCTION

A **mechanism** is a combination of rigid elements whose main objective is to transmit forces or transform motion to some desirable pattern, from a driving element (motor) to a receiver. They allow humans to carry out specific tasks effortlessly in comfort [1].

Mechanisms are classified according to the way they transmit or transform forces and motion [1]:

- Transmission mechanisms, which transmit forces or power from the motor to another point. The transmission can be linear (pulleys, levers…) or circular (gears, friction wheels…).

- Motion Transformation mechanisms, which convert rotatory movement to linear movement and vice versa. Some examples of this type of mechanisms are the rack-pinion system, screw-nut set, crankshaft-rod device…

- Alternative mechanisms, which modify or allow for determined motion such as mechanisms with one rotational direction only (pawls), mechanisms to reduce rotational speed (brakes), mechanisms to absorb energy (springs) or mechanisms to allow shafts coupling (clutches).

| TYPES OF MECHANISMS | | | |
|---|---|---|---|
| Transmission mechanisms | | Motion Transformation mechanisms | Alternative mechanisms |
| Linear | Circular | | One rotational direction only (pawls) |
| Pulleys | Gears | Rack-Pinion system | |
| | | | Reduce rotational speed (brakes) |
| | | | Absorb energy (springs) |
| Levers | Friction wheels | Screw-Nut set | Shafts coupling (clutches) |
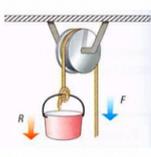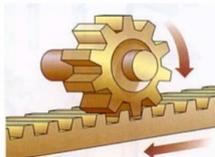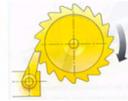
*Table 1: Classification of mechanisms [1]*

One of the most important mechanisms is the **four-bar linkage**, also called four-bar. It consists of three moveable bars or links connected by one-degree-of-freedom joints and linked in turn to a fourth fixed bar by pivots forming a closed kinetic chain. The link connected to the ground by a hinged joint (pivot) is called *crank*, it usually acts as the input and can rotate 360º. The other link connected to the ground whose rotation is normally limited is called *rocker*. The link that connects the crank and the rocker is called *extension* or *coupler* and in general, it contains the point which generates the motion of interest. Typically, the fourth link is stationary and assumed to be fixed to the ground. **Figure 1** illustrates a detailed representation of this mechanism.
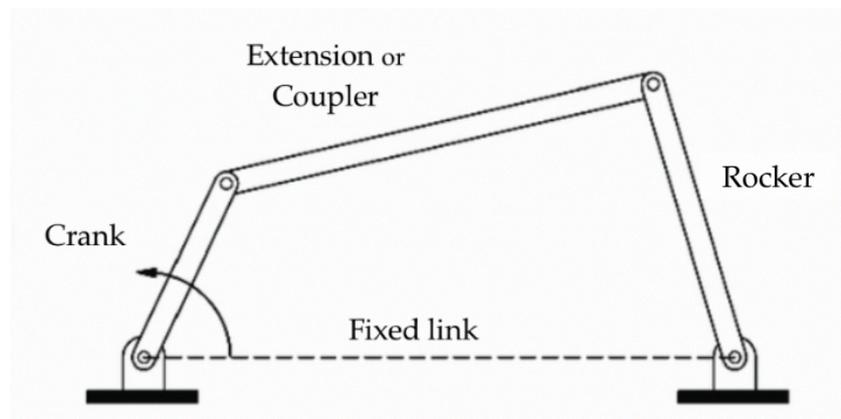


*Figure 1: Four-bar linkage*

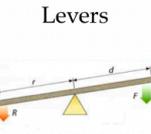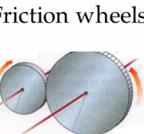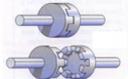Four-bar linkages can be used flexibly in many different fields of science such as mechanics, thermodynamics or material science. Nowadays, the applications of this type of mechanisms are wide and varied, from very simple applications like the support mechanism of a table to more complex applications such as the opening mechanism of a door or window, or the support mechanism of an excavator.

All the links that make up these mechanisms move in parallel planes. This is what is called planar linkages. Planar motion requires three independent parameters to determine the position of one link: the X position of the center of gravity, the Y position of the center of gravity and the angle of the link [WAND00]. These parameters define both location and orientation of one link.

Grübler criterion defines the mobility of a mechanism. It determines the **degrees of freedom** of a linkage which are the number of independent inputs required to fully define the position of all the links of a linkage. This formula is the following:

$$DOF = 3 \cdot (n - 1) - 2 \cdot j_1 - j_2$$

Where:

**DOF**: Degrees of freedom of the mechanism

**n**: Number of links

**j$_1$**: Number of lower pair connectors or pin joints (removes two DOF)

**j$_2$**: Number of higher pair connectors or roll-slide joints (removes one DOF)

In the case of four-bar planar linkages, the number of degrees of freedom is one:

$$DOF = 3 \cdot (4 - 1) - 2 \cdot 4 - 0 = 1$$

This means that by defining the motion of one link (usually the crank), the motion of the entire mechanism is defined.

Depending on the input crank motion and the rocker response, there can be defined different **classes** of four-bar linkages: crank-rocker mechanism, double-crank mechanism and a double-rocker mechanism [WAND00].

- A crank-rocker mechanism presents a specific combination of links dimensions where the input crank can rotate 360º whereas the rotation of the rocker is limited. This corresponds to the classic type of four-bar linkages.

- A double-crank mechanism, also called drag link, presents a certain configuration that allows both the crank and the rocker to rotate 360º.

- A double-rocker mechanism has the most limited motion. Neither the crank nor the rocker can rotate fully 360º. They can only oscillate.
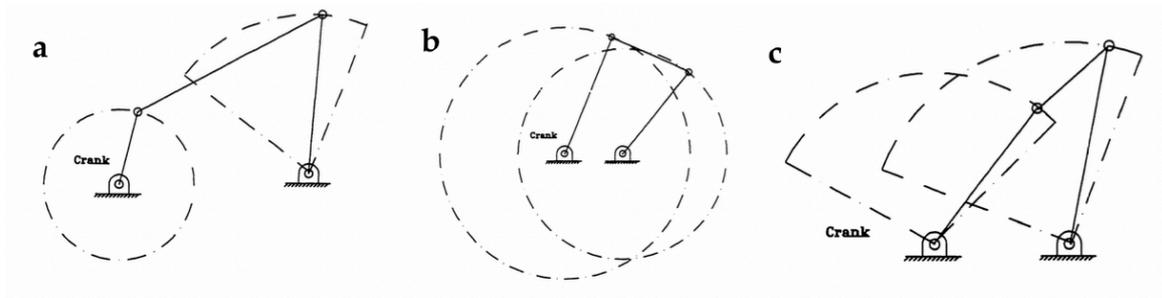
*Figure 2: Classification of four-bar planar linkages [WAND00]*

Through the relative motion of the links connected, it is possible to transform the rotation of the crank to very different movements. It is possible to generate very different curves from an easy input as it can be a constant speed rotatory motor. Moreover, four-bar linkages can be combined together to generate complex mechanisms and more complex motions. Besides, this type of mechanisms is one of the simplest and easier to design and manufacture. This is the reason why this project focuses on the synthesis of this type of mechanisms.

The design of mechanisms is fundamental to create the optimal device with particular motion characteristics. It consists of two different parts: synthesis and analysis.

- The **synthesis** of mechanisms is the iterative, creative and intuitive process for the design of mechanisms to describe a desired motion. It consists of choosing the most appropriate type of mechanism and once selected, find the number of necessary links, their dimensions, fixed points, the disposition of the parts and the materials to be used, so that the resulting mechanism generate the determined motion. The synthesis of mechanisms must ensure that the desired motion is described as accurately as possible without going beyond the stresses that the parts can handle [HERR12].

- The **analysis** of mechanisms is the process that come after the synthesis. It attempts to study that the designed mechanism complies with the requirements previously specified by analyzing the trajectory, speed and acceleration of different points that constitute it, verifying at the same time that all the stresses that appear are smaller than the stresses that the parts can handle [HERR12].

# 2.  STATE OF ART

*This chapter includes an overview of the synthesis of mechanisms as well as different types and problems associated with it. It also presents an introduction to a series of software currently used for this purpose as well as the system implemented by Disney to design computational mechanical characters.*

## 2.1.  OVERVIEW OF MECHANISM SYNTHESIS

The synthesis of mechanisms is a key step to create potential linkage design solutions for different kinematic applications. Anything can be analyzed until it has been previously synthesized into existence [NORT99].

The synthesis of mechanisms can be classified into the following **types** [NORT99]:

- Qualitative Synthesis
  It is based in the creation of potential solutions to generate the desired motion without the use of software or computational aid which predicts the solution. It is the first approach to the synthesis of mechanisms, and it intuitively provides a possible solution without the use of complex equations. This solution is to be analyzed and iterated several times between synthesis and analysis until obtaining a viable and successful solution.

- Type Synthesis
  It can be considered a type of qualitative synthesis. It tries to find the most suitable mechanism for the problem which gives the best trade-off of functionality against cost, reliability and other factors of interest. These solutions may be not optimal or practical, so further steps in the design process are necessary to achieve the objective pursued.

- Quantitative Synthesis or Analytical Synthesis

  Once the most appropriate type of mechanism is selected to solve the matter under consideration, the analytical synthesis sets out the equations that govern the motion in order to obtain a numerical solution. Throughout analysis and different iterations, it tries to find the optimal solution. Yet, the designer's criterion determines if it is the most appropriate.

- Dimensional Synthesis

  It is the determination of the dimensions of the links necessary to accomplish the desired motions. Specifically, this determines the link lengths, angles, pivot distances…

The problems presented by the synthesis of mechanisms can be classified into the following **categories** [NORT99]:

- Function generation

  This problem tries to address the response of a mechanism to a known input. In other words, it is the correlation of an input motion with an output motion in a mechanism.

- Path generation

  It aims to control the position of a point in the plane such that it follows some prescribed *path* or *curve*. The controlled points in a four-bar linkage are usually in the coupler bar. Depending on the shape of the coupler and the position of its selected point, different motions are produced generating the so-called coupler curves.

- Motion generation

  It attempts to control the motion of one of the solids in the plane so that it sequentially passes through some specific *positions*.

## 2.2. DESIGN TOOLS FOR MECHANISM SYNTHESIS

The design of mechanisms from scratch is a long and tedious process. To ensure its success, it involves the development of all the previously mentioned types of synthesis and entails different problems, including function, path or motion generation. Due to this complexity, some engineers consider the synthesis of mechanisms an art. Nevertheless, the versatility that mechanisms offer make the whole process worth it.

At this time, simple interactive systems have been developed to try to automate the synthesis process and to enable non-expert users to design their own mechanisms. Common numerical computer environments such as **Matlab** or **Mathematica** can be used to program user interfaces to facilitate the mechanism synthesis [DEJU10]. They represent the motion generated by four-bar linkages with specified dimensions and an easy input. They usually allow the user to modify the links dimensions and see the corresponding change in the generated motion. Adding an additional level of complexity, other methods automatically provide the design of optimized four-bar mechanisms with some dimensional and motion restrictions as an input [PINT07]. These methods require further knowledge of mechanism analysis and numerical methods to be coded.

There exists more complex software developed by different authors to solve the synthesis of mechanisms. Some of them, for instance, use a **matrix methodology** to create a library of mechanisms composed of building blocks. This allows to discretize complex functions into simpler sub-functions until a match is found in the database. Once all the matches are obtained, they are combined to generate the final mechanism [KOTA92]. Other methods include **iteration processes**, **computational software** or **algorithms** to find the optimal solution for a given motion.

**Entertainment Disney company** developed a methodology to facilitate non-expert users to design and manufacture complex animated mechanical characters, whose working principle is based on mechanisms and gears [CORO13]. What attracted Disney to this science is the simulation of animal or

human movements, as less identifiable by eye as possible, to animate the robots that appear in their movies, attractions or spectacles (see **Figure 3**).



*Figure 3: Dog galloping, pushing man and clocky Disney design mechanisms [CORO13]*

The method they implemented is based on the use of a database with parametrized mechanisms assembly types and the motion generated by each of them. The process begins with a specific articulated character and a gear box. The user can then draw or select a motion curve and decide the attachment points in the character. Through the new software developed, this motion curve is compared to the ones stored in the database until the best match is found. After an optimization process to get the curve as similar as possible to the given one, the mechanism is attached to the selected point with the parameter's values adapted to the case in particular. If more than one curve is needed, the mechanisms are connected by a gear train to transmit the motion. Once the software arranges the disposition of the mechanisms, ensuring that no collision occurs during operation, it generates the final support structures. After that the design is finished and ready to manufacture. The scope of this method is reduced as it only works for a limited type of mechanisms, planar mechanisms which only include cyclic motions, though this restriction does not affect to a lot of classic characters' motions. **Figure 4** illustrates this design system.
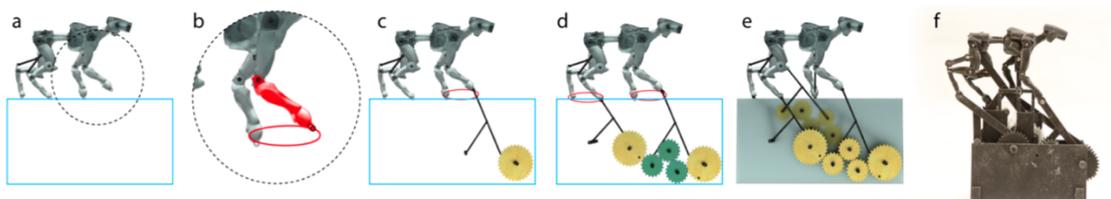


*Figure 4: Overview of Disney's interactive design system for a dog galloping motion [CORO13]*

# 3. OBJECTIVES

The goal of this project is to develop a methodology that allows designing four-bar mechanisms which reproduce the motion of a rigid body captured in a video sequence. The results of a particular case will be used to verify the possibility of obtaining the numerical position and velocity data from a video sequence, and to develop the methods required to complete the synthesis based on this data.

The main **objectives** of the project are the following:

1. Develop a method to obtain the path and kinematic parameters, such as positions and velocities, of a particular point in a rigid body from video sequences.

2. Develop a method for the virtual construction of skeleton models of a four-bar mechanism for path and motion generation using data from a video sequence.

3. A multi-body model that illustrates the practical application of the method developed.

4. A simulation of the mechanism designed in particular and test results that illustrates the feasibility of the method.

The idea is that these two methods developed from a practical application and validated with a simulation, constitute a simple and intuitive system for the design of mechanisms. Therefore, this methodology will allow non-experts to design four-bar linkages without the need for extensive knowledge about the synthesis of mechanisms but at the same time, it will allow them to learn the basic steps of the synthesis process. More specifically, it is intended to facilitate the first contact with the synthesis of mechanisms for engineering students, so that they can design four-bar planar linkages to move rigid bodies in trajectories that require simultaneously translation and rotation.

# 4.  METHODOLOGY

This project aims to simplify the four-bar linkages synthesis process from the development of a method to generate a mechanism for a practical application. In particular, from the design of a mechanism that facilitates the lifting of loads through the stairs.

The method developed in this project follows the idea implemented by Disney, but it is not so automatic, and it focuses more on showing the basic principles of synthesis. First, the starting point is not just drawing a curve to generate a motion or selecting it from a library, the user is able to record a movement and obtain the path of a particular point which will be used for the synthesis. This proposed method does not include the use of a database, instead it requires to follow the procedure of simple graphical methods to do the mechanism synthesis. These methods allow the user to either try and change different dispositions and links dimensions until they find one that generates a curve similar to the desired one, or to specify three positions of a line and generate a mechanism, varying the location of the fixed points, until finding one that goes through each position. At the same time, they can see how these changes affect to the generated path, they can control for no collision and the overall motion. However, it does not include an optimization process, so depending on the method used the movement can be reproduced more or less accurately. As Disney design method, it also ends up with the design of the mechanism parts which can be later 3D printed to test its functionality.

Therefore, this method presents two important **challenges**: first the substitution of the input parameters for a video sequence and second, the synthesis of the mechanism. For this synthesis two graphical methods are compared: The Three-positions synthesis with specified moving pivots and the use of Coupler Curves. Both methods are explained in detail in the following sections.

This method involves simplifying and solving **kinematic synthesis** problems, which imply trying to find the right mechanism to imitate a particular motion caught in a videotape. It focuses on the study of the relative motion of the linkage

without considering statics (the study of forces and moments) and kinetics (the study of action of forces) of solid mechanics [WAND00].

It is developed from the synthesis of a mechanism which reproduce the motion of human's feet climbing stairs captured in a video sequence. All the process is implemented using the computer. Three different **technical resources** are used in the process: Matlab, Math Illustrations and SolidWorks.

- Matlab is the program used to solve the path or motion generation problem. From a video sequence, it detects the position of the points of interest and returns their trajectory described during the motion.

- Math Illustrations is the program used for the qualitative synthesis of the mechanism. By means of its simple and intuitive user interface, it allows the user to design a mechanism which respects the motion restrictions and follows the path or positions obtained from the video sequence. The mechanism is designed with simple tools by a careful process of trial and error until finding the one which satisfy the motion specifications. It is the first approach to the final mechanism. It provides the disposition of the fixed points and the proportions between the links of the four-bar mechanism.

- SolidWorks is the program used for the dimensional synthesis of the mechanism. Using the proportions obtained from the first design, the user can extrude and assemble all the elements together. Finally, activating SolidWorks Motion and Simulation add-ins, the proper motion of the mechanism can be evaluated.

However, this method also presents some **restrictions**. It is limited to the synthesis of four-bar planar linkages with an extension in the coupler, for cyclic motions and using a rotatory motor generally attached to the crank. The starting point for the synthesis is limited, only three positions or the path of a particular point in the coupler can be used as input. However, for the purpose of its use, this method covers a wide range of possible applications, adequate for undergraduate students learning.

# 5. PROCESS DESCRIPTION

The process consists essentially in designing a mechanism that reproduces the motion captured in a video sequence.

The effectiveness of this method is tested by applying it to a particular case: the synthesis of a mechanism that reproduces the movement of human's feet climbing stairs. It can be divided in following main steps (see **Figure 5**):
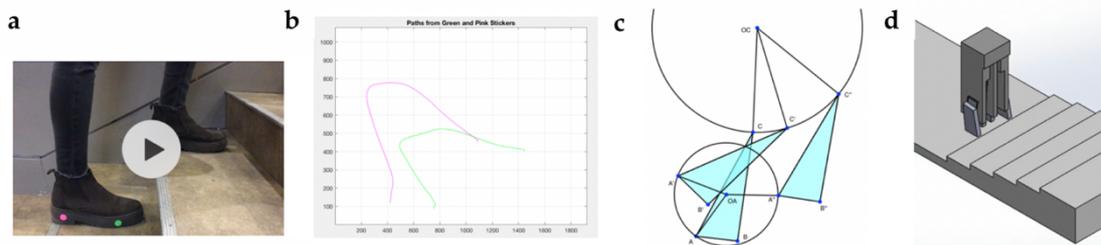


*Figure 5: Overview of the main stages of the synthesis process: a) Video sequence used as input; b) Trajectories described by each sticker; c) Synthesis of the mechanism by three-positions method; d) Simulation of the designed mechanism*

1. Video sequence of the desired motion. It is the input for the problem to solve.

2. Position detection from the video using Matlab: A code was developed to follow the path of a particular point in the video sequence and generate the trajectory it described during the video (Sec 5.1).

3. Mechanism synthesis using Math Illustrations: Design of a mechanism that generates a similar motion to that obtained from the video. Two different graphical methods are considered for the synthesis which do not require a database (Sec 5.2).

4. Verification of its functionality with a simulation in SolidWorks: Design of the links that composed the mechanism with SolidWorks to get them ready to be 3D printed. Also, a simulation can be carried out to test its functionality (Sec 5.3).

## 5.1. STEP 1: PATH AND MOTION GENERATION

*This section describes how Matlab is used to obtain the path or positions needed to start the synthesis problem, that is, how the input data for the synthesis can be simply replaced with a video sequence. It defines the required set up for recording the video sequence as well as how the path of a particular point and numerical data can be obtained from it.*

### 5.1.1. Overview of Path and Motion Generation

The synthesis process always starts with a path or motion generation problem. In other words, mechanisms are designed to try to accomplish a specific task effectively, to follow either a prescribed path or a series of determined positions of a solid. The output path or motion of the mechanism of interest is based on the specified input.

This project tries to solve creatively these problems and specify these positions or path in an easy, effective and visual way by means of a video sequence. The advantages associated with the use of a video sequence as input are all related to the purpose of simplifying the synthesis process as much as possible. First, it eliminates the need of using complex mathematical expressions to define the desired path. Second, it also provides a more accurate starting point for the mechanism synthesis rather than randomly or approximately defining the path or positions. Besides, today's society is very close to new technologies, so undergraduates would not find any difficulty with this first step.

### 5.1.2. Matlab: Code Description and Functions Definition

The algorithm developed in Matlab tracks the position of a sticker in the video and generates a graph with the path it follows during the video duration. Just by typing at the beginning of the code the corresponding file path in the function *vision.VideoFileReader* and running the adequate code for the color desired to be detected, the graph is obtained. Two sticker colors are analyzed in this project: green and pink.

Matlab analyzes videos as a sequence of images referred as **frames**. Each frame or image is considered as a combination of three two-dimensional **matrices**, corresponding to the red, green and blue colors (see **Figure 6**). Each **element** in these matrices specifies the color for one **pixel** of the image. The row and column indices of these elements determine the centers of the corresponding pixels. The basis of this code is detecting the position of the sticker in each frame and storing its column and row number of the matrix in two different vectors, of size equal to the number of frames in the video.
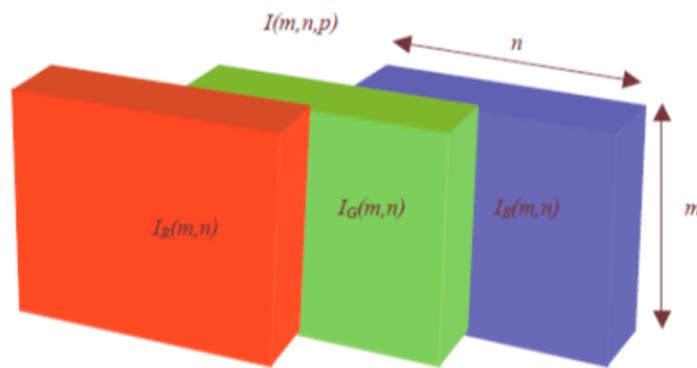


*Figure 6: Representation of an image or frame in Matlab*

In order to achieve a clear result, the video must have a particular **setup**. The video must contain stickers of clearly differentiated colors compared to the background. The camera must not move during the video recording and the plane on which the camera is focused must film the desired motion without any distortion.

Code Description

The main part of the code is a loop which repeats the same procedure to find the stickers position in each frame. First, it creates a matrix resulted from a certain combination of the matrices that make up a frame and it detects the position of the sticker by finding the pixels with significantly different values. Second, it stores the values of the coordinates in the matrix of those different pixels in two different vectors. Finally, it uses the information stored in those two vectors to graph the path of the sticker throughout all the frames in the video.

To detect the combination of colors that best distinguish the sticker from the background, different options with trial and error were tested until the best one was found. An image ($p$) or matrix is created, resulted from the combination of basic colors, which maximizes the difference in pixel's values between the stickers and the background. **Figure 7** shows the resulted image of different color combinations in the trial and error process to find the best one for the pink sticker.
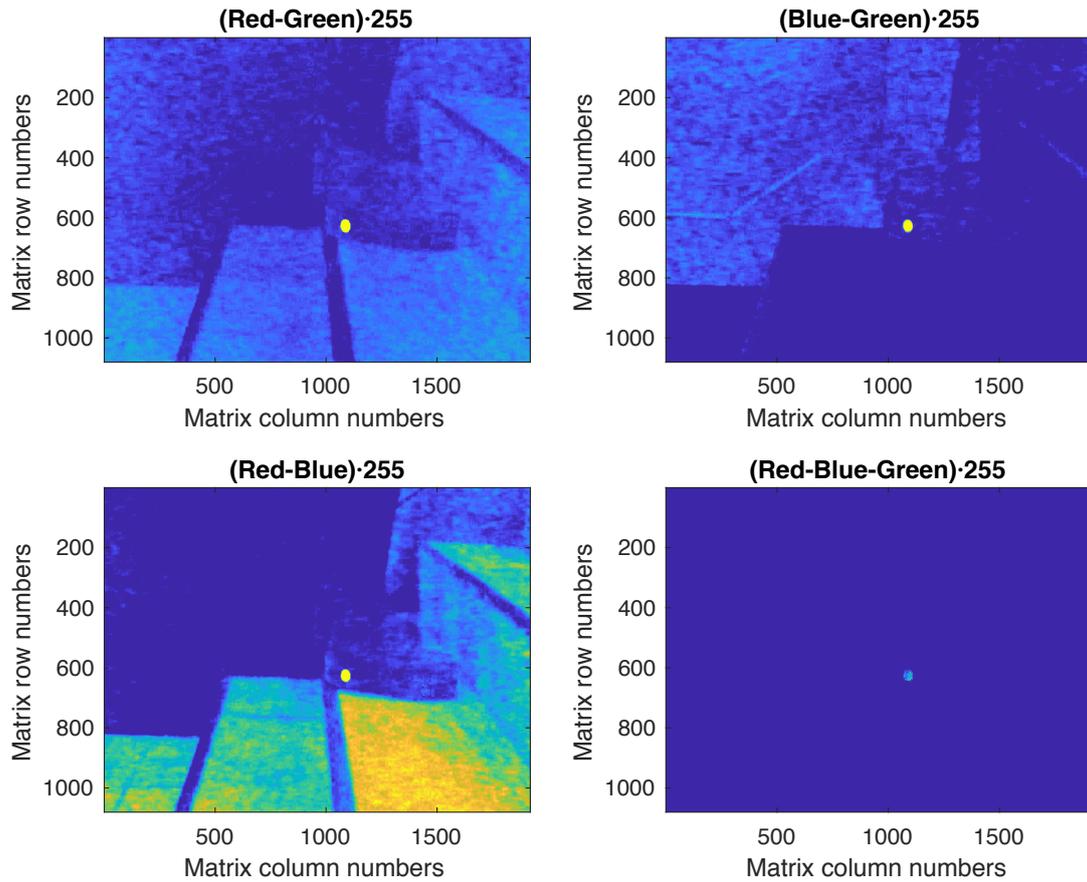


*Figure 7: Trial and error process to find the best combination for the pink sticker*

The following table gathers the best colors combinations for both green and pink stickers. Regarding to the case study in particular, **Figure 8** represents the resulted image ($p$) that best differs the green and pink sticker respectively from the background, in the last frame of the video.

| | |
|---|---|
| **Green sticker** | $p = (green - red) \cdot 255$ |
| **Pink sticker** | $p = (blue - green) \cdot 255$ |

*Table 2: Best matrices color combinations for both green and pink stickers*

GREEN STICKER: (Green-Red)·255     PINK STICKER: (Blue-Green)·255
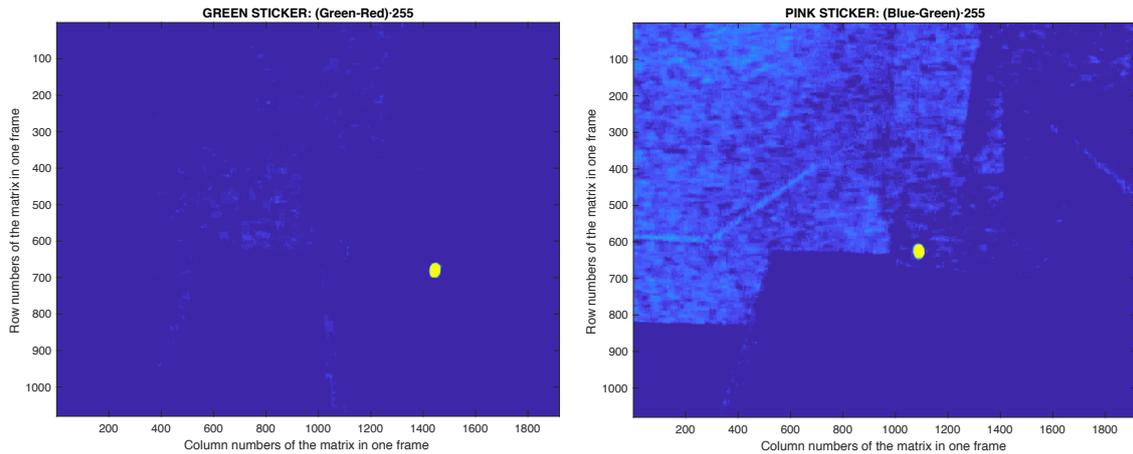
*Figure 8: Best combination of colors to distinguish the green and pink stickers respectively from the background*

Then, pixel's values of the resulted matrix in each frame are stored in a vector (*pvec*) column after column. Matlab detects the values which are higher than a specified threshold and their position in the vector are stored in a new vector (*pos*). The values higher than the threshold are converted to the maximum possible value for a pixel (255) and the rest are converted to zero. **Figure 9** shows a graph of the pixel's values of the resulted matrix in one frame. Clearly, a peak can be differentiated among all the values. It corresponds to the sticker.



Pixel values in the resulted image for the green sticker
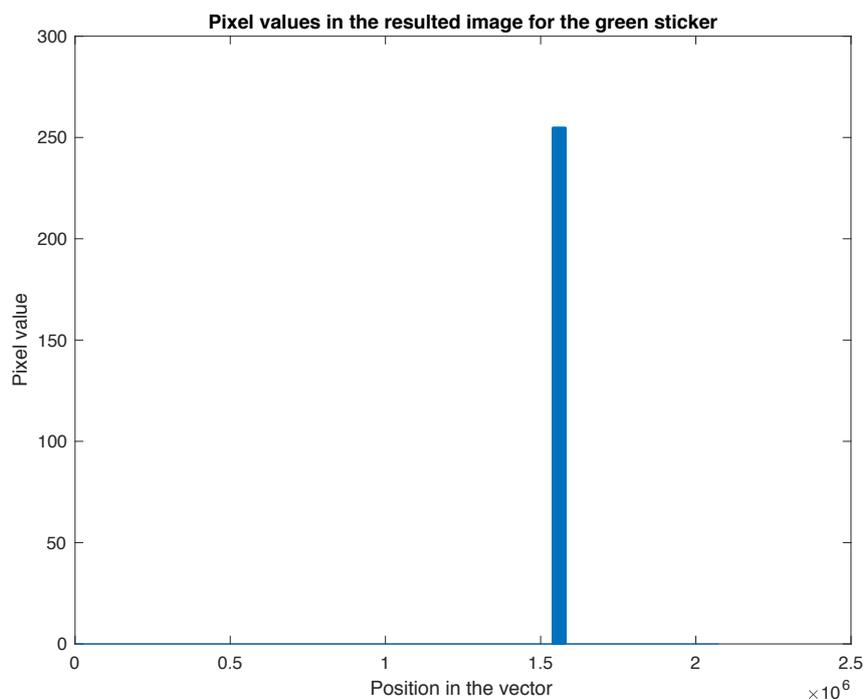
*Figure 9: Pixel's values in the resulted image for the green sticker*

After, a *for* loop is run to determine the row and column number of this positions in the original matrix (or image $p$). As **Figure 10** shows, more than one pixel detects a difference in colors. In order to represent one sticker per frame, it was considered that the best pixel which represents the stickers position is the centroid of the resulting shape.
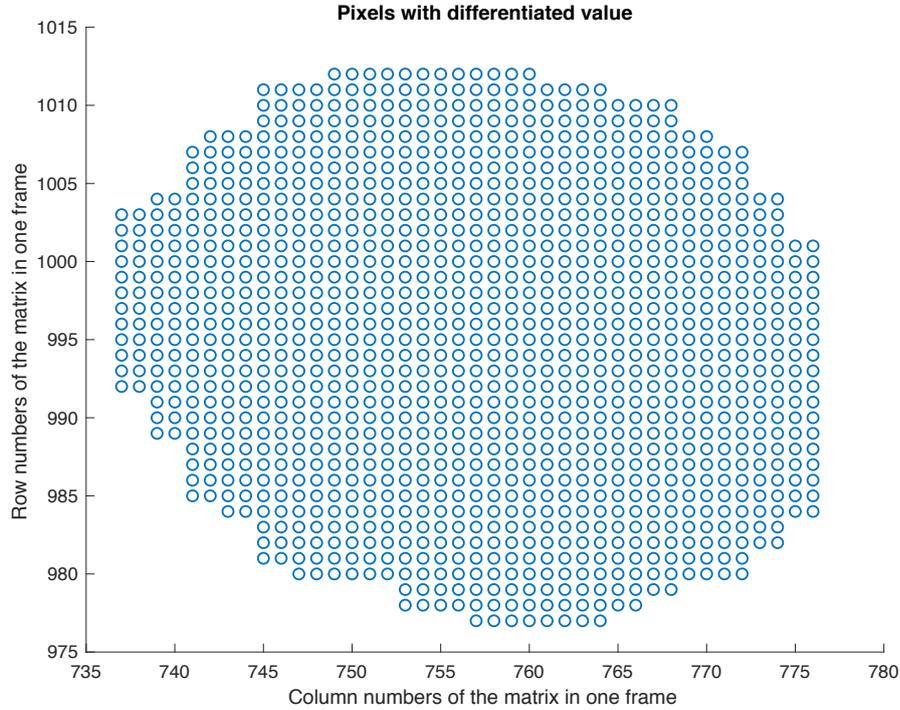


*Figure 10: Pixels in one frame which detected a difference in color*

The final position of the sticker is computed approximating this shape to a circle. The center is calculated with the mean between the highest and lowest values in each direction. Considering that the x axis refers to the number of columns in the image matrix and the y axis to the number of rows, the position of the sticker in each frame is stored in two vectors, each of them for one of the axes. These positions are computed as:

$$X = \frac{\max(column) + \min(column)}{2} \qquad Y = \frac{\max(row) + \min(row)}{2}$$

As the image matrix has the y axis values reversed, meaning that the lowest values are on top of the axis, the Y vector has to be corrected:

$$Yc = total\ number\ of\ rows - Y$$

Finally, once all the frames are analyzed, the trajectories are plotted with the information stored in the $X$ and $Yc$ vectors. It is important to note that the trajectories represent the path generated by the sticker during the video but also, the path generated by overlapping the different pixels values detected in the matrix, in each frame. This is the reason why the x axis corresponds to the column number of the matrix and the y axis corresponds to the row number of the matrix.

### 5.1.3. Practical Application: Process, Decisions adopted and Results

The example analyzed in particular tries to reproduce the movement of human's feet moving upstairs. The video used for the synthesis of mechanisms represents the motion of one foot climbing up one step of the stairs. Green and pink stickers were used in a grey and brown background and the motion was filmed from a perpendicular perspective (see **Figure 11**).



*Figure 11: Initial, intermediate and final positions of the foot in the video sequence*

The results obtained from Matlab are presented in the following figures. For each sticker, **Figure 12** represents its approximate position in each frame. The distance between the position of the sticker in one frame and the following one can be used to estimate the variation of speed. Thus, the first and the last frames, where the foot remains still, the stickers are in the same position. During translation from the initial position to the intermediate one and from the intermediate position to the last one, the distance between the stickers in different frames is larger meaning that the speed is increasing. Reaching the intermediate position, the speed is reduced as the distance between the stickers in different frames is smaller.
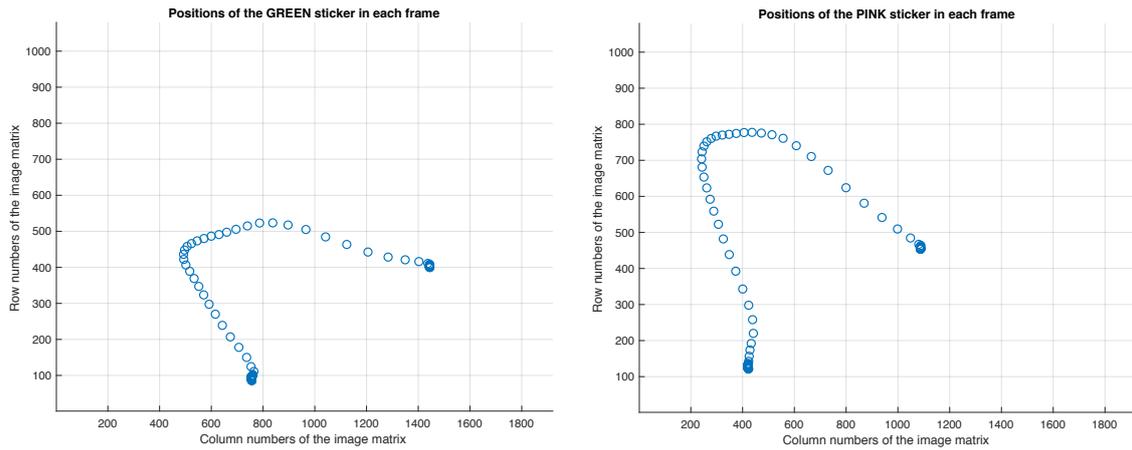
*Figure 12: Green and Pink stickers positions in each frame*

**Figure 13** represents the path generated by each sticker during the video sequence. The main output from this first step is used as inputsm in the synthesis process.
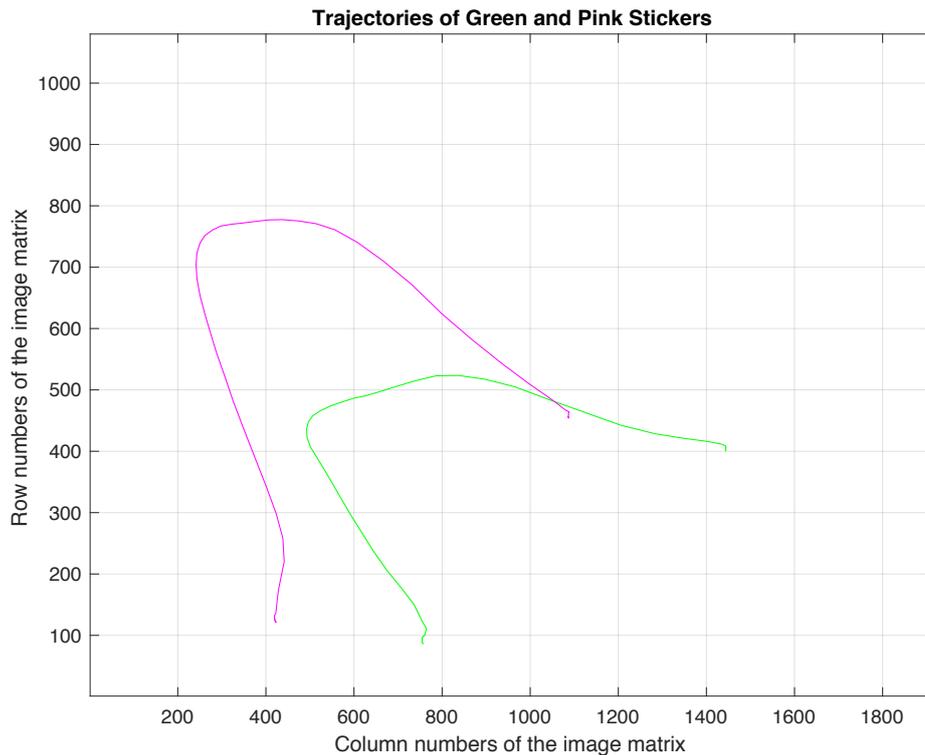


*Figure 13: Path generated by green and pink stickers during the video sequence*

The idea is designing a mechanism that will repeat sequentially the motion captured in the video and represented in the previous graph.

This graph displays the trajectories with respect to the reference frame which is not moving. Using them, it could be designed a mechanism to be hold to the building, to the wall next to the stairs. The mechanism would remain still in the wall while the motor is running and moving the links. When the package reaches the end position, as it would have climbed one step, the motor would be stopped and by means of a guiding rail, the mechanism would be moved to the next step. Then, this cycle would be repeated again until reaching the last step. This idea is kind of similar to the way platforms stairlifts for wheelchairs work.

The objective of this example is creating a mechanism that moves at the same time as the package. In this way, it could be added as an accessory to trolleys. Therefore, the trajectories obtained with respect to the reference frame have to be modified based on the relative movement of the stickers to the center of gravity of the package. The following equation is considered where r(t) refers to the trajectory of the stickers and x(t) to the trajectory of the package center of gravity:

$$r(t)|_{package} = r(t)|_{reference\ frame} - x(t)|_{reference\ frame}$$

The trajectories obtained in **Figure 13** do not consider the motion of the center of gravity of the body. Regarding previous equation, they considered x(t) = 0. In order to focus on the design of the mechanism, the trajectory followed by the center of gravity of the body was approximated by considering that it remains between the initial and final position of the green sticker (see **Figure 14**).
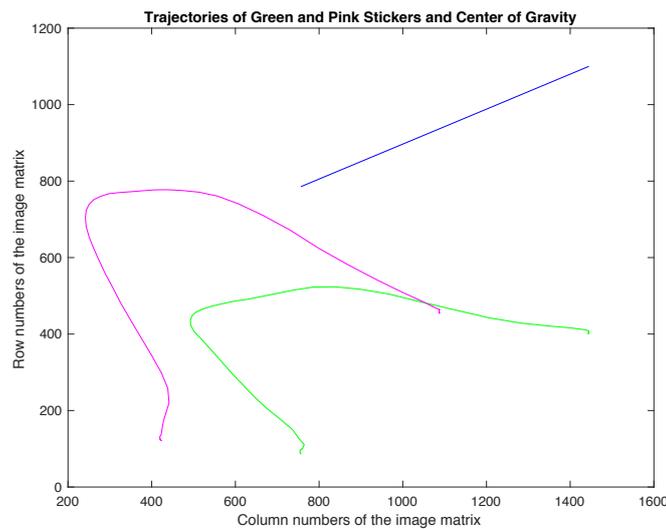


*Figure 14: Trajectories of green and pink stickers with respect to the reference frame and trajectory of the center of gravity of the body*

The relative trajectories are computed by subtracting for each x value of the original trajectories, the x value of the trajectory of the center of gravity. The same applies to the y direction, for both the green and pink stickers trajectories. **Figure 15** shows the resulting relative trajectories with a marker at their starting point.
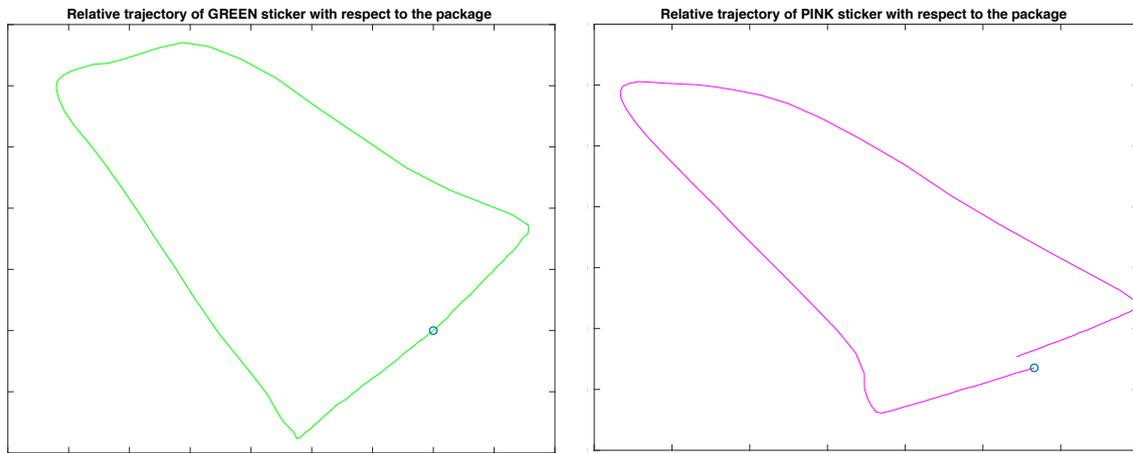


*Figure 15: Trajectories of the green and pink stickers considering the motion of the center of gravity of the package*

**Figure 16** shows a comparison between both trajectories of the stickers, with respect to the reference frame and with respect to the package.
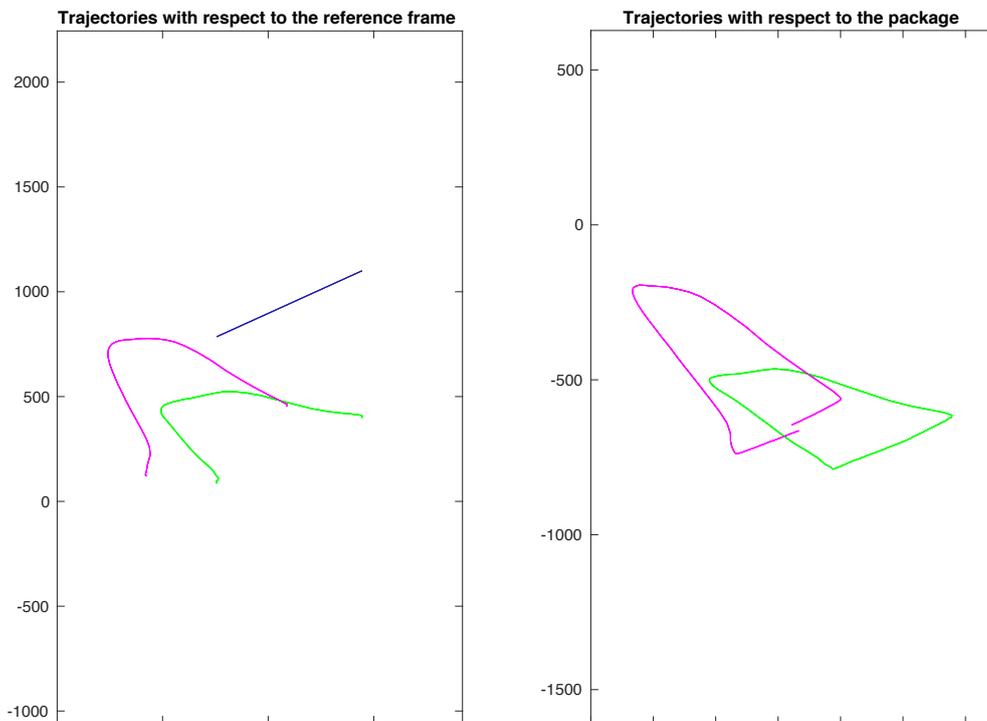


*Figure 16: Comparison between the resulting trajectories with respect to the reference frame or package center of gravity*

### 5.1.4. Scale

To obtain a relationship between pixels and inches, a new video sequence recording the motion of a ruler was analyzed using Matlab with the same procedure described before (see **Figure 17**).
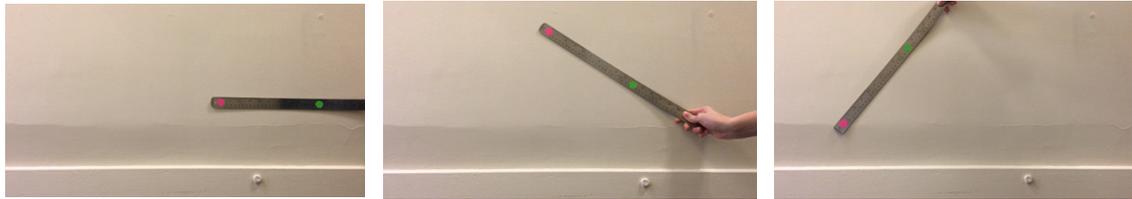


*Figure 17: Initial, intermediate and final positions of the ruler in the video sequence*

The setup for the video is the appropriate to successfully complete the motion analysis with Matlab. The stickers colors are completely different from the background and the camera plane is perpendicular to the motion and without any distortions.

**Figure 18** presents the results obtained from Matlab: the trajectories of the two stickers as well as the three positions where the ruler stopped.
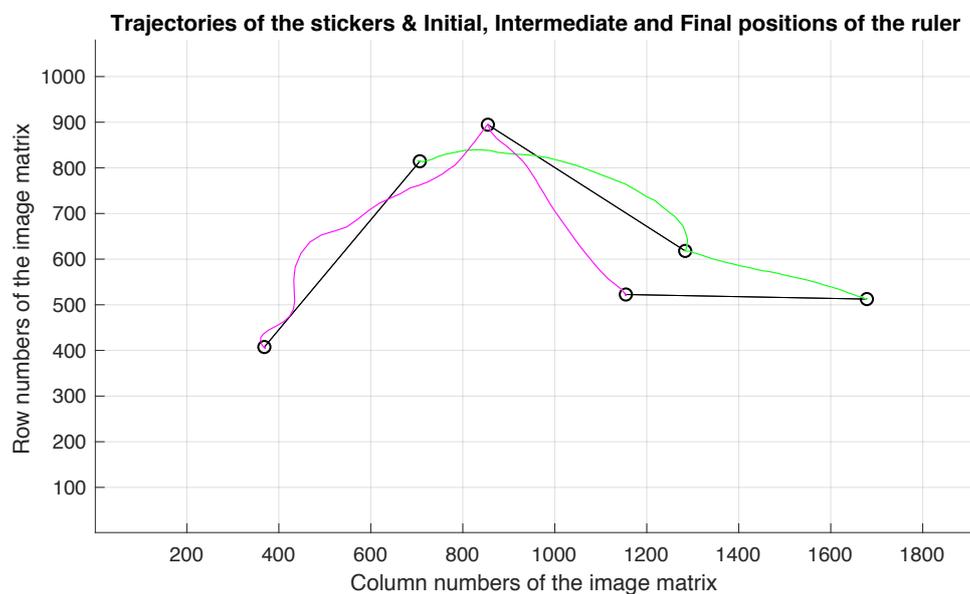


*Figure 18:  Path generated by green and pink stickers during the video sequence and three positions of the ruler*

The result from this video sequence could be also used to design a mechanism to move the ruler through these three positions.

The ruler used in the video sequence measures *10 inches*. In each frame, the length of the ruler can be computed from the x and y coordinates of the stickers. The mean among all the frames resulted in approximately *520 pixels*. Therefore, it can be obtained the relationship between inches and pixels:

**1 inches ≡ 52 pixels ≡ 0.05 cm**

The validity of this approximation can be compared with the length between the stickers in the video sequence of human's feet moving upstairs. The mean distance between the green and pink stickers is *355.46 pixels*. Using the scale obtained from the ruler videotape, this equals to *6.83 in* or *17.36 cm*. The person moving upstairs in the video sequence uses shoes of European size 39, the equivalent of 25 cm. As the stickers where not at the ends of the feet, the result obtained from the approximation makes sense. This scale can be used to transform any desired dimension from the video sequence to reality.

## 5.2. STEP 2: DESIGN

*This section describes two different graphical methods for the synthesis of mechanisms. It is explained how the links dimensions and the location of the fixed points can be obtained from a curve and how can be verified that the designed mechanism generates that curve.*

### 5.2.1. *Overview of Graphical Methods for Four-bar Mechanism Synthesis*

There exist different methods to approach the synthesis of mechanisms and therefore, multiple solutions are possible for the same problem. The key of this science is trying to find the optimal solution depending on the conditions and objectives in each case. Current synthesis techniques are varied from documented displacement paths and velocities [HRON51] to graphical methods and analytical techniques.

All these different ways to do the synthesis of mechanisms try to solve function, path or motion generation problems, defining both the dimensions and orientation of the links. However, currently all of them present one of the following limitations [WAND00]:

- Valid candidate solutions from the design process may be missed as the type of mechanism has to be previously defined.
- Some methods require the definition of particular points on the curve desired to generate. These are usually selected by the designer, who may not select the most suitable ones.
- The number of points that can be selected is limited. Depending on the method selected up to nine points can be selected on the output path.
- Numerical techniques usually require an initial guess for starting the synthesis process. Their results highly depend on this first approach.
- Some authors have successfully addressed the synthesis of path generation mechanisms for closed path curves using Fourier descriptors. However, there are no solution for partial path curves as well as for function and motion generation synthesis.

In this methodology, two different graphical methods are considered for the mechanism synthesis: Three-Position Synthesis Method and Coupler Curves Method. Both of them allow non-expert users to get started in the knowledge of the basics of the synthesis of mechanisms.

The main reason to choose graphical methods instead of other synthesis techniques are related to the purpose of simplifying as much as possible the whole process. The decision was also adopted to try to reduce the limitations associated with the synthesis. First, the points selected from the output path are obtained from the video sequence analyzed from Matlab. Second, unlike numerical methods, these do not need an initial guess for the mechanism. And finally, they address both the synthesis of path and motion generation.

### Three-Position Synthesis Method

This method is a **motion generation** problem. It allows to specify three positions of a solid and design a four-bar linkage that passes through those positions [NORT99]. In order to illustrate this method, the following problem is solved: *synthesis of a mechanism to control the opening and closing motion of a container's door.*
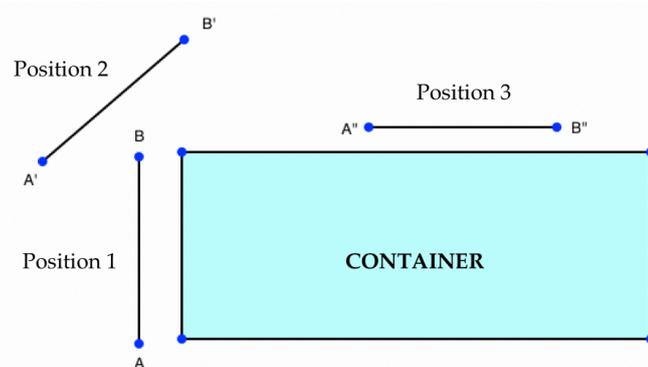


*Figure 19: Input data for the Three-Position Synthesis Method*

The synthesis process is based on basic steps used in technical drawings. The fixed pivots are obtained by finding the center of the circumference represented by three points. The first fixed pivot is the center of the circumference containing A, A', A'' and the second one, is the center of the circumference which contains B, B', B''. This center is obtained by finding the intersection between the perpendicular bisectors of AA' and A'A'' or BB' and B'B''. **Figure 20** shows this drawing process:
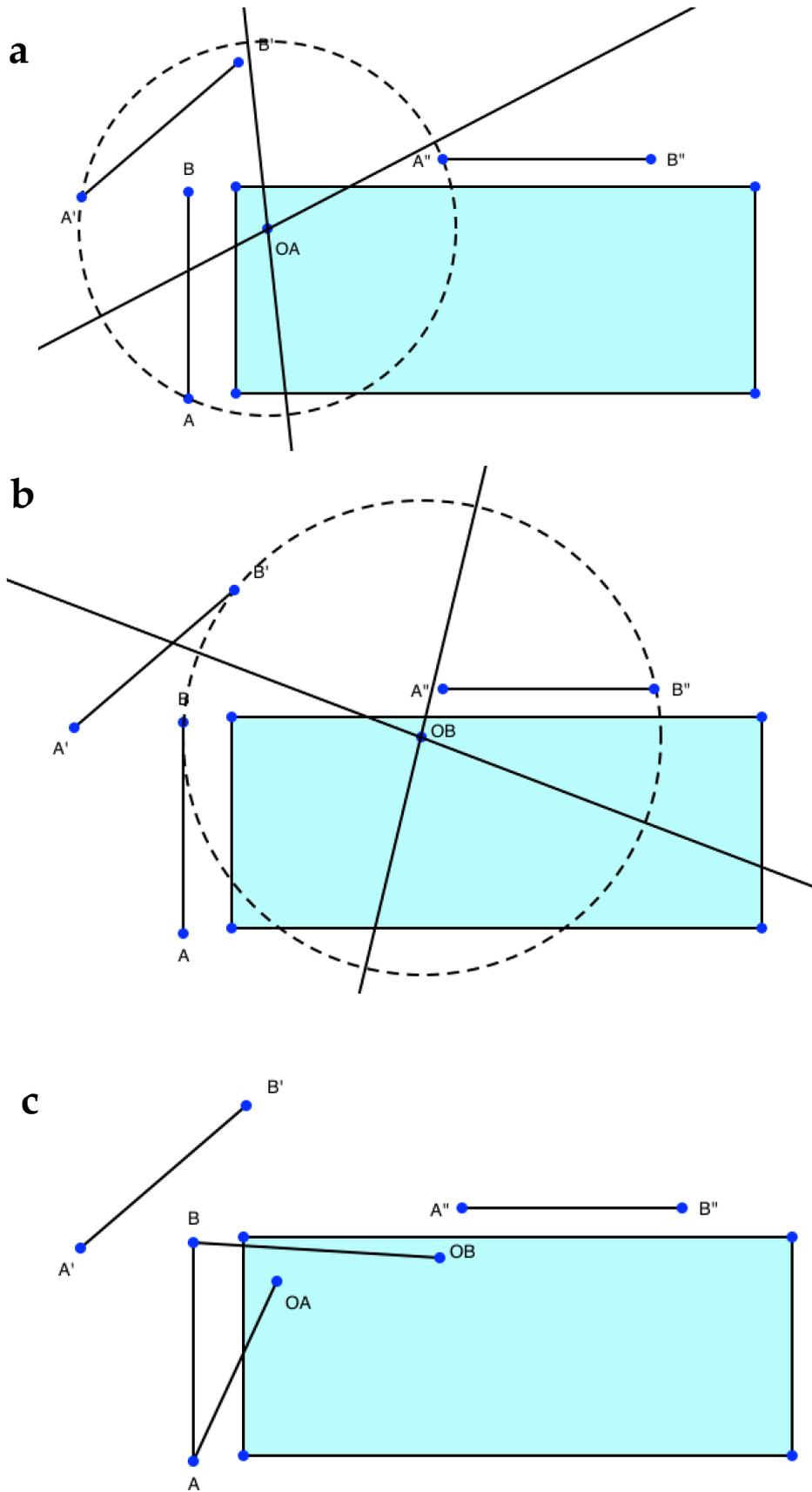
*Figure 20: Overview of the Three-Position Synthesis Method using Math Illustrations:*
*a) First fixed pivot OA; b) Second fixed pivot OB; c) Resulted mechanism*

In order to have a little control over the location of the fixed points, the addition of a **dyad** in the extension bar may be required. This adds one or two degree of freedom to the problem, depending on the shape of the dyad, as it allows you to specify one or both fixed pivots.

The main problem with this method is that it does not ensure that the resulting mechanism can go from position 1 to position 3 without passing a limiting position or **toggle position**. In other words, the resulted mechanism may not be able to move the linkage continuously from one position to another without having to disassemble it. This issue is analyzed in the last subsection of this section: *Analysis of toggle points*.

<u>Coupler Curves Method</u>

This method is a **path generation** problem. It focuses on the **coupler** of the linkage. It allows to design a four-bar linkage with a triangular coupler link controlling for a point in the coupler such that it generates a desired path. **Figure 21** represents different paths generated by the motion of the linkage depending on the shape of the coupler and the location of the coupler point. These curves are named **Coupler Curves** [NORT99].
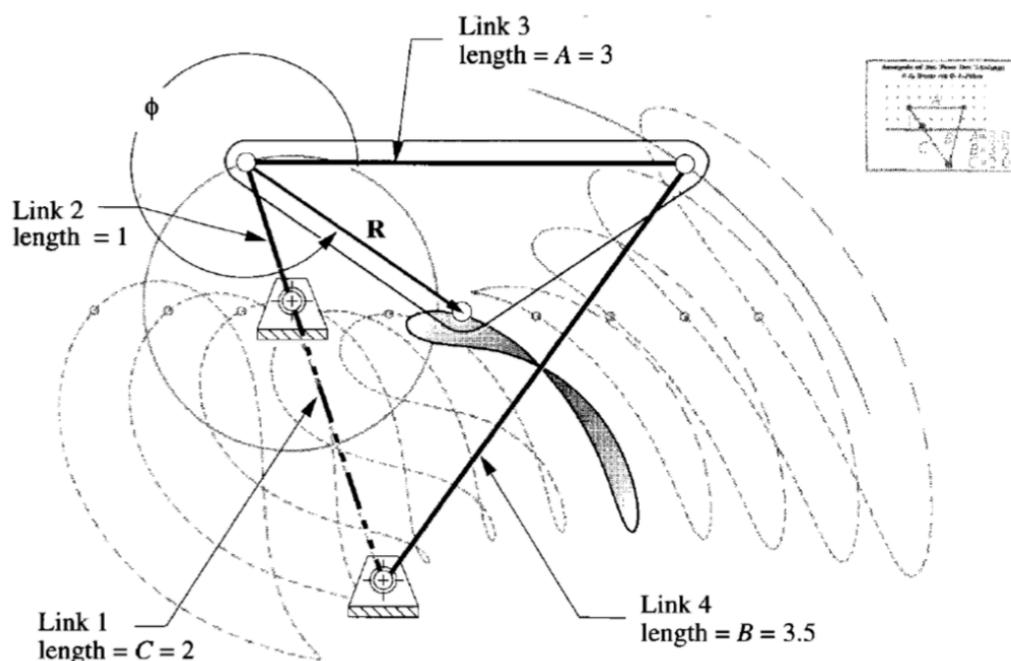


*Figure 21: Coupler curves depending on the shape of the coupler in the linkage [NORT99]*

Some authors have already classified these curves depending on the dimensions of the links and the shape of the coupler. In particular, Kota did an extensive study about coupler curves and four-bar symmetrical linkages [NORT99]. He mapped the resulting coupler curves as function of three linkage parameters (see **Figure 22**):

- Ground link ratio: L1/L2
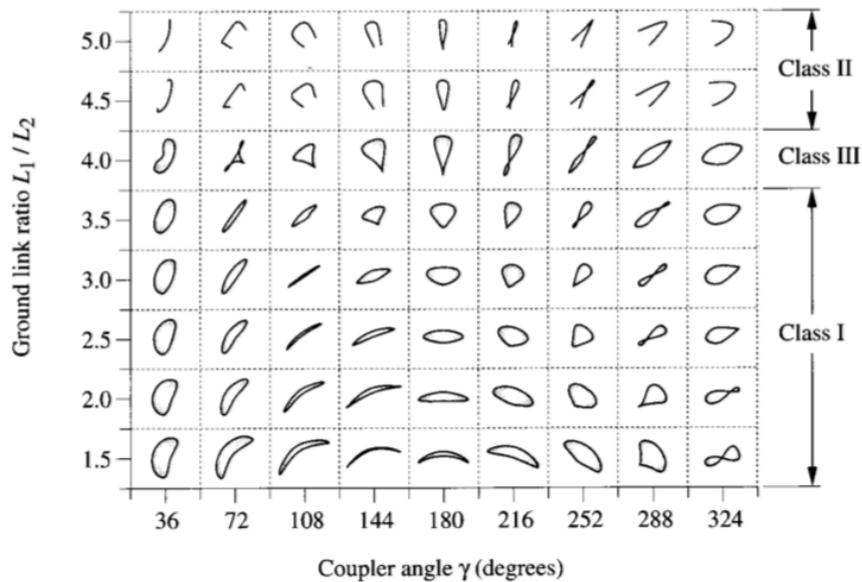- Common link ratio: L3/L2 = L4/L2 = BP/L2
- Coupler angle: $\gamma$



$$\delta = \frac{180° - \gamma}{2}$$

$$AP = 2(AB)\cos\delta$$
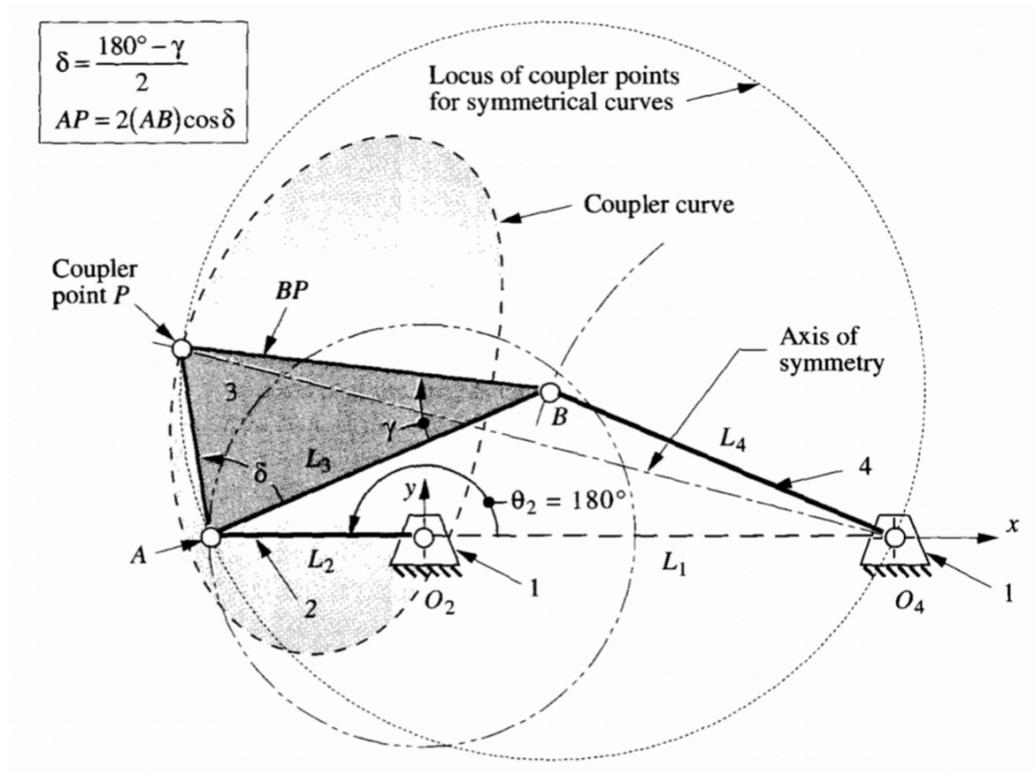
*Figure 22: Four-bar linkage with a symmetrical coupler curve [NORT99]*

The classification is presented in **Figure 23**. It is important to note that the links can be sized up or down that the coupler curve would change its size but not its shape [KOTA92'].
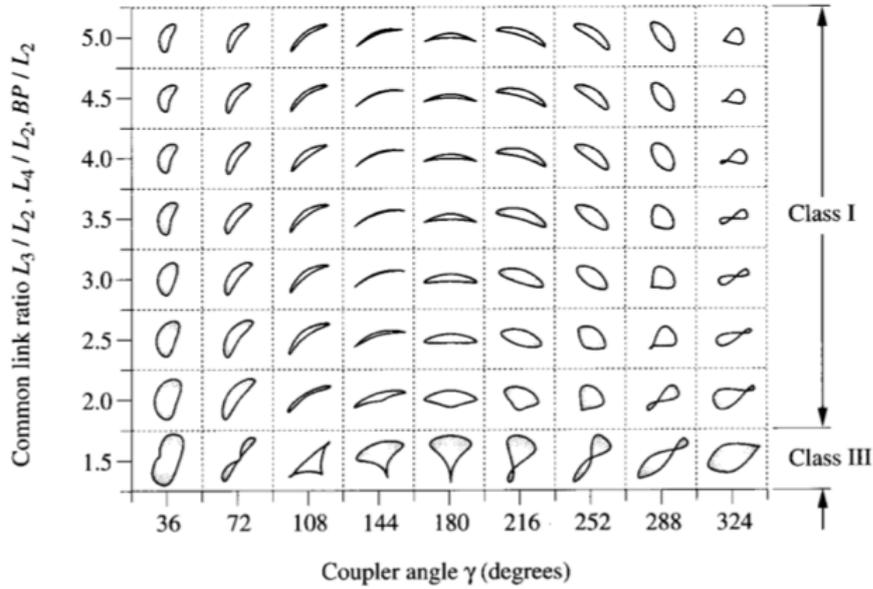
(a) Variation of coupler curve shape with common link ratio and coupler angle
for a ground link ratio $L_1 / L_2 = 2.0$



(b) Variation of coupler curve shape with ground link ratio and coupler angle
for a common link ratio $L_3 / L_2 = L_4 / L_2 = BP / L_2 = 2.5$

*Figure 23: Coupler curve shapes of symmetrical four-bar linkages [NORT99]*

The idea of this method is using this classification as a first approach to the
design of a mechanism which generates a particular path. First, design a four-bar
symmetric linkage using the parameters obtained from the map after choosing
the most similar curve to the desired one. Then, using Math Illustrations, modify
the coupler or other links until obtaining the best approximation.

The main problem with this method is that it can only be applied when the desired path is a closed curve as the classification done by Kota only applies for this type of curves.


## 5.2.2. *Math Illustrations: Implementation of Graphical Methods*

These two methods can be implemented in a very easy and intuitive way by using the software Math Illustrations. It allows to draw different elements and constraint its position or dimensions and to construct basic drawing operations.


For the **Three-Position Synthesis Method**, the process can be summarized in drawing the three positions that the mechanism requires to follow and construct the perpendicular bisectors and corresponding intersections to find the fixed pivots according to the method illustrated in **Figure 20**. The necessary constraints should be applied in order to make constant links lengths or joints coordinates. Once designed, it has to be checked that the three positions can be reached continuously without going through any toggle point. In case that a limitation is found, an additional dyad in the coupler is required to solve the problem by changing the location of the fixed pivots. First a triangular extension should be tried and if no solution is found, then a quadrilateral polygon should be tried until obtaining a valid solution. A triangular dyad allows the variation of the location of one fixed pivot and a quadrilateral polygon allows for the variation of the location of the two fixed pivots.


The dyad should be drawn in each position, with its corresponding orientation. The triangular or quadrilateral dyads are defined by three or four parameters respectively, the same ones for each position, which should not be constrained during the testing to allow for modifications. If the required parameters are defined in the same way in the three positions, considering length AB fixed, the changes in the dyad due to moving the C or D vertexes in one polygon, changes the shape of the other two in the same way. At the same time, the location of the fixed points, if unlocked, would change accordingly too. This allows to try different mechanisms until finding a combination of dimensions which does not find limitations in the linkage motion.
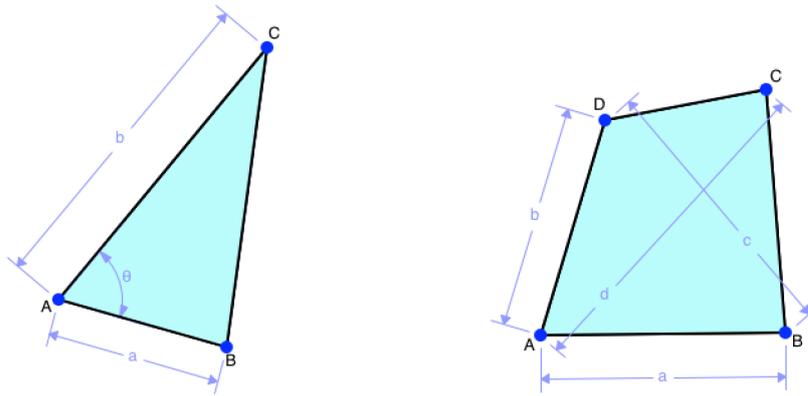
*Figure 24: Parameters required to be defined for a triangular or quadrilateral dyad*

For the **Coupler Curves Method**, the implementation in Math Illustrations is similar. Using Kota's coupler curves classification in **Figure 23**, the most similar four-bar symmetrical linkage for the desired path is drawn. All the geometric parameters of the links should be named with letters and remained unlocked. Then, the **locus** of the point of interest is constructed. Once all set, the lengths and angles of the linkage can be modified, the coupler curve generated would change at the same time. The changes should be done until the closest path is found considering that the linkage can be sized and rotated as necessary to match the scale and orientation of the desired curve.
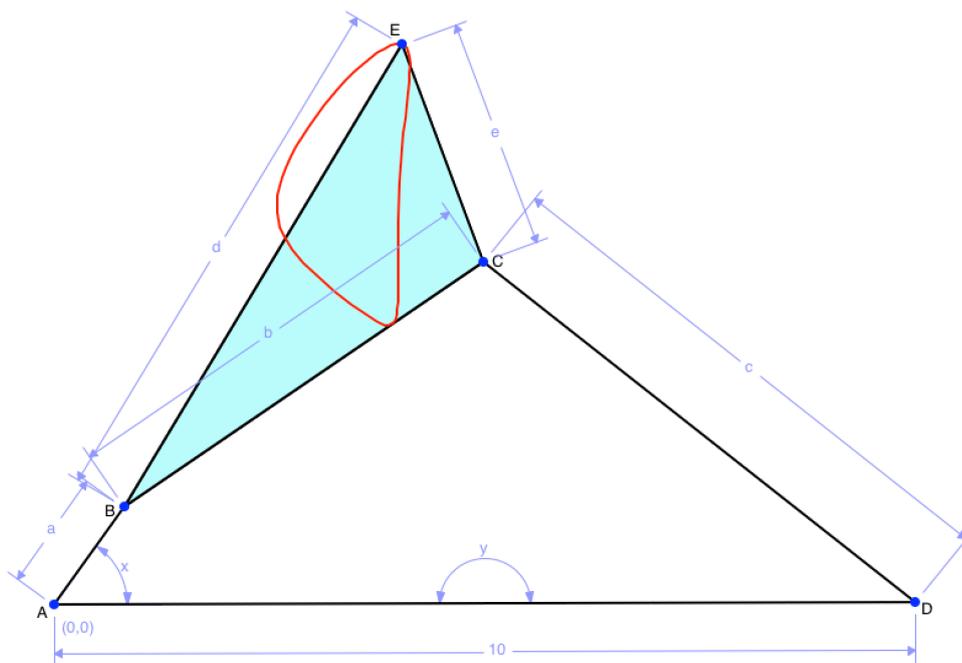


*Figure 25: Four-bar linkage designed using coupler curves*

These methods allow the users to approach to the synthesis of mechanisms and understand how changes in shape or dimensions modify the resulting motion. They can be considered as the basic steps of the method implemented by Disney but without the need of using a database and having to design the mechanisms manually. Both of them do not include an optimization process to arrange the linkage dimensions and disposition to achieve the best possible result. Therefore, these methods can be also used to provide an initial approach to the final mechanism.

The linkages obtained from Math Illustrations does not have the final dimensions, they can be scaled up or down as necessary. However, the **proportions** between the link's lengths and angles must be always the same.

## 5.2.3. Practical Application: Mechanism Designs

These two methods were applied to try to find the best mechanism for the purpose of reproducing the motion of human's feet climbing stairs. More than one mechanism was designed. First, a mechanism which reproduces the trajectories of the stickers with respect to the reference frame. Second, a mechanism that reproduces the relative motion of the stickers with respect to the center of gravity of the body. Various mechanisms of this type were designed using different methods, the best solution was selected regarding to the simplest design.

The starting point for the synthesis is the trajectories obtained from the video sequence.

<u>Synthesis of the mechanism with respect to the reference frame</u>

The *Three-Position Synthesis Method* is applied to design a mechanism which will reproduce the trajectories of the two stickers with respect to the reference frame. The $20^{th}$, $40^{th}$ and $70^{th}$ frames of the video sequence are considered to obtain the three positions required as input (see **Figure 26**).
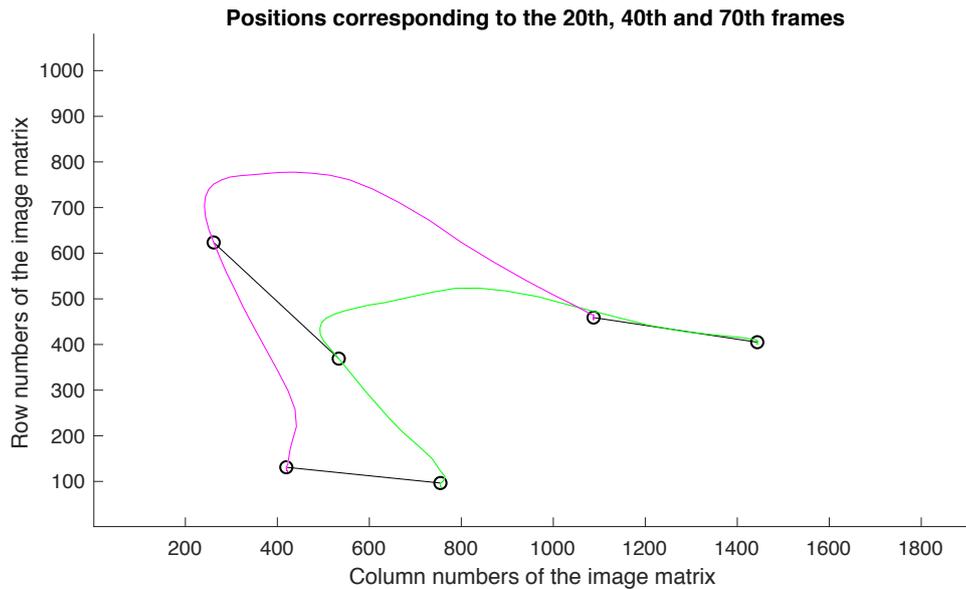
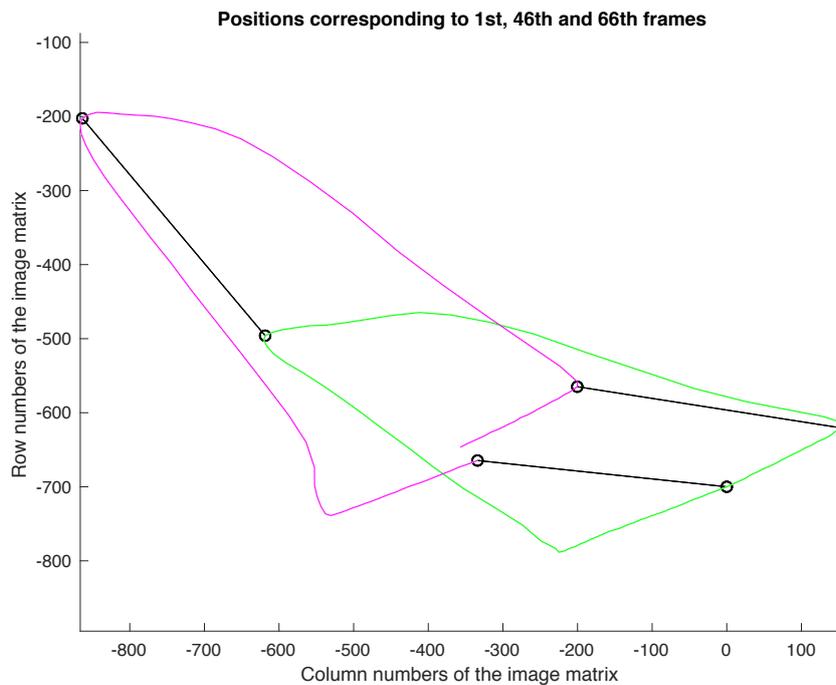*Figure 26: Three positions used for the synthesis of the mechanism with respect to the reference frame*

This image was inserted in Math Illustrations and the following mechanism was designed following the steps explained before. A triangular dyad was required to solve the toggle points encountered with the simplest design.

**Figure 27** shows the resulted designed mechanism with respect to the reference frame and the parameters which define the proportions of the resulted mechanism. It is a crank-rocker mechanism. **Figure 28** shows the complete motion of the mechanism.



| Variables | Value |
|---|---|
| a | 2.5477 |
| b | 7.2650 |
| c | 6.4282 |
| d | 3.1705 |
| $\overline{OA\ OC}$ | 10.4136 |
| x (degrees) | 67.8538 |
| $z_2$ and $z_3$ in degrees | |
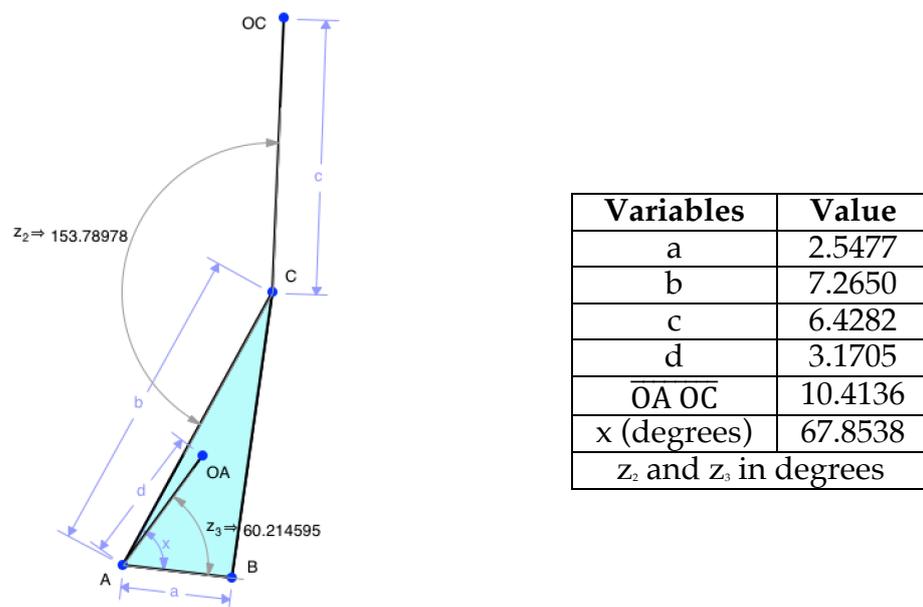
*Figure 27: Proportions of the designed mechanism with respect to the reference frame*
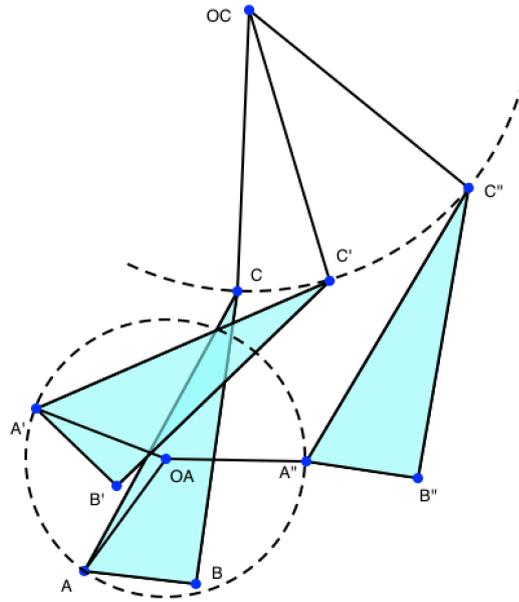
*Figure 28: Complete motion of the mechanism with respect to the reference frame*

## Synthesis of the mechanism with respect to the relative motion of the package

The *Three-Position Synthesis Method* is also applied to design a mechanism which will reproduce the relative trajectories of the two stickers with respect to the package. The 1st, 46th and 66th frames of the video are considered to obtain the three positions required as input (see **Figure 29**).



*Figure 29: Three positions used for the synthesis of the mechanism with respect to the relative motion of the package*

This image was inserted in Math Illustrations and the following mechanism was designed following the steps explained before. A quadrilateral dyad was required to solve the toggle points encountered with simpler designs.

**Figure 30** shows the resulted designed mechanism with respect to the relative motion of the package and the parameters which define the proportions of the resulted mechanism. It is also a crank-rocker mechanism. **Figure 31** shows the complete motion of the mechanism.



| Variables | Values |
|---|---|
| a | 3.1292 |
| b | 5.4832 |
| d | 6.8783 |
| e | 5.5427 |
| f | 1.5354 |
| g | 1.7111 |
| $z_1$ and $z_2$ in degrees | |
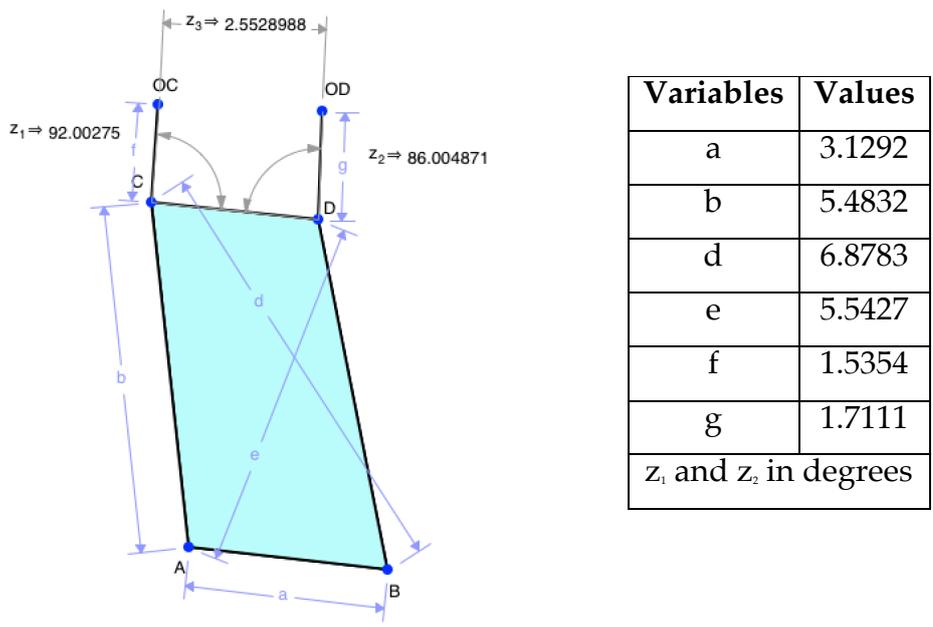
*Figure 30: Proportions of the resulted designed mechanism with respect to the relative motion of the package*
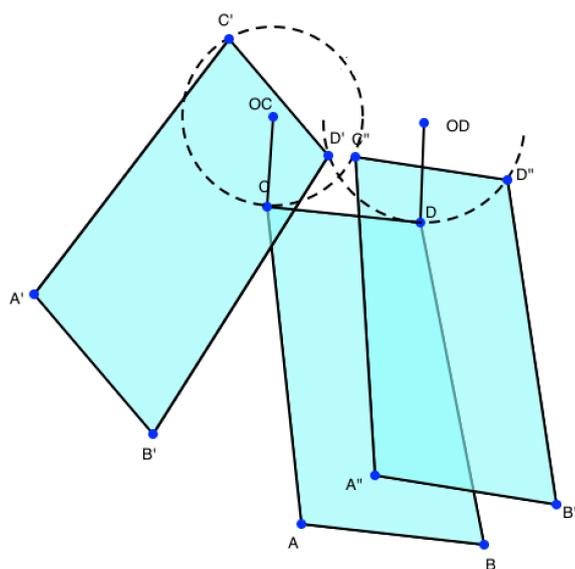


*Figure 31: Complete motion of the mechanism with respect to the relative motion of the package*

The *Coupler Curves Method* can be applied to design two mechanisms which generate the path described by the stickers with respect to the center of gravity of the package. The four-bar symmetrical linkages from Kota's coupler curves classification used as first approach to the final design are presented in the following table:

| Initial four-bar symmetrical linkages | | | | |
|---|---|---|---|---|
| | GREEN sticker | | PINK sticker | |
| $L_3/L_2 = L_4/L_2 = BP/L_2$ | 2,5 | | 3 | |
| gamma | 216 | | 216 | |
| $L_1/L_2$ | 2,5 | | 2 | |

*Table 3: Parameters for the initial four-bar symmetrical linkages*

After several modifications, the final mechanisms are shown in the following figures:
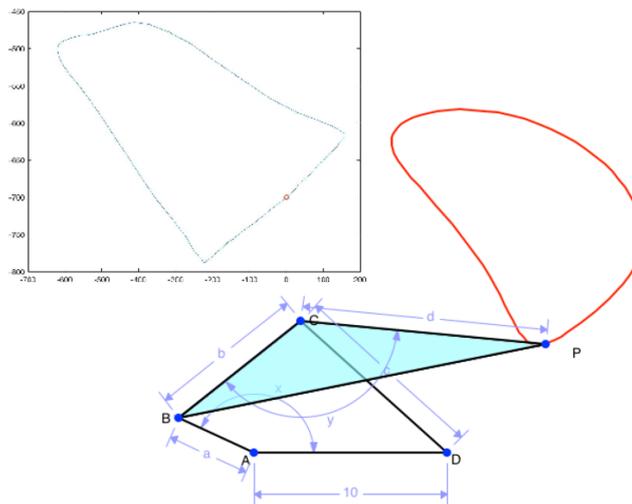


*Figure 32:  Four-bar linkage to generate the relative path of the GREEN sticker*
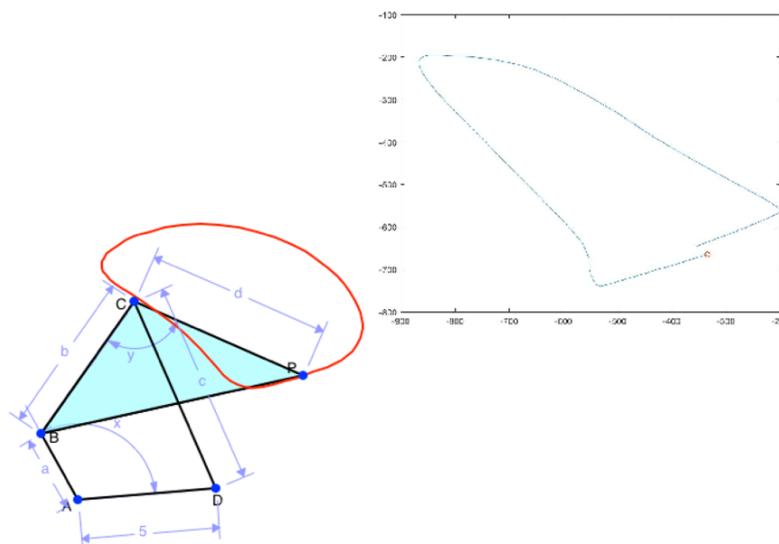


*Figure 33: Four-bar linkage to generate the relative path of the PINK sticker*

In this particular example, the mechanisms used for the design of the final device are the ones obtained from the Three-Position Synthesis Method due to several reasons:

- The mechanisms designed with the Coupler Curves Method do not ensure that they are not going to bump into the stairs during their motion.
- Using the Three-Position Method, only one mechanism is needed in each side as it controls for the trajectory of both stickers. It is cheaper and easier to manufacture.
- An optimization procedure would be required to apply to the mechanisms designed by the Coupler Curves Method for obtaining a better approximation to the relative curves obtained from the video.

## 5.2.4. Analysis of Toggle Points

Once a potential solution for a mechanism is found, it is necessary to check its quality. One important test is that the mechanism can in fact reach all the desired positions without encountering a limiting or toggle position. The toggle points in a mechanism are determined by collinearity of two of the moving links and will not allow for further motion in that direction [NORT99].

As mentioned before, these methods do not control for the toggle points in a mechanism. It is for this reason that it is necessary to check that the designed linkage can in fact reach all the positions continuously without the need to disassemble it.

There are two ways to identify a toggle position: using **Grashof rule** and optimizing the **transmission angle**. Besides, based on all the designs analyzed during the development of the project, some rules were identified to try to avoid this toggle positions problem. First, it is analyzed the optimal design to ensure continuous motion of a four-bar linkage using formulas and controlling for important parameters. Second, the conclusions after the previous analysis are presented as well as the rules identified during the mechanism synthesis of the particular example developed in this project.

Grashof rule

It is a formula used to analyze the motion of a four-bar linkage. To ensure a continuous motion, the sum of the length of the shortest and largest links can't be greater than the sum of the length of the rest of the links.

Therefore, the following equations apply for each class of four-bar linkage to avoid encountering a toggle position [WAND00]:

- Crank-rocker

$$The\ crank\ has\ to\ be\ the\ shortest\ link$$
$$Fixed\ link + Crank < Extension\ bar + Rocker$$

- Double-crank

$$The\ fixed\ link\ has\ to\ be\ the\ shortest\ link$$
$$Fixed\ link + Crank < Extension\ bar + Rocker$$

- Double-rocker

$$The\ extension\ bar\ or\ coupler\ has\ to\ be\ the\ shortest\ link$$
$$Extension\ bar + Rocker < Fixed\ link + Crank$$

For the final two mechanisms designed to reproduce the motion of the feet climbing stairs (see **Figure 34**), the Grashof rule is applied to ensure that there are no toggle points between the three positions defined. Both of the mechanisms designed are of the type crank-rocker. Therefore, the shortest link is the crank.
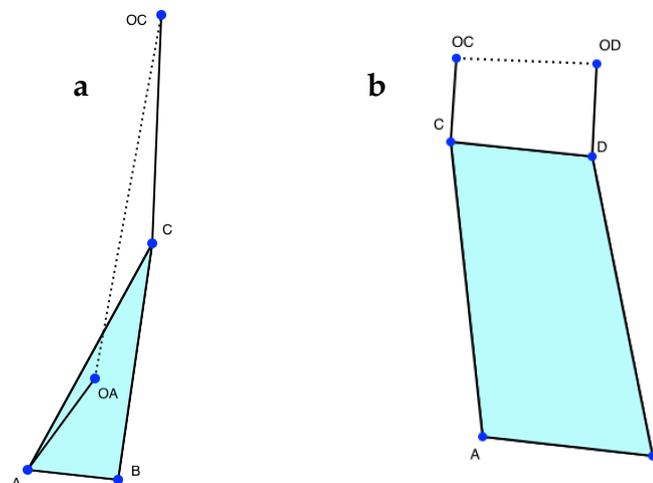


*Figure 34: Final design of the mechanisms*

For the mechanism to reproduce the motion of the feet with respect to the reference frame (see **Figure 34a**):

| | **Grashof Rule** |
|---|---|
| $\overline{OA\,OC}$ ≡ Fixed link = 10.4136 | |
| $\overline{A\,OA}$ ≡ Crank = 3.1705 | *Fixed link + Crank < Extension bar + Rocker* |
| $\overline{A\,C}$ ≡ Extension bar = 7.2650 | $10.41 + 3.1705 < 7.2650 + 6.4282$ |
| $\overline{C\,OC}$ ≡ Rocker = 6.4282 | |

*Table 4: Verification of Grashof rule in the first mechanism*

The mechanism designed to reproduce the motion of the feet climbing stairs with respect to the reference frame is a Grashof linkage (see **Table 4**). Not only it reaches the three particular positions specified from the video sequence but also it ensures that there are no toggle points between those positions.

For the mechanism to reproduce the relative motion of the feet with respect to the body center of gravity (see **Figure 34b**):

| | **Grashof Rule** |
|---|---|
| $\overline{OC\,OD}$ ≡ Fixed link = 2.5528 | |
| $\overline{C\,OC}$ ≡ Crank = 1.5354 | *Extension bar + Crank < Fixed link + Rocker* |
| $\overline{C\,D}$ ≡ Extension bar = 2.6126 | $2.6126 + 1.5354 < 2.5528 + 1.7111$ |
| $\overline{D\,OD}$ ≡ Rocker = 1.7111 | |

*Table 5: Verification of Grashof rule in the second mechanism*

The mechanism designed to reproduce the relative motion of the feet climbing stairs with respect to the body center of gravity is also a Grashof linkage (see **Table 5**). Not only it reaches the three particular positions specified from the video sequence but also it ensures that there are no toggle points between those positions. However, it approaches the limits of Grashof rule (4.148 < 4.2639). These mechanisms usually do not operate well in reality so it would be necessary to check its proper motion with the manufacture of a first prototype.

<u>Transmission angle</u>

The transmission angle is an important parameter to measure the quality of a four-bar linkage. It is the angle between the extension bar and the output link, in our case of study, the angle between the extension bar and the rocker (see **Figure 35**).
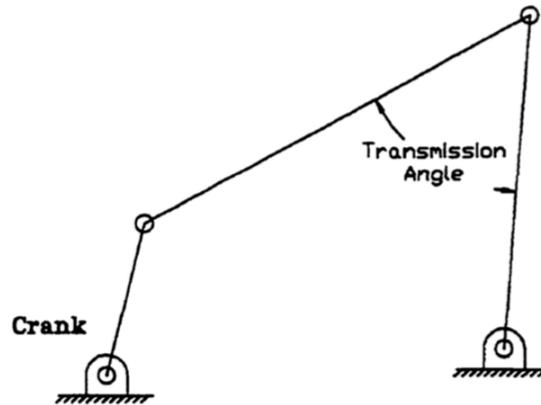


*Figure 35: Four-bar linkage transmission angle [WAND00]*

This angle varies continuously from a minimum value to a maximum value through its range of motion. The optimal range of values for the transmission of motion depends on the intended use of the mechanism. For low-speed applications the minimum value is 40º and the maximum is 140º. For high-speed applications the minimum value is 50º and the maximum value is 130º. The optimal transmission angle for the transmission of forces and velocities is 90º whereas a value of 0º would not transmit any force [WAND00].

For the two mechanisms designed in this project, the transmission angles obtained from the program Math Illustrations vary between the values presented in **Table 6**:

| TRANSMISSION ANGLE | | |
|---|---|---|
| Mechanism to reproduce motion with respect to the reference frame | Maximum | 153.8º |
| | Minimum | 67.4º |
| Mechanism to reproduce the relative motion | Maximum | 134.54º |
| | Minimum | 12.88º |

*Table 6: Transmission angle for each designed mechanism*

Comparing the range of values for the transmission angle in the two mechanisms designed to the range of optimal values, it can be concluded that an optimization focused on the transmission angle [PINT07] is required to improve the motion of each linkage.

<u>Rules</u>

Some rules can be formulated to guess if, during the application of the Three-Positions graphical method for the mechanism synthesis in Math Illustrations, a mechanism is going to be able to complete its motion without finding a toggle point. They can be summarized in the following:

- The maximum distance between the two circumferences that define the location of the fixed points has to be equal to or smaller than the coupler's link length (see **Figure 36**). Only if the coupler has to go through it to reach all the specified positions.
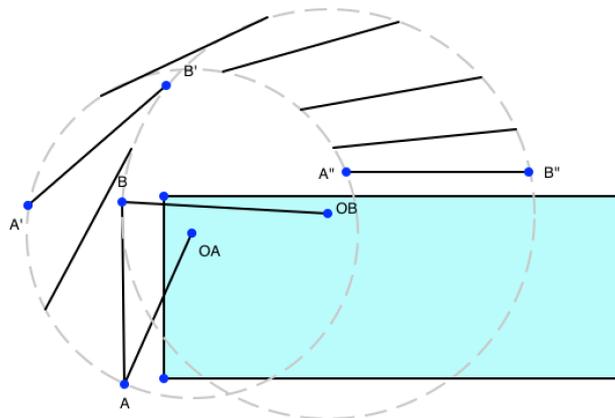


*Figure 36: Gate motion to open and close a container*

- In the practical application analyzed, the coupler link represented foot's sole. It could not rotate in any moment so that the package would not lose its balance. Therefore, the vertex B must always be located to the right side of the vertex A.

Different configurations and applications were analyzed to try to come up with a clear rule that solves this problem in all cases. However, the results were proved inconclusive due to the reduce amount of cases analyzed leaving open a wide field of research.

## 5.3.  STEP 3: SIMULATION

*This section describes the last step in the process. The aim here is to verify the functionality of the mechanism designed with a simulation as close as possible to reality that will allow the manufacture of the device by 3D printing the designed parts. It explains how the results from Math Illustrations are used in the simulation as well as the process followed to build the device: types of joints, motors, kinematic restrictions, contact forces and gravity.*

### 5.3.1. SolidWorks: Mates, Forces and Functions

The main idea is to build on the sketches from Math Illustrations. As explained before, the dimensions obtained from the synthesis are not yet certain. They refer to the **proportions** among the links and the angles which should be kept constant, but the mechanism can be scaled up or down as required. First, the parts are separately designed and subsequently, assembled to result in the mechanism. Then, the mechanism can be incorporated to a bigger assembly or part to validate its proper operation by means of a simulation.

All the joints used for assembling the parts together are **hinge** type. It requires both a coincident and concentric mate between the two parts being assembled. This type of joint allows rotation between the two parts but blocks the movement of one respect to the other.

Activating SolidWorks Motion and Simulation add-ins allow to make a simulation very close to reality. In order to get closer to reality, different **forces** are considered:

- **Gravity**, negative in the y direction.
- Solid **Contact forces** between two bodies. The material of each part or friction and elastic properties are required to be specified. Every contact has to be defined separately.
- **Motor** applied to the crank. It can be either a linear or rotatory motor. Its motion can be defined in different ways: as constant speed, by segments, with an expression …

Besides, **kinematic restrictions** can be considered to ensure consistency with reality. For example, parallel mates between two surfaces, adding a linear motor to a particular point…

The simulation usually requires a high number of frames to be run consistently, especially if contact forces are included to avoid that the program do not detect contact between the two specified parts.

### 5.3.2. Practical Application: Simulation Specifications and Results

The main purpose of the mechanisms designed using Math Illustrations is imitating the movement of human's feet climbing stairs and then, incorporate them to packages or heavy loads to facilitate carrying them upstairs. To achieve this goal more than one four-bar linkage is needed.

The final design consists of **four mechanisms**: two exterior mechanisms designed with respect to the reference of frame and two interior mechanisms designed with respect to the relative motion of the package center of gravity. Each pair of mechanisms are designed in two different forms: one in the exact same way as the sketch done in Math Illustrations, for the right side of the device, and the other one as a reflection of the sketch, for the left side of the device. The reasoning behind this design is human's way of climbing stairs. While the first foot is moving to the next step, the second foot is firmly on the ground avoiding loss of balance, and the center of gravity is moving forward. The exterior feet correspond to the first foot and thus, they are designed with respect to the relative motion of the package. Then, once the first foot reaches the next step, the second foot moves upstairs while the center of gravity stands at its position. The interior feet correspond to this second foot, and hence, they are designed with respect to the reference frame. The reason why the device uses four mechanisms instead of two is just a matter of stability, two feet are always going to be firmly on the ground keeping the center of gravity of the package in the middle.

The configuration of the final device can be also justified using the paths of the stickers obtained from the video sequence analyzed with Matlab. The final motion can be divided in a sequence of cycles. **Figure 37** illustrates one cycle of the final motion that will be repeated until reaching the last step.
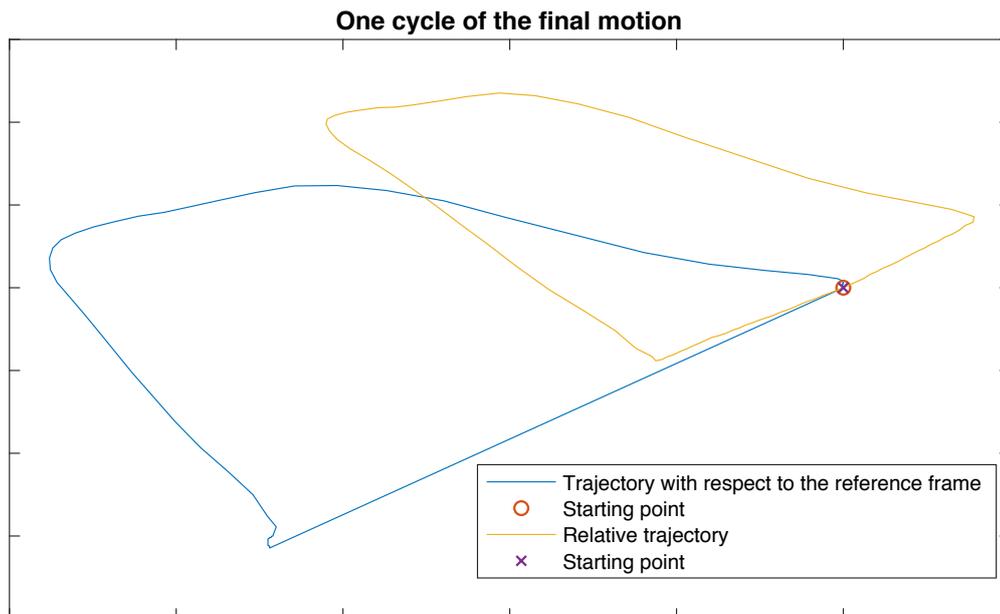
*Figure 37: One cycle of the final motion*

Each cycle that completes the final motion can be divided in two intervals. It is a combination between the two trajectories described by the stickers depending on the point of view. During the first interval, the center of gravity of the package is moving following approximately a straight line with positive slope. The exterior mechanisms are moving while the interior mechanisms remain still. With respect the center of gravity, the exterior mechanisms describe the relative trajectory whereas the interior mechanisms describe a straight line with negative slope. During the second interval, the center of gravity of the package is not moving. The exterior mechanisms are stopped while the interior mechanisms are moving. With respect the reference frame, the exterior mechanisms do not move whereas the interior mechanisms describe the trajectory with respect to the reference frame.

The following figures represent the design of all the mechanisms, the two internal mechanisms (see **Figure 38**) and the two external mechanisms (see **Figure 39**). Besides, the exact dimensions are presented in the drawings included in **Appendix B**. It is important to note that in order to have four mechanisms of the same size that can be combined together, it is necessary that the common link among them is of the same size. The dimensions of the interior mechanisms are adapted to the dimensions of the exterior mechanisms.

45
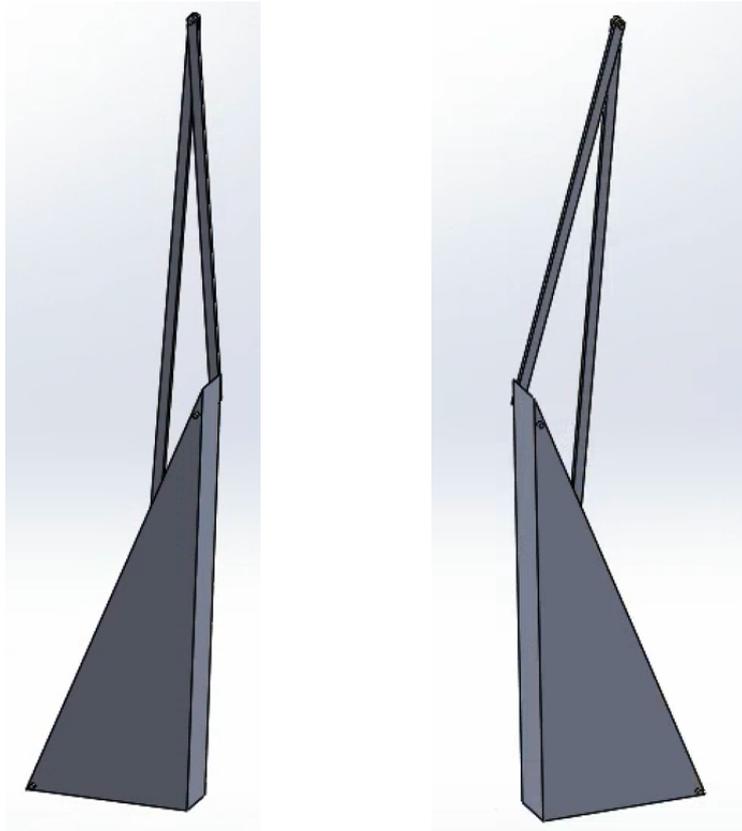
*Figure 38: Right and Left mechanism designed with respect to the reference of frame*
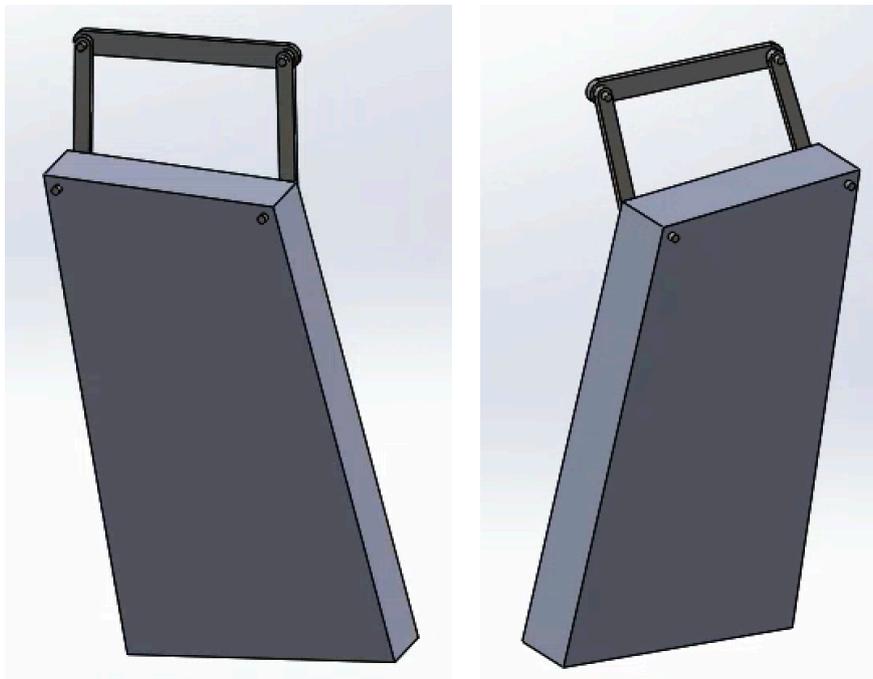


*Figure 39: Right and Left mechanism designed with respect to the relative motion of the center of gravity*

The design of the container for the simulation attends different criteria. It is designed to ensure stability and to be as compact as possible. After several simulations, the following design has resulted to be the best one (see **Figure 40**). It was necessary to add a mass on the top part of the container to prevent it from falling backwards.
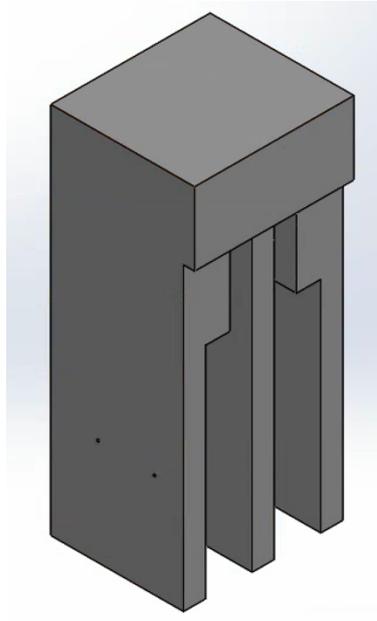


*Figure 40: Design of the container used in the simulation*

The resulting device consisting of the four mechanisms and the container is presented in **Figure 41**.
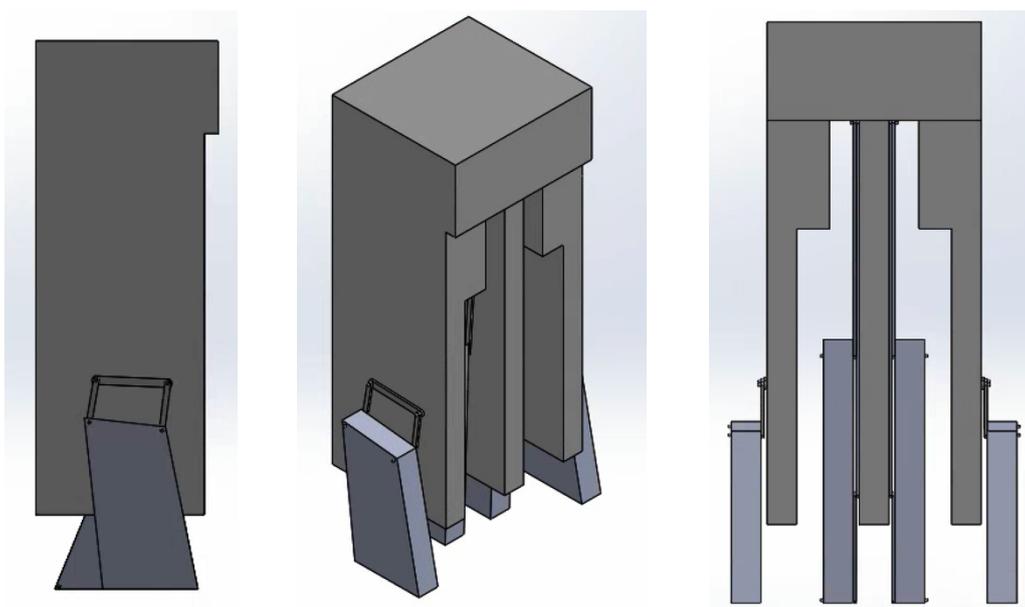


*Figure 41: Resulting device to reproduce human's feet motion climbing stairs*

After the synthesis of mechanisms, the design of all the parts and the assembly of all the components together, a simulation is possible to run to verify the potential of the designed device.

The **forces** considered in this simulation are the following:

- **Gravity**, negative in the y direction.

- **Solid Contact** between the four feet and the stairs. The values for the parameters avoid the feet to pass through the stairs and to slip. The kinetic coefficients of friction are 10.16 mm/s and 0.8. The static coefficients of friction are 0.10 mm/s and 0.8. The stiffness of the contact is 111149.92 N and the rest of the parameters are defined by default. The minimum number of frames required to ensure that this contact is detected is 150.

- **Rotatory Motors**. Each mechanism contains one motor in the link beneath, the crank. The motors of the right sided mechanisms rotate clockwise whereas the motors of the left sided mechanisms rotate counterclockwise. The torque of the motor is set for making the linkage rotate at constant speed 20 rpm, which means that one complete turn lasts 6 seconds. In order to maintain stability and move the container upstairs, the motors are outdated by pairs (see **Figure 42**).



Motor A: Exterior mechanisms

Motor B: Interior mechanisms
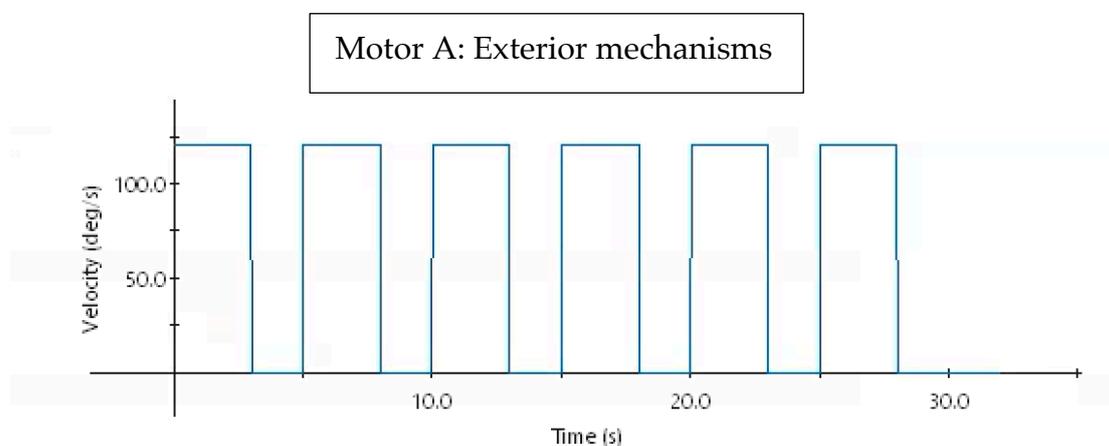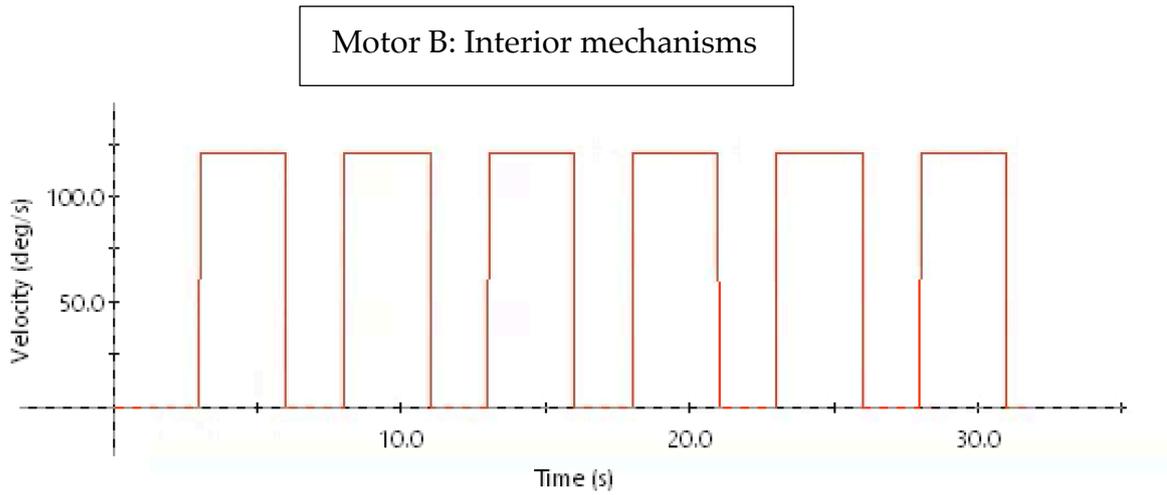
*Figure 42: Motors applied to the exterior and interior mechanisms*

One **kinematic restriction** is considered to simulate the stability that our body naturally presents. It is implemented by creating a parallel mate between the bottom side and the stairs floor.

The final simulation is shown in **Figure 43**:
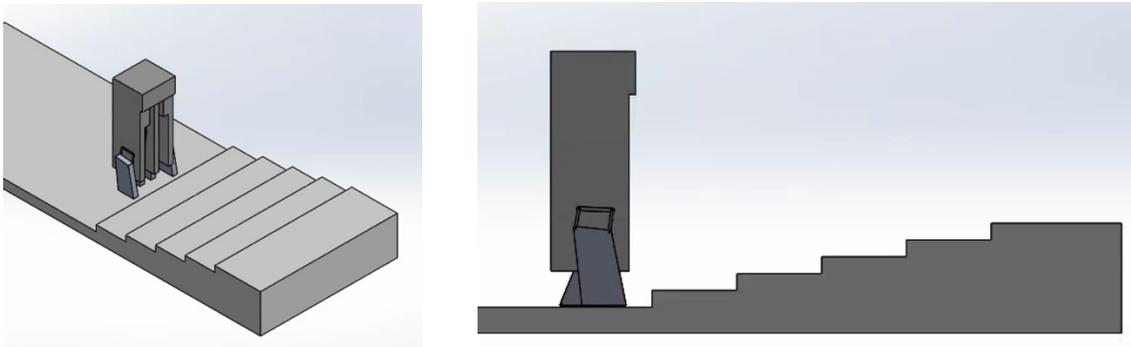


*Figure 43: Final simulation*

## 5.4. SUMMARY

In view of the abovementioned, the methodology implemented in this project follows the same line as the system that Disney uses for designing animated mechanical characters. It proposes a complete and simple process for the synthesis of mechanisms, in particular four-bar planar linkages, from the definition of the motion desired to be reproduced to the design of the mechanism that moves in the same way. It is based on generating a mechanism from a particular curve used as input and combining the resulted mechanism as many times as needed for the purpose in particular.

It consists in three steps. Once decided the motion desired to be reproduced, it has to be recorded with a particular setup. First, this videotape is analyzed to obtain the paths described by the points of interest. Second, the synthesis of mechanisms is solved by applying easy graphical methods. From the path obtained from the video sequence, a four-bar linkage is designed containing two points that describes the same trajectories as the ones from the video. Finally, a simulation is done to validate the motion and leave all the parts of the mechanism ready to 3D print and test its proper working in the real world.

# 6. CONCLUSIONS

The methodology that has been developed in this project pretends to be a first approach to the synthesis of mechanisms. It eliminates the most complex parts of the process such as the mathematical expressions for the input, replaced by a video, or the need of using a software or database to do the synthesis, replaced by simple graphical methods.

Despite the positive results achieved, this methodology presents some limitations especially regarding to the graphical methods used for the mechanism synthesis. The Three-Position Synthesis Method can only specify a maximum of three positions of the motion desired to be represented and the Coupler Curves Method is only valid to generate a closed path curve.

The main conclusions from the three steps which compose this methodology are summarized in the following lines. The **code** implemented in Matlab turns out to be very efficient even with different background colors, provided that they are clearly different from the stickers' colors. The **graphical methods** introduced to do the synthesis of mechanisms are easy to understand and based on the basics of the synthesis. They are easy enough to be understood quickly by non-expert users but also provide basic knowledge for more complex methods for the synthesis of mechanisms. However, they still require further develop and optimization as they depend highly on the designer's criteria and provide designs resulted from a trial and error process. Finally, the **simulation** provides a first good impression of how the final mechanism is going to work and it allows to detect and correct possible failures before starting the manufacturing process.

The results of this methodology are mechanisms which fulfill their purpose, they imitate a previous specified motion without encountering a limiting position. However, the transmission of motion is usually not optimized. Therefore, the mechanisms obtained from this methodology can be used as an initial guess for numerical techniques. They provide an initial approach to the final mechanism and after the application of these more complex and precise procedures, an optimal solution for the initial problem can be obtained.

Regarding to the case example studied in particular, it resulted to be more complex than expected. The motion of human's feet climbing stairs is difficult to be imitated with many simplifications. The final device proposed in this project required some approximations. It can be considered as a first prototype of a device that could be incorporated in trolleys or even in wheelchairs, with the appropriate size modifications, to make them move upstairs without human intervention.

# 7. POSSIBLE FUTURE IMPROVEMENTS

This project leaves the way open for several improvements.

Regarding to the method developed, it leaves open a question for further study: finding a way to predict when a mechanism is going to find a toggle point. Intuition, experience, critical thinking and trial and error seem to be the only way to detect these limitations. Added to this, an important area of improvement is related to optimization. It is necessary to implement a method to compare and minimize the error between the desired curve and the approximation obtained with the Coupler Curves Method.

Regarding to the example case analyzed to prove the effectiveness of the method, two important issues should be considered. First, the first prototype obtained should be manufactured to check its functionality. Furthermore, it should be done a forces analysis to check that it is not going to break as well as a test to prove the stability of the assembly, especially during the motion. Moreover, this design presents an important limitation, it is only valid for one type of stairs of the same size as the one in the video. The solution posed for future improvements is to design variable lengths links or a rail in the container to make possible to change the dimensions according to the size of the stairs about to climb which could be detected by the use of sensors.

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# 9. APPENDIX

## APPENDIX A: Matlab Codes

### *Matlab code for obtaining the path of a particular point from a video sequence*

- ▪ <u>VideoAnalysis GREEN.m</u>

```matlab
% Read a video file and play it
videoFReader=vision.VideoFileReader('/Users/cris/Desktop/Stairs.MOV');
videoPlayer=vision.VideoPlayer

ct=0; % Number of frames counter

while ~isDone(videoFReader)
    videoFrame=step(videoFReader); % Choose a frame and updates it
    step(videoPlayer, videoFrame); % Shows the chosen frame

    red=videoFrame(:,:,1);
    green=videoFrame(:,:,2);
    blue=videoFrame(:,:,3);

    % Detects position of GREEN STICKER

    p=(green-red)*255; % Shows the difference between green and red
    [r,c]=size(p);
    th=50; % Threshold
    pvec=p(:); % Converts a matrix into a vector
    pvec_bn=double(pvec>th)*255; % Detects values in the vector > th and
                                      substitutes them for 255
    pos=find(pvec>th); % Stores positions in the vector with values>th

    % Find the rows and columns in the matrix for those positions
    numpos=length(pos);
    row1=zeros(1,numpos);
    column1=zeros(1,numpos);
    for i=1:numpos
        j=1; % Check columns
        while (row1(i)==0 || column1(i)==0)
            if((pos(i)-j*r)<=0) % Column found
                column1(i)=j;
                row1(i)=pos(i)-(column1(i)-1)*r;
            else
                j=j+1; % Check the next column
            end
        end
    end

    % Find the centroid
    X1(ct+1) = (max(column1)+min(column1))/2;
    Y1(ct+1) = (max(row1)+min(row1))/2;

    p1=double(reshape(pvec_bn,r,c)); % Reassemble the matrix
    figure(1),image(p1) % Shows the frame with the sticker differentiated
    ct=ct+1;
```

```matlab
end
release(videoPlayer);
release(videoFReader);

% Correction of y values: flip the y axis
Y1c=r-Y1;

% Plot the centroid of the sticker in each frame
figure(2)
sz=50; % Determines the size of the marker
scatter(X1,Y1c,sz)
grid
axis([1 c 1 r])

% Plot the sticker's trajectory
figure(3)
plot(X1,Y1c)
grid
axis([1 c 1 r])
```

- VideoAnalysis_PINK.m

```matlab
% Read a video file and play it.

videoFReader=vision.VideoFileReader('/Users/cris/Desktop/Stairs.MOV');
videoPlayer=vision.VideoPlayer

ct=0; % Number of frames counter

while ~isDone(videoFReader)
    videoFrame=step(videoFReader); % Choose a frame and updates it
    step(videoPlayer, videoFrame); % Shows the chosen frame

    red=videoFrame(:,:,1);
    green=videoFrame(:,:,2);
    blue=videoFrame(:,:,3);

    % Detects position of PINK STICKER

    p=(blue-green)*255; % Shows the difference between green and red
    [r,c]=size(p);
    th=50; % Threshold
    pvec=p(:); % Converts a matrix into a vector
    pvec_bn=double(pvec>th)*255; % Detects values in the vector > th and
                                 %                substitutes them for 255
    pos=find(pvec>th); % Stores positions in the vector with values>th

    % Find the rows and columns in the matrix for those positions
    numpos=length(pos);
    row1=zeros(1,numpos);
    column1=zeros(1,numpos);
    for i=1:numpos
       j=1; % Check columns
       while (row1(i)==0 || column1(i)==0)
          if((pos(i)-j*r)<=0) % Column found
             column1(i)=j;
             row1(i)=pos(i)-(column1(i)-1)*r;
          else
```

```matlab
                j=j+1; % Check the next column
            end
        end
     end

    % Find the centroid
    X2(ct+1) = (max(column1)+min(column1))/2;
    Y2(ct+1) = (max(row1)+min(row1))/2;

    p1=double(reshape(pvec_bn,r,c)); % Reassemble the matrix
    figure(1),image(p1) % Shows the frame with the sticker differentiated
    ct=ct+1;
end
release(videoPlayer);
release(videoFReader);

% Correction of y values: flip the y axis
Y2c=r-Y2;

% Plot the centroid of the sticker in each frame
figure(2)
sz=50; % Determines the size of the marker
scatter(X2,Y2c,sz)
grid
axis([1 c 1 r])

% Plot the sticker's trajectory
figure(3)
plot(X2,Y2c)
grid
axis([1 c 1 r])
```

# *Matlab code for obtaining the relative path of a particular point from a video sequence*

- ▪ RelativeTrajectories.m

```matlab
% Stickers trajectories considering the package motion

% FIRST: Trajectory of the package with respect to the reference frame

xcg=linspace(X1(1),X1(end),length(X1));
ycg=linspace(Y1c(1),Y1c(end),length(Y1c))+700;


% SECOND: Trajectories of the stickers with respect to the package's
motion (relative motion)

% Relative trajectory of GREEN sticker
X1r=X1-xcg;
Y1r=Y1c-ycg;

% Relative trajectory of PINK sticker
X2r=X2-xcg;
Y2r=Y2c-ycg;
%% Plots

% Relative trajectory of GREEN sticker and starting point
figure(11)
plot(X1r,Y1r,X1r(1),Y1r(1),'o')

% Relative trajectory of PINK sticker and starting point
figure(12)
plot(X2r,Y2r,X2r(1),Y2r(1),'o')

% Comparison
figure(13)
subplot(1,2,1)
plot(X1,Y1c,'g')
hold on
plot(X2,Y2c,'m')
plot(xcg,ycg)
axis([1 c 1 r])
axis equal
title('Trajectories with respect to the reference frame')
subplot(1,2,2)
plot(X1r,Y1r,'g')
hold on
plot(X2r,Y2r,'m')
axis([-1000 300 -800 -100])
axis equal
title('Trajectories with respect to the pacakge')
```

# APPENDIX B: Drawings

The following drawings presents the disposition of the final device as well as the dimensions of the mechanisms designed for the simulation.

*SeniorProject*: Final device

*SeniorProject01A01*: Interior mechanism. Four-bar linkage which reproduces the motion of the stickers in the video sequence with respect to the reference frame.

*SeniorProject01P01*, *SeniorProject01P02*, *SeniorProject01P03*, *SeniorProject01P04*: Components of the interior mechanism, respectively the fixed link, crank, rocker and coupler.

*SeniorProject02A01*: Exterior mechanism. Four-bar linkage which reproduces the relative motion of the stickers in the video sequence with respect to the body center of gravity.

*SeniorProject02P01*, *SeniorProject02P02*, *SeniorProject02P03*, *SeniorProject02P04*: Components of the exterior mechanism, respectively the fixed link, crank, rocker and coupler.

| 4 | 3 | 2 | 1 |

**REVISIONS**

| REV | DESCRIPTION | DATE | APPD |
|-----|-------------|------|------|
|     |             |      |      |
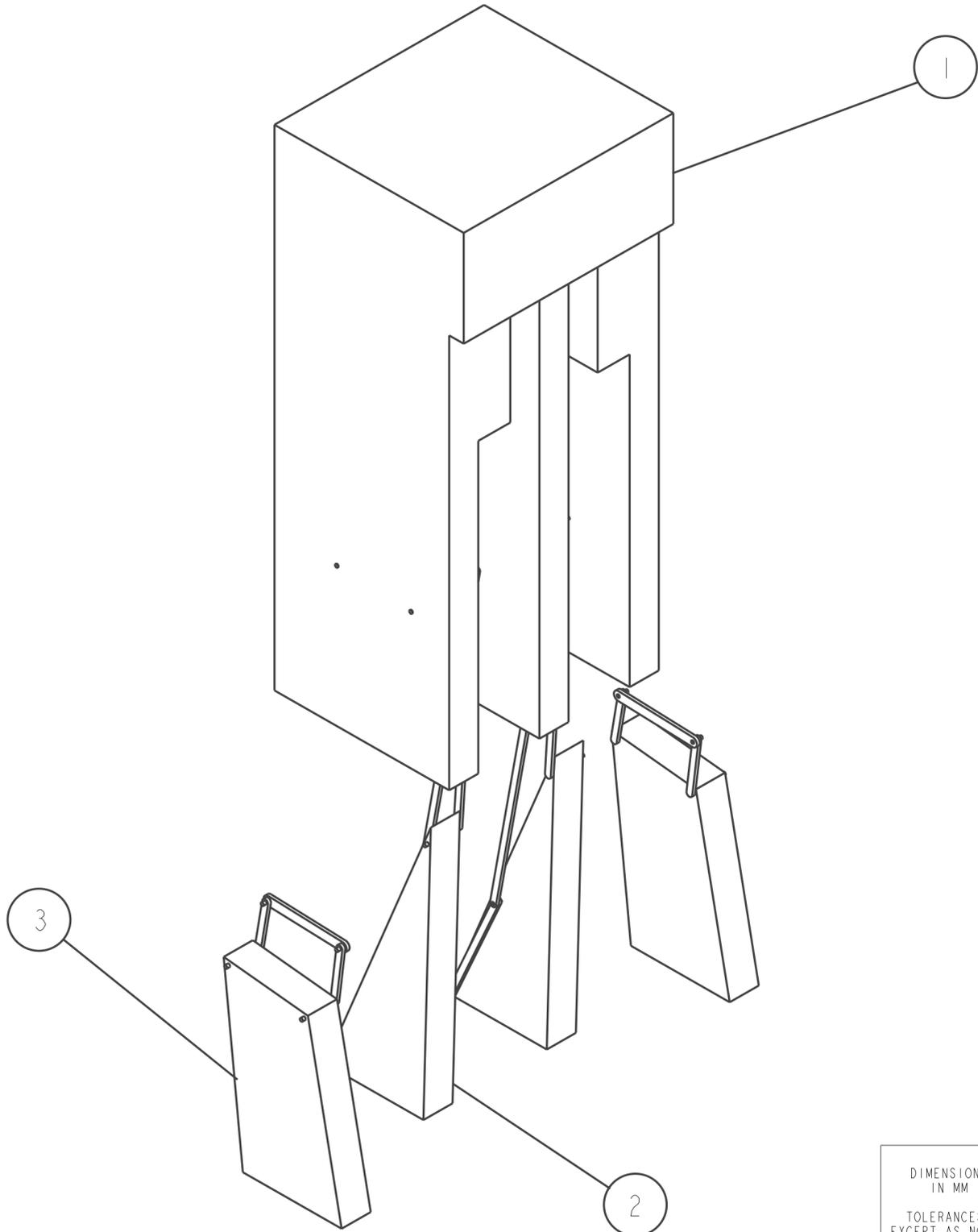
**BOM TABLE**

| ITEM | PART NO. | QTY | DESCRIPTION | VENDOR | VENDOR NO. |
|------|----------|-----|-------------|--------|------------|
| 1 | - | 1 | Package | | |
| 2 | SeniorProject01A01 | 2 | Interior Mechanism | | |
| 3 | SeniorProject02A02 | 2 | Exterior Mechanism | | |

DIMENSIONS IN MM

TOLERANCES EXCEPT AS NOTED

X.X     ±0.25
X.XX    ±0.01
ANGLES  ±0.5°

THIRD ANGLE PROJECTION

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

FINAL DEVICE

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|----------|------|-------|-------|------|-------------|-----|
| Cristina de Lorenzo García, crisdlg@bu.edu | 06/01/2019 | 1 of 1 | 1:10 | A3 | SeniorProject | - |

NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009
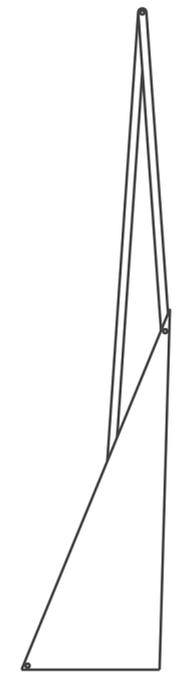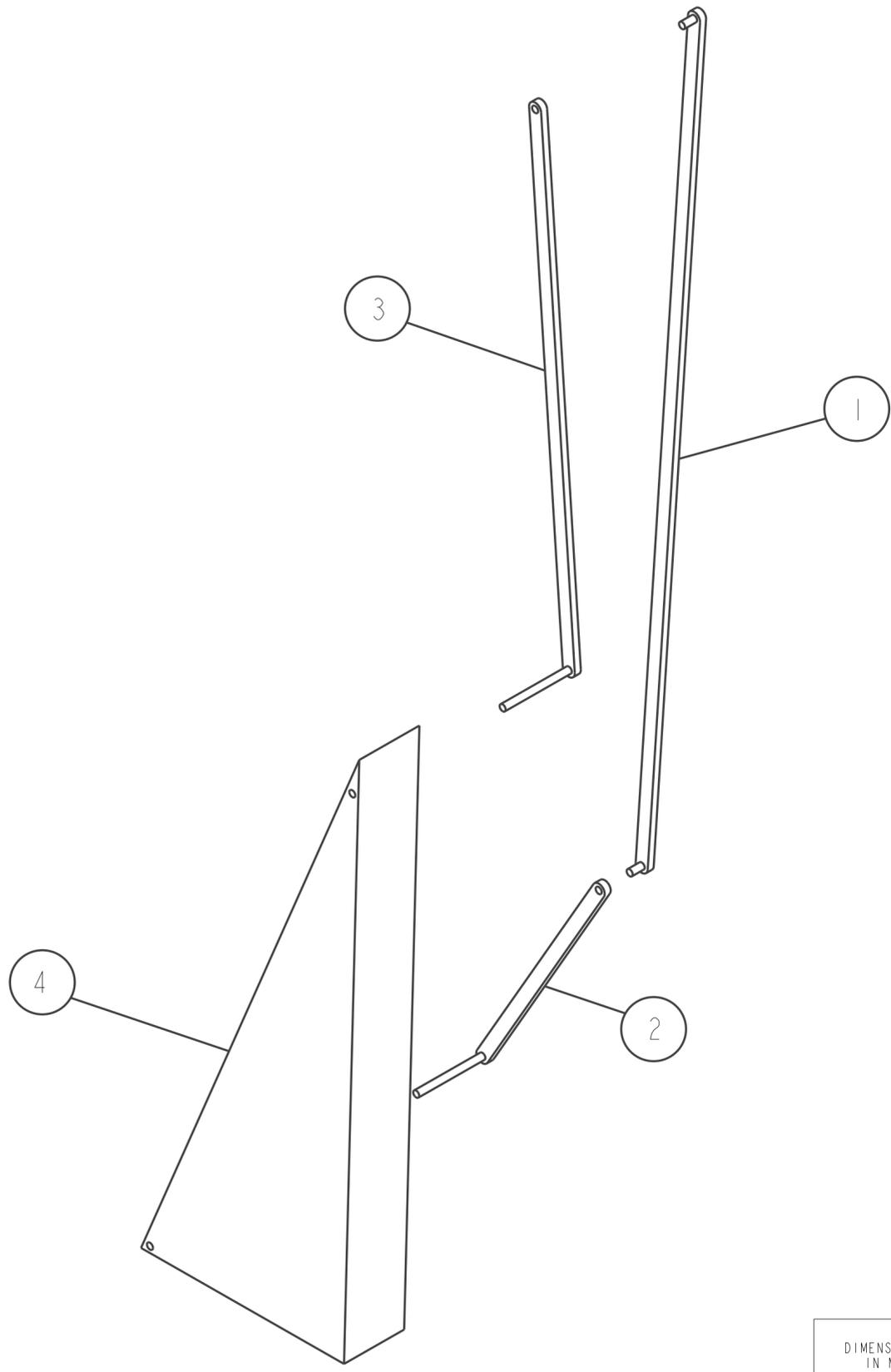
SCALE 1:12.5

| BOM TABLE | | | | | |
|---|---|---|---|---|---|
| ITEM | PART NO. | QTY | DESCRIPTION | VENDOR | VENDOR NO. |
| 1 | SeniorProject01P01 | 1 | Fixed link | | |
| 2 | SeniorProject01P02 | 1 | Crank | | |
| 3 | SeniorProject01P03 | 1 | Rocker | | |
| 4 | SeniorProject01P04 | 1 | Coupler with triangular dyad | | |

DIMENSIONS IN MM

TOLERANCES EXCEPT AS NOTED

X.X    ±0.25
X.XX   ±0.01
ANGLES ±0.5°

THIRD ANGLE PROJECTION

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

INTERIOR MECHANISM

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|---|---|---|---|---|---|---|
| Cristina de Lorenzo García, crisdlg@bu.edu | 06/01/2019 | 1 of 5 | 1:5 | A3 | SeniorProject01 A01 | – |

| REVISIONS | | | |
|---|---|---|---|
| REV | DESCRIPTION | DATE | APPD |
| | | | |

NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009

1279.37

2X ⌀10

2X R10

20

30

SCALE 1:8

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

FIXED LINK

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|---|---|---|---|---|---|---|
| Cristina de Lorenzo García, crisdlg@bu.edu | 06/01/2019 | 2 of 5 | 1:4 | A3 | SeniorProject01 P01 | - |

NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009

389.4

110

120

2X ⌀10

2X R10
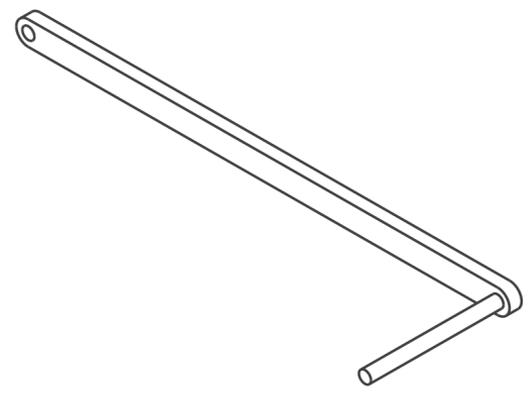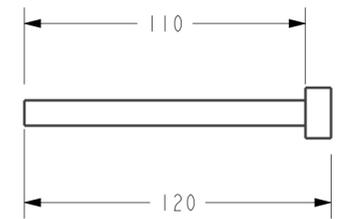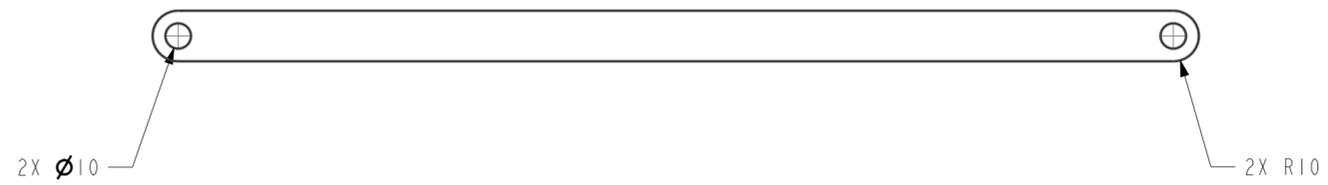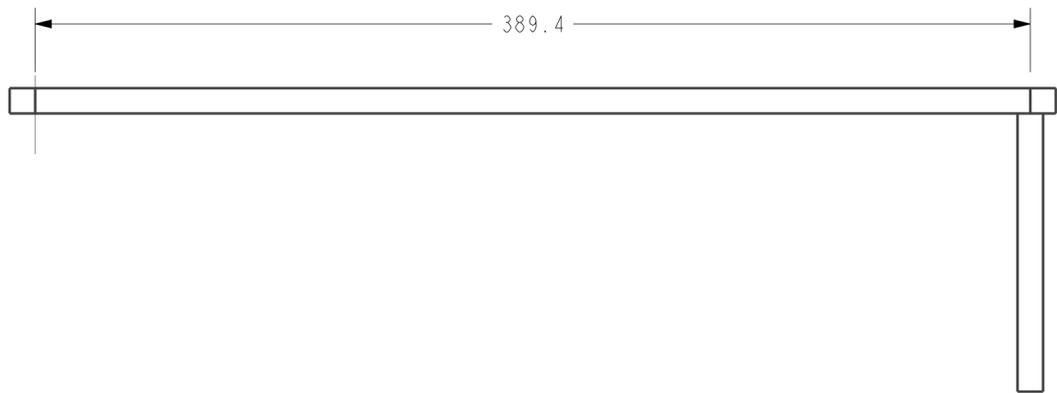
SCALE 1:3

DIMENSIONS IN MM

TOLERANCES EXCEPT AS NOTED

X.X   ±0.25
X.XX   ±0.01
ANGLES   ±0.5°

THIRD ANGLE PROJECTION

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

CRANK

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|---|---|---|---|---|---|---|
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REVISIONS

| REV | DESCRIPTION | DATE | APPD |
|-----|-------------|------|------|
|     |             |      |      |

NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009

789.7

2X Ø10

2X R10

110

120
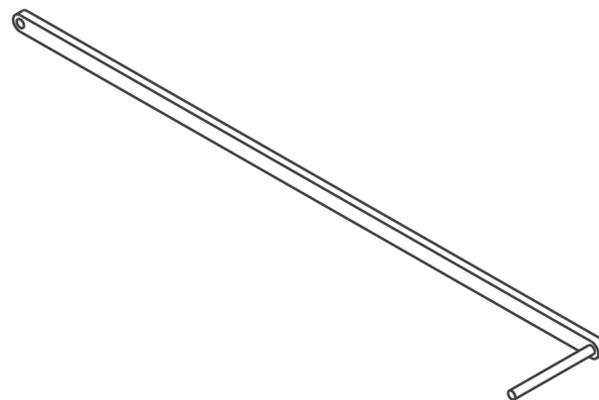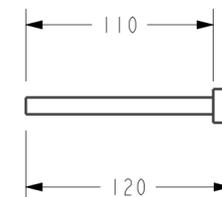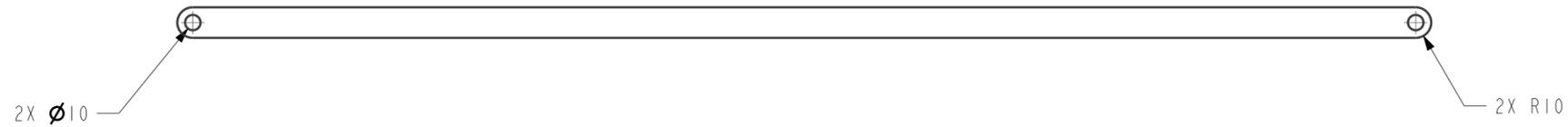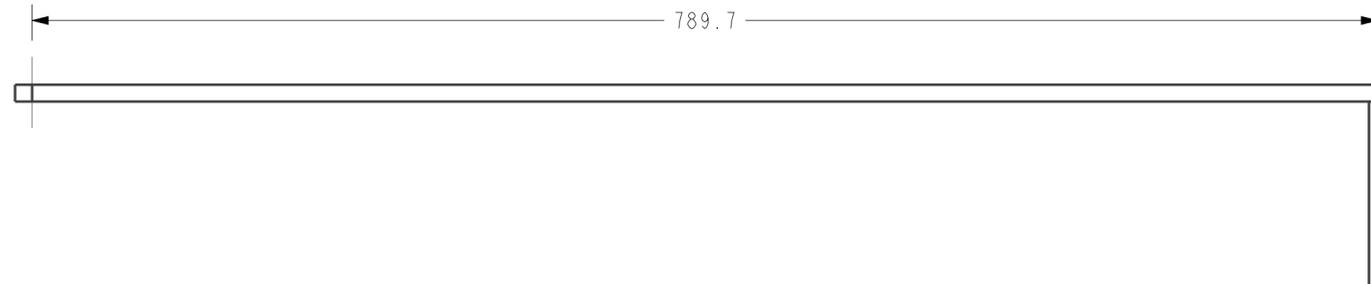
SCALE 1:5

DIMENSIONS IN MM

TOLERANCES EXCEPT AS NOTED

X.X　　±0.25
X.XX　　±0.01
ANGLES　±0.5°

THIRD ANGLE PROJECTION

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

ROCKER

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|----------|------|-------|-------|------|-------------|-----|
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| REVISIONS | | | |
|---|---|---|---|
| REV | DESCRIPTION | DATE | APPD |

NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009

362.94

14.87

100

54.94

891.57

2X ⌀10

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

COUPLER WITH TRIANGULAR DYAD

DRAWN BY

Cristina de Lorenzo García,
crisdlg@bu.edu

| DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|---|---|---|---|---|---|
| 06/01/2019 | 5 of 5 | 1:6 | A3 | SeniorProject01 P04 | - |

NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009
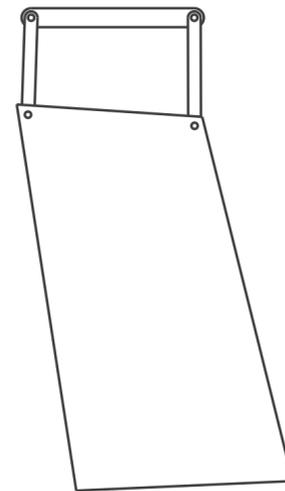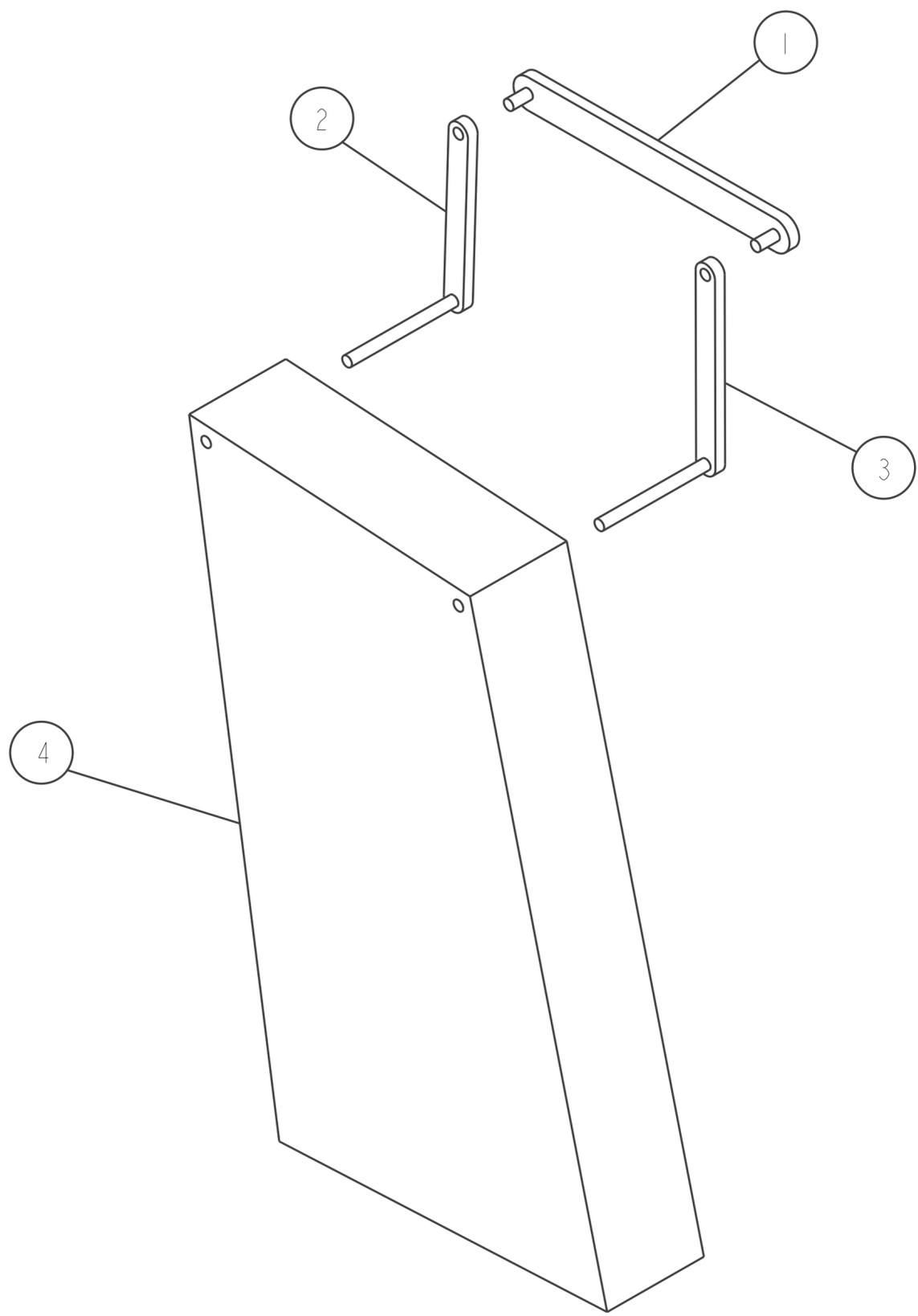
SCALE 1:8

| BOM TABLE | | | | | |
|---|---|---|---|---|---|
| ITEM | PART NO. | QTY | DESCRIPTION | VENDOR | VENDOR NO. |
| 1 | SeniorProject02P01 | 1 | Fixed link | | |
| 2 | SeniorProject02P02 | 1 | Crank | | |
| 3 | SeniorProject02P03 | 1 | Rocker | | |
| 4 | SeniorProject02P04 | 1 | Coupler with quadrilateral dyad | | |

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

DIMENSIONS IN MM

TOLERANCES EXCEPT AS NOTED

X.X    ±0.25
X.XX   ±0.01
ANGLES ±0.5°

TITLE

EXTERIOR MECHANISM

THIRD ANGLE PROJECTION

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|---|---|---|---|---|---|---|
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NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009

255.3

2X ⌀10

2X R15

20

30

SCALE 1:2

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

FIXED LINK

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|---|---|---|---|---|---|---|
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NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009

153.5

110

120

2X ⌀10

2X R10
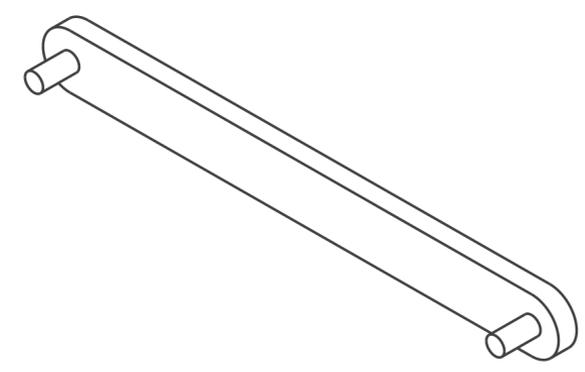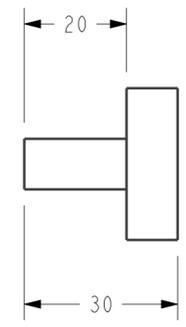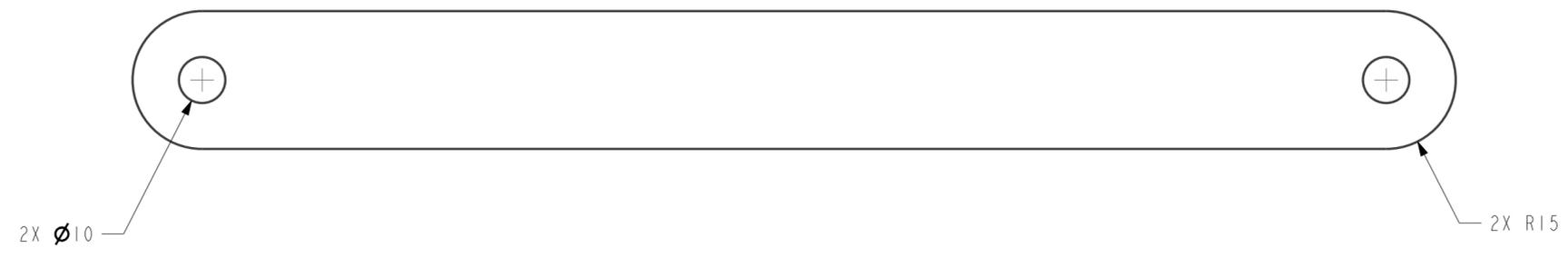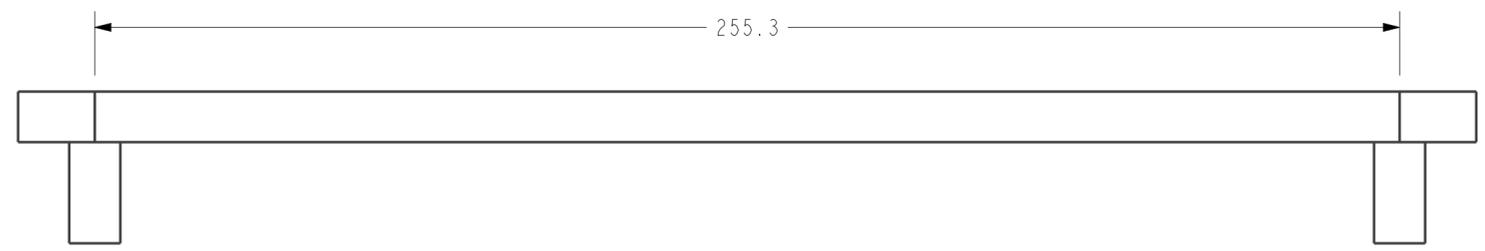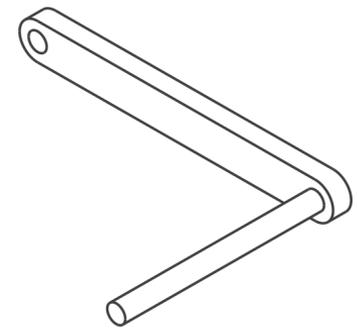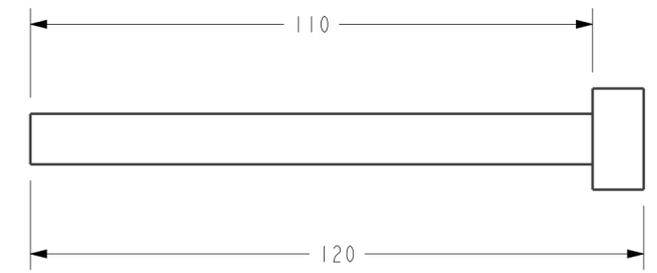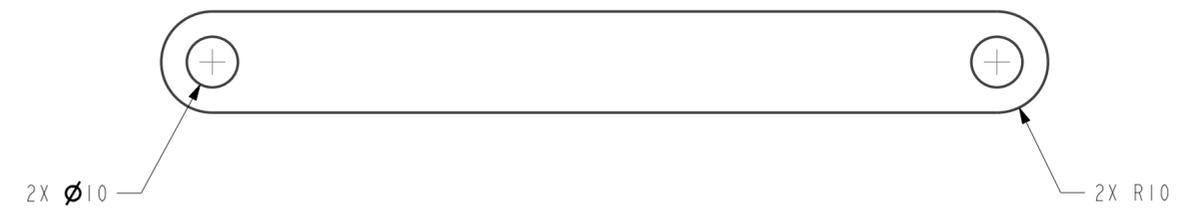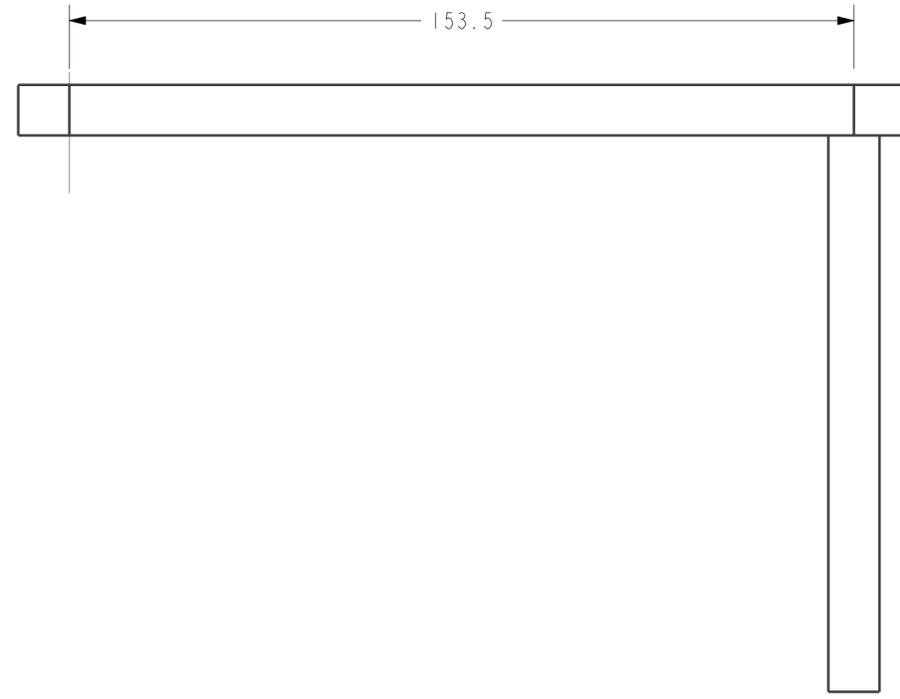
SCALE 1:2

DIMENSIONS
IN MM

TOLERANCES
EXCEPT AS NOTED

X.X      ±0.25
X.XX     ±0.01
ANGLES   ±0.5°

THIRD ANGLE PROJECTION

BOSTON UNIVERSITY COLLEGE OF ENGINEERING

TITLE

CRANK

| DRAWN BY | DATE | SHEET | SCALE | SIZE | PART NUMBER | REV |
|----------|------|-------|-------|------|-------------|-----|
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NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M-2009

171

110

120

2X Ø10

2X R10

SCALE 1:2

NOTES:

1. INTERPRET PER ASME Y14.5M-2009

290.96

18.7

2X Ø10

617.89

96.1°

78.7°

339.26

100

15

SCALE 1:6