Project Number: YR-CH03

Design of Automated Packaging Machine

A Major Qualifying Project Report:

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by

Nathan Spiegel
Sean Ivey

Partners from Huazhong University of Science and Technology,

Liu Wen, Yan Xuekai, and Yang Jin

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Approved:

Professor Yiming Rong,
Advisor

Abstract

Due to a Chinese factory's pressing need to increase the speed of paperclip packaging and decrease operating costs, our team was assigned to design a machine that would fold boxes and load them with paperclips. With very few preexisting designs for automated packaging/loading devices, we essentially had to come up with a design from scratch. To make our machine as simple as possible, we decided to make it primarily linkage based. Using both the graphical and analytical methods for linkage synthesis and with the aid of computer aided design software such as Pro/ENGINEER, we were able to determine the details of our linkages. Our results were encouraging, although the speed of machine must increase in order to compete with the current method of packaging/loading. We found this process should be automated because it is a series of repeated actions and motions. If our work is continued and our machine is made more efficient, this could be a breakthrough for packaging/loading because it doesn't require the aid of a human at any point during the packaging phase and because of its relatively small size.

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Goal Statement

Our goal is to design a machine that will automate a Chinese paper-clip factory's packaging process in order to increase the efficiency of their operation.

Chapter 1 - Introduction

A Chinese factory currently packages a variety of paper-clips into small boxes. Their means of operation is a group of about twelve women who do the job manually. The women stand around a table and take unfolded paper-clip boxes from a common pile. They proceed to fold the boxes, load one hundred clips into each, and pass them on for shipping. They package an estimated 70,000 boxes of paper-clips every day.

There are several types of boxes for several types of paper-clips. The dimensions of each type vary slightly, but they are all of similar shape. The most common dimensions of a folded box are 55 x 38 x 20 millimeters in length, width, and height respectively. The pictures below show one type of box in its partially folded and completely folded states.

Figure 1: Paper-Clip Box

The factory would like to increase the speed of packaging and decrease its costs as much as possible. Its current operating cost primarily consists of the salaries of the twelve workers. The factory has requested that we automate their process as much as possible in order to reduce the number of paid workers to the smallest number while maintaining or improving upon the speed of the current operation. Our team will conduct a design of an automated paper-clip packaging machine. The machine will fold the boxes as well as load one hundred paper-clips into each box.

From the beginning of our project, we constrained our design with seven task specifications. They are listed below.

1. Machine is to be composed of conventional mechanisms
2. Machine is to open box from initial flat position to open position.
3. Machine is to fold and interlock bottom box tabs.
4. Machine is to neatly load one hundred (+/- 1) paper-clips into each box.
5. Machine is to fold and close top box tabs.
6. Machine is to package boxes of paper-clips as quickly as possible.
7. Machine is to cost less than its performance equal in human workers

The first order of business for our team is to conduct research on box folding in general, existing processes, mechanisms, and folding methods. A clear understanding of the problem and any existing automated folding technology is the first step in developing our conceptual design.

Chapter 2 - Background Research

The background research for this project occurred in three stages. We first researched preexisting designs to gain an understanding of commercially available box-folding solutions. After completing a preliminary design and determining the mechanism would be primarily linkage based, it became paramount to find a motor that would be able to drive the linkages and accurately pause at predetermined angle steps. The final stage occurred when it became obvious that the folding and loading processes must take place at different locations. This realization forced us to consider different conveying options to transport the partially folded boxes.

Researching automated package assembling devices has opened our eyes to the reality that very few designs for complex box folding exist. To gain an understanding of solutions currently being implemented in industry, we have looked at box folding apparati by Kluge; in particular the Small Box Automated Folder/Gluer. This machine is designed to fold a box that most closely resembles the box the paperclip factory currently uses. We dissected the processes of this machine and analyzed each of them. When the process is broken down and analyzed on a process flow diagram, it’s easy to discern that the whole operation is just a combination of two folding methods, hook and plow. Hook folding is the simple process of using hooks, usually attached above the conveyor system, to catch on flaps of an unfolded box and force them in the opposite direction from which the stock is fed. This folding technique is commonly used to fold smaller flaps and flaps that interlock to keep the box held in place. The second technique, plow folding, is a process in which flaps are fed into a ramp and forced in the opposing direction. In this process the box needs to be held in place. This is done by plow shoes. This technique of box folding is usually reserved for large sections of the unfolded cardboard box or sections that need to be folded over each other.

Figure 2: Kluge Small Box Automated Folder/Gluer

Analyzing this process offers insight, but doesn't provide a great foundation to build off of. Common to this machine and all other currently existing box folding machines are the use of glue and a human to complete complex folds. To incorporate box loading into this process, the box would have to be transported to a totally different machine. In addition to the above flaws, the machine is largely inefficient. It takes up much space and is only capable of the simplest of folding operations. Based on these confounding factors, we feel it is best to start our design from scratch borrowing only the hook folding method for our simplest folds.

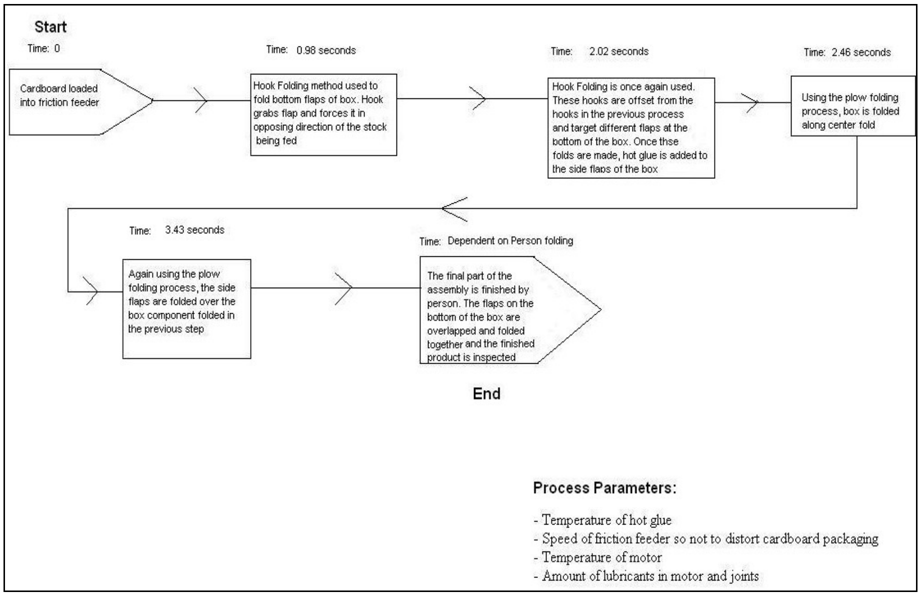


Figure 3: Process Flow Diagram of Kluge Small Box Automated Folder/Gluer

The next step of background research was completed after our preliminary design was completed and it was decided that our machine would be linkage based. To fill the motion requirement of pauses at predetermined angles, we concluded our machine was best served using step-motors. Step-motors are motors that offer accurate digital motion control. Typically step-motors offer angle steps of 7.5 to 15 degrees. To research these motors we visited the Hankou business district of Wuhan, China to gather prices and a list of components necessary to implement the step-motors. In addition to the step-motor itself, a driver would also be needed in order program the starts and pauses at the specified angle steps. We found the total package of step motor and driver would cost us roughly 360 RMB or 42.50 USD.

Figure 4: Step Motor and Step Motor Driver

The final step of background research occurred when it became apparent that the bottom folding operation and loading operation must occur at different locations. This realization forced us to consider different conveying options to transport the partially folded boxes. Due to the boxes low weight and the precise positioning needed for folding operations to be completed, we felt it would be necessary to find a belt that would either have a high grip and coefficient of friction or a belt that would limit the vibrations transmitted to the box. Based on these characteristics we decided to use a belt constructed of Polyvinyl Chloride, or PVC, with a conveyor side surface featuring a quad/inverted diamond woven pattern. The side offers a bare surface with low grip coefficient of friction <0.15. Although this belt doesn't absorb many vibrations it has the highest grip rating available, "Super", and is capable of holding the box in the precise position needed to complete the remaining folding/loading operations.

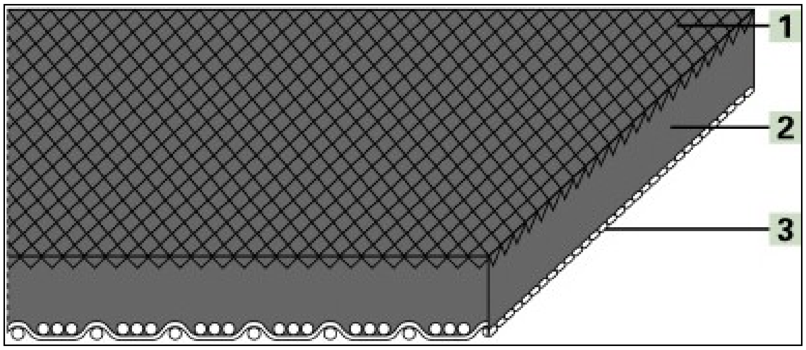


Figure 5: 3-Layer View of Conveyor 1) Top, conveying surface made from PVC woven in a quad/inverted diamond woven pattern 2) Solid Middle Layer made from PVC 3) Bottom, pulley surface made of low friction Polyester Fiber

Chapter 3 - Methodology & Design Description

This section of our report explains the detailed structure of our project. More specifically, it will detail how we broke the process down into several discrete operations and required motions and designed our machine accordingly.

3.1 Folding Operations / Required Motions

Unlike the simpler boxes processed by existing automated packaging machines, our boxes require complex folds and several different types of folds. The complexity and variation of the types of necessary folds call for the folding mechanisms to be very precise. A machine comprised of precise path generating linkages will not be able to handle all the various box types and sizes without adjustment. We decided to design for one type of paper-clip box for this reason. Because of the boxes' similar shape, interchangeable parts on the mechanisms can be designed to tailor them to the different boxes. We chose to design the machine for the most common box. Its dimensions are 55 x 38 x 20 millimeters in length, width, and height respectively.

There are a total of eight folds necessary to completely process the box from its initial flat state to its closed state. The first fold is the transformation of the box from its flat configuration to a 3-D, open configuration as shown below.

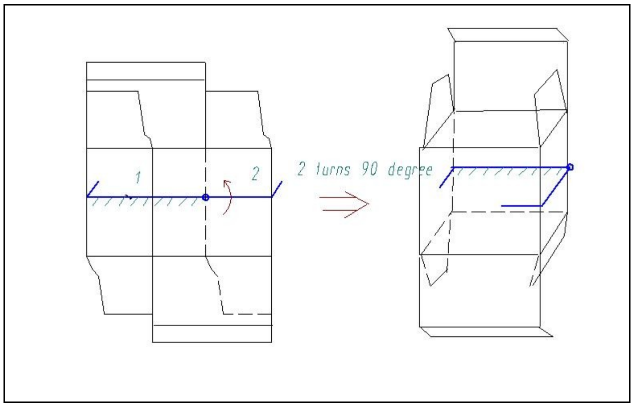


Figure 6: Initial Folding Operation

This fold requires 90-degree parallelogram motion as the top profile of the box changes from a flat line to a rectangle.

The next four folds are on the bottom of the box. Listed in folding order, they are the back tab, the two symmetrical side tabs, and the front tab, which interlocks with the other three. The bottom tabs are shown below.

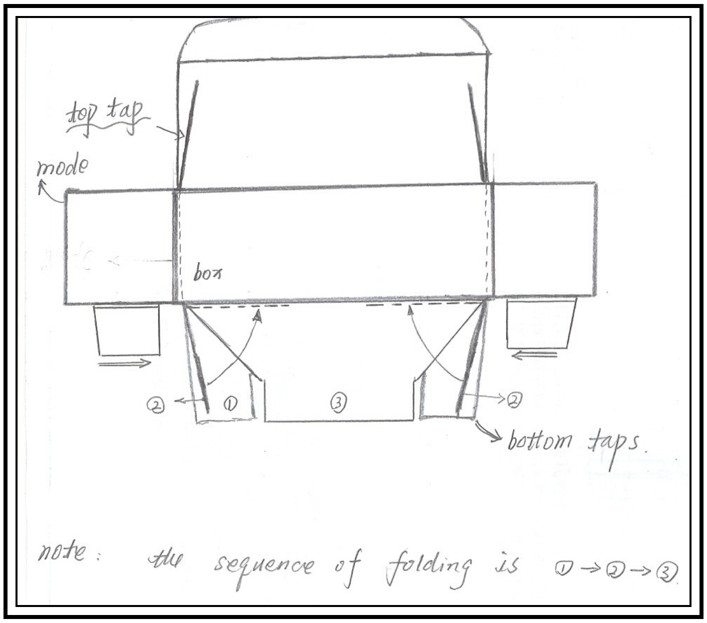


Figure 7: Bottom Tabs and Folding Motions

The back and side tabs must fold inward at 90 degrees and must be held in place until the front tab interlocks with them and secures the bottom. These tabs can be folded by synchronized linear manipulation. The front tab requires a vertical upward push (assuming the box is held upright) in order to interlock with the other three. This can be achieved by either two linear or one circular manipulation.

The final three folds comprise the folding of the top of the box. There are two symmetrical side tabs which can be folded in the same way as the back and side tabs on the bottom of the box. They require linear manipulation. The top back tab is arguably the most complex fold. The top tabs are shown below.

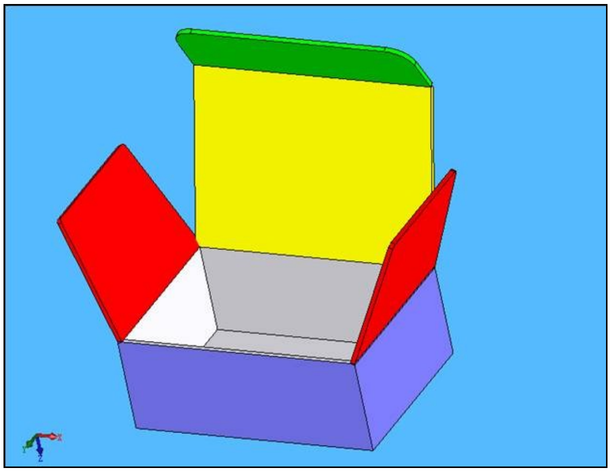


Figure 8: Top Tabs

The creased section at the end of the back tab must be guided into the space between the folded side tabs and the front of the box (the front being closest to the reader in this picture). The folding of the back tab can be achieved by circular motion around the axis which joins the back tab and the back face of the box. The creased section at the end of the tab must be guided into its final position in some way.

The operations and required motions for folding the box are tabulated below.

	Folding Operation	Motion Type Required
1	Initial Fold (Flat to 3-D)	90-Degree Parallelogram
2	Bottom Back Tab	Linear
3	Bottom Left Tab	Linear
4	Bottom Right Tab	Linear
5	Bottom Front Tab	Linear / Circular
6	Top Left Tab	Linear
7	Top Right Tab	Linear
8	Top Back Tab	Linear / Guided Circular

Table 1: Folding Operations and Required Motions

All of these motions are well suited for linkage based solution. Linkages, if designed correctly, are very precise. Also, the linkage is as conventional as a mechanism can be, so the linkage will be the primary type of mechanism in our machine.

3.2 Stages of Our Design

When you look at Table 1 it is important to note that fold 6 does not immediate follow after fold 5 in the operation sequence of our machine. After the bottom tabs have been folded, the paper-clips must be loaded into the box before the top tabs can be folded. So, although there are eight necessary folds, there is the additional paper-clip loading process to be taken into account.

In order to clearly define the structure of our machine's process, we decided to break the entire process into four "stages." The purpose of the distinction is to help our team isolate each required function and design its respective solution in the most appropriate way. When we defined the four stages, we set the goal of designing one mechanism to handle each stage. When all four mechanisms were designed, we integrated them all into one machine. Descriptions of the four stages and the final mechanisms we chose for each are shown below.

Stage	Function	Mechanism
1	Initial Fold	Crank Rocker Linkage
2	Bottom Folding	Crank-Slider Linkage w/ Hook
3	Paper-Clip Loading	Vertical Motion Funnel / Mold / Spring Combo
4	Top Folding	Crank-Slider Linkage w/ Hook

Table 2: Stage Descriptions

Of course, we went through many preliminary designs and iterations of each of the mechanisms listed above before coming to a final decision. In the following section of this chapter we will outline the course of our designs for the mechanisms in each stage.

3.2.1 Stage 1 – The Initial Fold

Our team defines the initial folding operation (fold 1 in Table 1) as stage 1. The initial folding operation is the transformation of the paper-clip box from the flat, 2-D state in which the factory receives it to an open, 3-D position. This initial 90-degree fold must be made before the subsequent stages can take place.

The stage 1 mechanism has four necessary functions. They are:

1) To receive the unfolded box from an outside mechanism such as a friction feeder.
2) To support the box in an upright position while it is being manipulated.
3) To unfold the box from its flat position to a 3-D configuration.
4) To hold the 3-D box in place after the stage 1 manipulation so that the stage 2 mechanism can fold the bottom tabs.

The fourth function was added later, when we decided that the stage 2 mechanism would manipulate the box in the same position as the stage 1 mechanism. Our rationale for this decision was based on the fact that the fewer times we have to transport the box to a new location, the simpler the process will be. Ideally, we would have liked to process the entire box in one location of the machine, but four mechanisms working in such a small space would encounter interference. Therefore, we decided to split the process into two locations, with stages 1 and 2 occurring at the first location and stages 3 and 4 occurring at the second location.

90-degree rocker output is desired from the stage 1 mechanism. To achieve this motion, we graphically synthesized a Grashof crank-rocker with link 4, the rocker, corresponding to the length of the 38 mm side of the box which will experience the motion.

3.2.2 Stage 2 – Folding the Bottom Tabs

Our team defines stage 2 as the folding of the bottom four tabs of the box. The stage 2 mechanism is situated directly below the stage 1 mechanism and is attached to the same frame as pictured below.

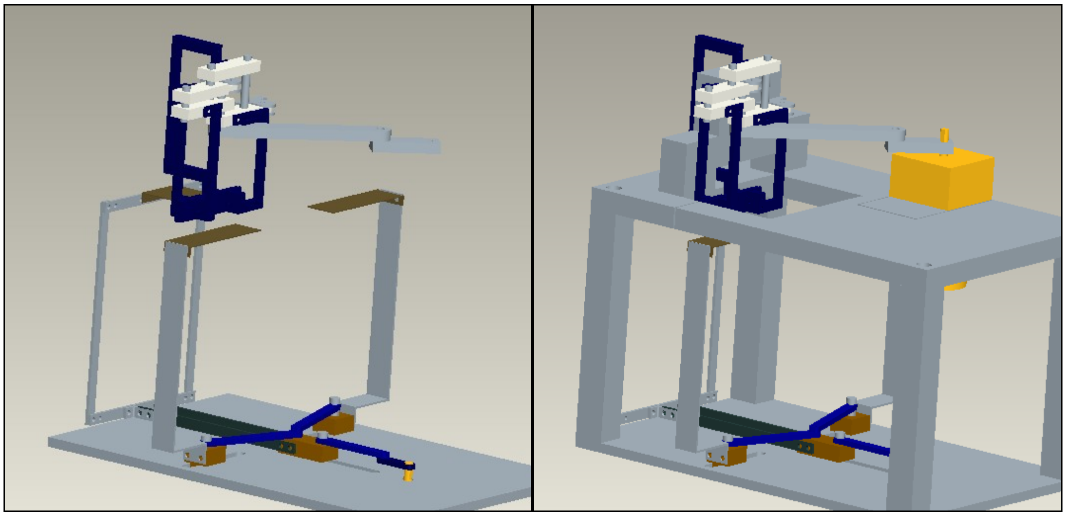


Figure 9: Stages 1 and 2 Mechanisms (With and Without Frame)

After the stage 1 mechanism has received the flat box and transformed it into its 3-D configuration, the box's bottom tabs are exposed under the plane of the top frame platform. The stage 2 mechanism has access to the bottom tabs from below while the box is held steady at its sides by the stage 1 linkage.

The stage 2 mechanism has two required functions. They are:

1) To fold the four bottom tabs of the box.
2) To clear the area below the box after folding the bottom tabs so that it can drop down to the conveyor for transportation to stages 3 and 4.

The stage 2 mechanism must be capable of three linear motions, one for each of the side tabs and one for the back tab. It must also be capable of a circular motion which will manipulate the bottom front tab into its locked position. Aiming for simplicity of design, we wanted to design a solution for stage 2 with as few mechanisms and motors as possible.

A solution to the linear motion is possible using linear actuated pneumatic cylinders, but each cylinder would require its own supply and timing device. Some graphical synthesis and link length calculations proved that all four motions could be accomplished by one crank-slider linkage driven by either a step motor or a low-speed motor with an activation / deactivation switch.

We assigned lengths of 30 mm and 70 mm for the crank and coupler respectively. The lengths of the other two links that connect the side folding sliders must be calculated so that they don't come into effect until after the back tab has been folded.

3.2.3 Stage 3 – Paper-Clip Loading

We define stage 3 as the positioning of the box underneath the paper-clip loading apparatus and the stage 4 mechanism and the subsequent loading of the 100 clips into the box.

After the bottom tabs have been folded by the stage 2 mechanism, the slider linkage reverts to its outermost position and the motor-driven hook rotates out from underneath the box. This leaves a clear path for the box to fall down onto the conveyor belt selected during our background research phase. Not included in our conceptual design is a mechanism to push the box down out of the grip of the stage 1 mechanism. This could be a Hoeken straight-line linkage, which is easily synthesized and generations close to straight-line motion of its coupler point. The linkage would be completely above the stage 1 mechanism while the stage 1 and 2 mechanisms operate, but when they finish, the coupler point of the straight-line mechanism would come down through the stage 1 mechanism and push the box out, then retract again.

When the box comes down, the conveyor carries it until it is guided into position by two inclined planes. The box comes to rest directly underneath the loading funnel and the stage 4 mechanism.

The stage 3 mechanism has three necessary functions. They are:

1) To secure the box under the loading funnel and the stage 4 mechanism.
2) To load 100 paper-clips into the box
3) To apply vibration to the box to settle the paper-clips

The required motions of the stage 3 mechanism are the vertical motion of the loading funnel. The funnel, which is situated directly above the box when it is secured between the inclined planes, moves vertically down until its end fits inside the box. Springs which attach to the sides of the mold made up of the inclined planes are used to apply vibration to the box. The vibration serves to settle the clips as they are loaded into the box for an even arrangement which allows the top to be shut easily. Finally, the front-side of the mold which contains the box in its stage 3 position must open to allow the box to move on after the stage 4 mechanism folds the top tabs of the box. In all, there are three required motions. They are:

1) The vertical motion of the loading funnel.
2) The vibration of the springs.
3) The opening / closing of the front gate.

These motions each warrant their own solution since they are actually separate mechanisms.

3.2.4 Stage 4 – Folding the Top Tabs

Stage 4 is defined as the folding of the top tabs of the box. Stage 4 occurs at the same location as stage 3. Stage 4 is actually a combination of two mechanisms, a four-bar slider linkage and a hook mechanism. As soon as the box has been shaken in order to settle the paper-clips, the linkage closes to symmetrical side tabs and, immediately after that, the hook mechanism closes top back tab. The hook mechanism is pictured below on the left and the linkage, positioned directly underneath, is shown on the right.

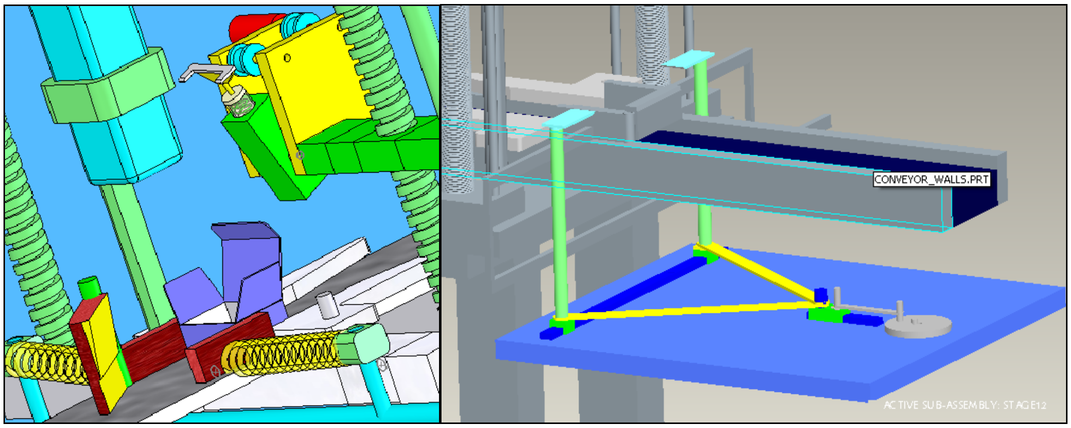


Figure 10: Stage 4 Mechanism

The stage 4 mechanism has one required function. It is:

1) To fold the top tabs of the box.

Even though there is only one function required of the stage 4 mechanism, its required motions proved to be somewhat complex. The required motions are:

1) Linear Motion
2) Guided Circular Motion

The symmetrical side tabs require the same type of motion as the symmetrical side tabs on the bottom of the box. These motions are easy to achieve with a mechanism similar to the one used in stage 2. The top back tab required circular motion like the interlocking bottom tab, but this time the folding operation is more complex. The creased portion of the top back tab must fit between the front side of the box and the front-most sides of the folded top symmetrical side tabs. A hook mechanism similar to the one used in stage 2 is necessary, except the creased portion of the top back tab must be guided into place.

Chapter 4 - Results

Having decided which mechanisms to use for each stage, we synthesized them primarily through graphical means, using Pro/ENGINEER and SolidWorks. In the following pages, we will detail the results we achieved and the final mechanisms we designed for each stage. After the design results for each stage are laid out, the entire machine will be shown.

4.1 Stage 1 Mechanism

Using the sketch feature of Pro/ENGINEER, we synthesized the proper link lengths for 90-degree rocker output. However, this linkage has a toggle position at 0 degrees, so we adjusted the rocker output to 89 degrees. This change will have a minimal effect on the 3-D configuration of the box. On the next page is a screenshot of our graphical synthesis.

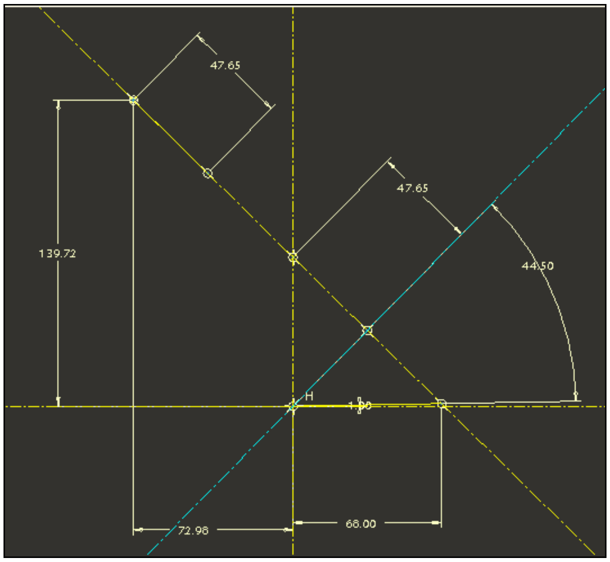
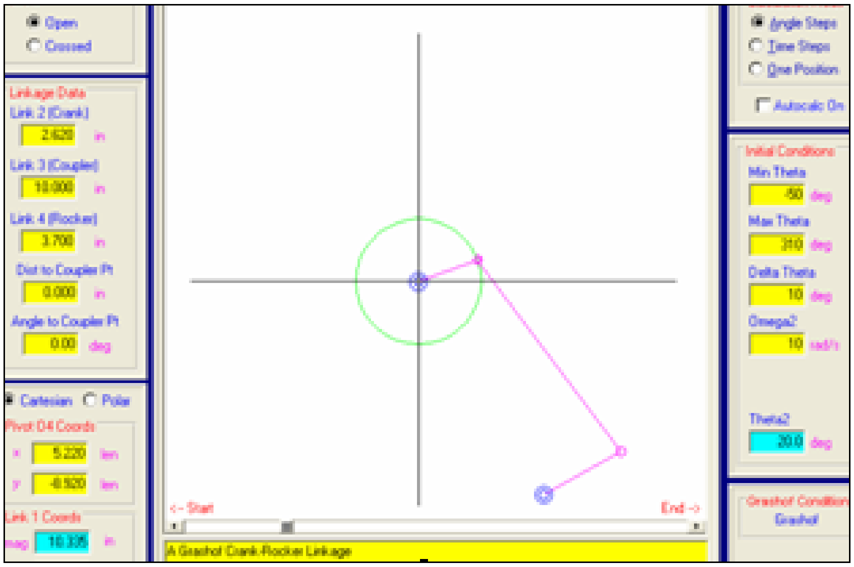


Figure 11: Graphical Linkage Synthesis

We used Program FOURBAR by R.L. Norton to check the validity of our linkages. A screenshot of our linkage in that program is shown.


● Open
○ Crossed

Linkage Data
Link 2 (Crank) 2.620 in
Link 3 (Coupler) 10.000 in
Link 4 (Rocker) 3.700 in
Dist to Coupler Pt 0.000 in
Angle to Coupler Pt 0.00 deg

● Cartesian ○ Polar
Pivot O4 Coords
x 5.220 len
y -8.520 len
Link 1 Coords
mag 10.335 in

● Angle Steps
○ Time Steps
○ One Position
☐ Autocalc On

Initial Conditions
Min Theta -50 deg
Max Theta 310 deg
Delta Theta 10 deg
Omega2 10 rad/s
Theta2 20.0 deg

Grashof Condition
Grashof

A Grashof Crank-Rocker Linkage

Figure 12: Stage 1 Linkage in Program FOURBAR

The link lengths of the crank-rocker are:

L1: 157.63 mm

L2: 47.65 mm

L3: 100 mm

L4: 68 mm

The effective link shape of the rocker is a parallelogram which fits around the sides of the box. We extended the length of the rocker from 38 mm to 68 mm in order to allow for underside support of the box while it is in its flat position. However, the rocker is designed so that when the linkage moves to its 89-degree position, there is no interference underneath the box. The stage 2 mechanism will have ample space to perform its function and there will be a clear path underneath the box so that it can fall down to a conveyor which will transport it to the location of the stages 3 and 4 mechanisms.

Because of the very nature of the parallelogram shape of the link 4 rocker, the links that make up the effective link 4 will spend much of there time overlapping each other. To manipulate the box with minimal interference, we chose to drive the linkage with a parallel linkage situated above. To reduce friction between the driver links, we spaced them out with connecting pins. The rocker, which is effectively link 4, is shown below.

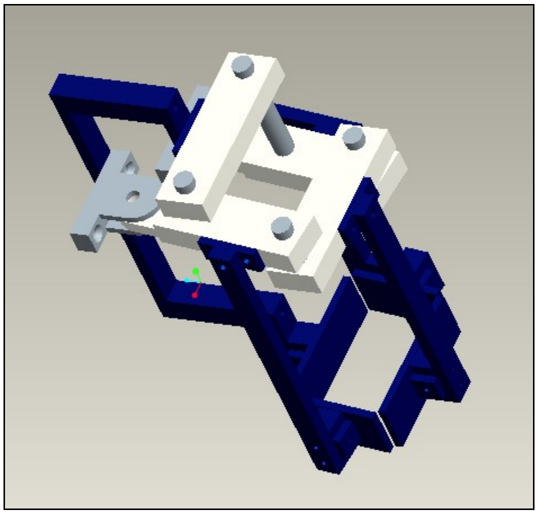


Figure 13: Effective Link 4

The entire stage 1 mechanism is shown below.

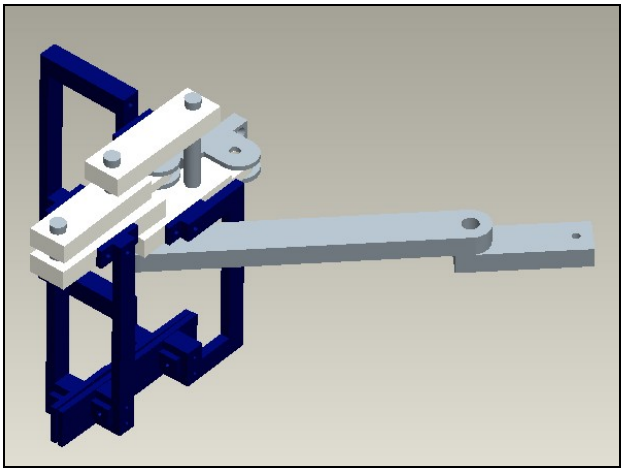


Figure 14: Stage 1 Mechanism

The hinges and the crank, which is the rightmost link as pictured, are attached to a frame that is common to the stages 1 and 2 mechanisms.

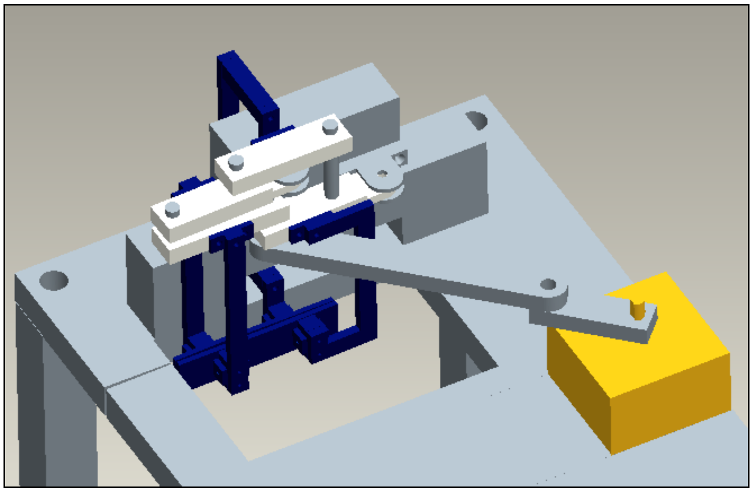


Figure 15: Stage 1 Mechanism on Frame

Several special considerations needed to be taken into account when designing this mechanism.

1) A step motor is the best way to drive this mechanism because the linkage must pause at 0 and 89-degrees exactly so that the stage 2 mechanism can properly fold the bottom of the box.
2) Pins should be used to space out the driver links that compose the effective link 4 in order to minimize friction as the crank revolves.
3) The linkage must be made of a strong, lightweight material to ensure there is no bending because the links are so thin. (Remember, the box is only 55mm x 38mm x 20mm)

4.2 Stage 2 Mechanism

The graphical synthesis for finding the maximum and minimum positions of the sliders of the stage 2 mechanism is shown below (referenced to non-rotating global coordinate system.)

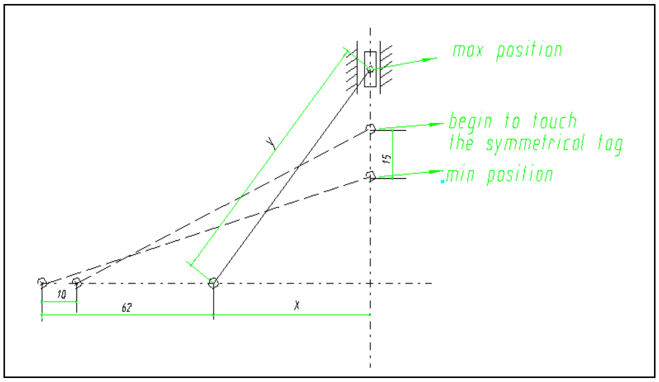
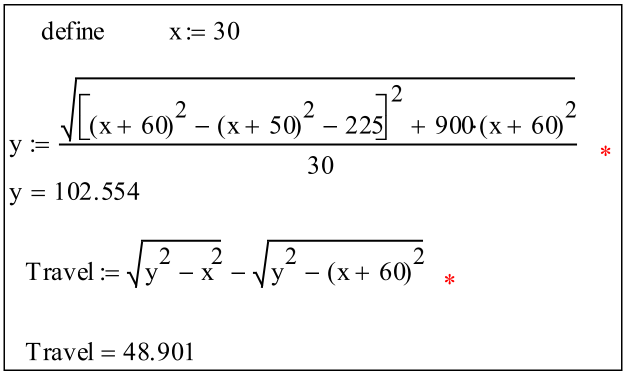


Figure 16: Graphical Linkage Synthesis

The calculations for the lengths of the links leading to the side sliders are shown below, where y is the vertical distance in millimeters of the slider from the horizontal crank.



define $\quad x := 30$

$$y := \frac{\sqrt{\left[(x+60)^2-(x+50)^2-225\right]^2+900\cdot(x+60)^2}}{30} \quad *$$

$y = 102.554$

$$\text{Travel} := \sqrt{y^2-x^2}-\sqrt{y^2-(x+60)^2} \quad *$$

$\text{Travel} = 48.901$

Figure 17: Side Slider Length Calculations

The graphical synthesis and link length calculations gave us final link lengths for the stage 2 mechanism. They are:

Crank: 30 mm

Coupler: 70 mm

Side Slider Links: 48.90 mm

This linkage is not the only solution to this motion problem but it is feasible and easy to implement.

In order to minimize interference underneath the box, the coupler link and side slider links attach to razor guiders which move parallel to the linkage. These razors are well-suited for folding the side and back tabs because they are compact and can easily retract out of the way afterwards, allowing for the box to drop down.

Circular motion is required for folding the fourth tab. This tab must be folded in and then pushed in order to interlock with the other three tabs. The hook is attached perpendicular to the shaft of the motor. The motor-driven hook looks as shown below.

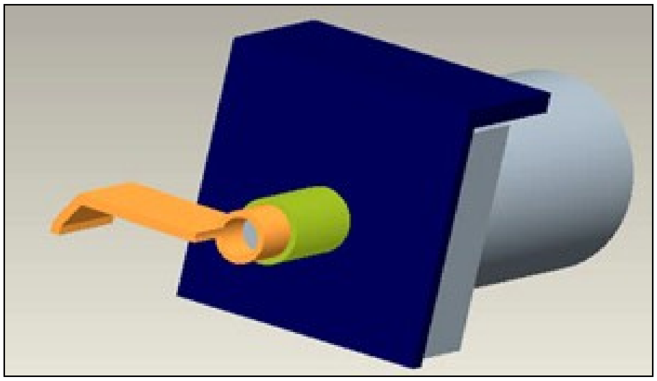


Figure 18: Motor-Driven Hook

The length of the hook was calculated so that it would stay in contact with the last bottom tab as the hook rotates with the shaft. This length was calculated graphically as well. The length of our hook is 27.86 mm. The sketch for the hook length calculation is shown below.

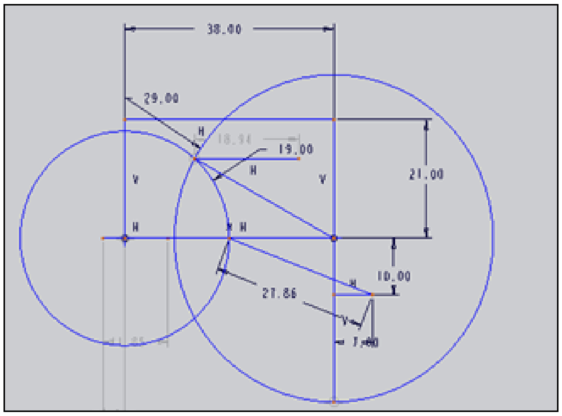


Figure 19: Graphical Synthesis for Motor-Driven Hook

It is important that the coefficient of friction between the sliders of the stage 2 linkage and the bottom frame platform is low. If the frictional forces are too high then the sliders may not move well. Also, the motor that drives the hook must be set up to run in both directions since it will not be making full revolutions.

4.3 Stage 3 Mechanism

The stage 3 mechanism was mostly designed in conjunction with the stage 4 mechanism because of their close proximity. For that reason, the design results for the elevating screws shown below, which also move the stage 4 hook mechanism, will be explained with the stage 4 mechanism. The stage 3 mechanism accomplishes the functions detailed in the design description chapter. The stage 3 mechanism appears as shown below.

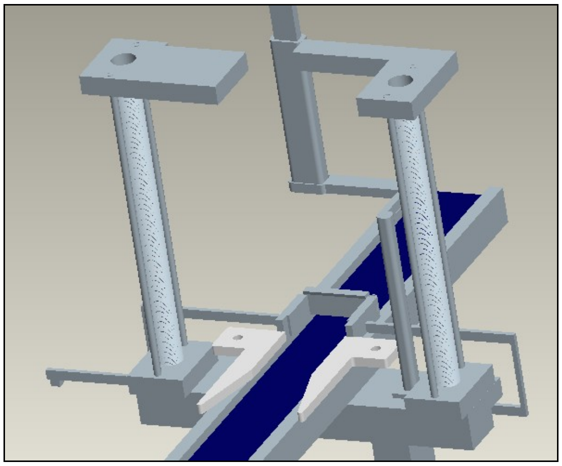


Figure 20: Stage 3 Mechanism

. In our conceptual design (Pro/ENGINEER model), we used a bracket supported by the two vertical screws to raise and lower the stage 3 loading funnel as pictured above.

4.4 Stage 4 Mechanism

To achieve the desired motions for stage 4, we designed a four-bar crank-slider linkage for the symmetrical side tabs and a guided hook mechanism for the top back tab. The crank slider linkage, shown above on the right, is very similar to the one used in the stage 2 mechanism. The link lengths were calculated in a similar fashion. The graphical calculations for the lengths of the links connected to the sliders are shown below.

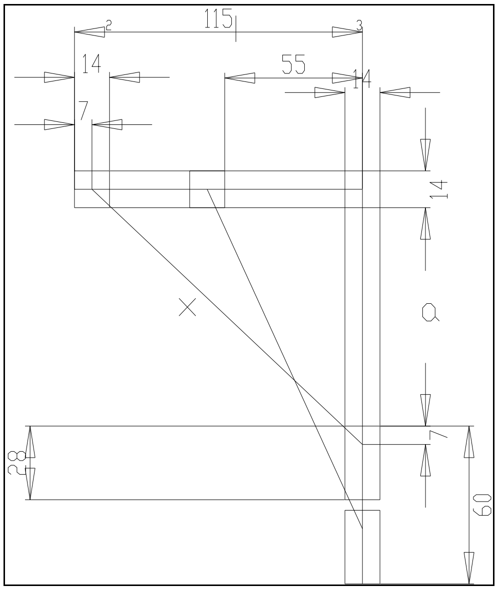
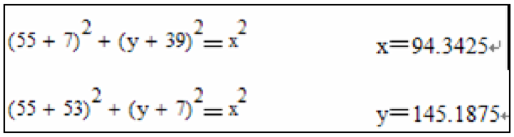


Figure 21: Stage 4 Linkage Synthesis

The sketch above was used to calculate the length of one slider link. The two links are symmetrical and will act identically.



$$(55 + 7)^2 + (y + 39)^2 = x^2 \qquad x = 94.3425$$

$$(55 + 53)^2 + (y + 7)^2 = x^2 \qquad y = 145.1875$$

Figure 22: Slider Link Length Component Calculation

The above calculations were made using the Pythagorean Theorem. The lengths of the links are:

Crank: 28mm

Coupler: 60mm

Slider Links: 2 x 173.15mm

The hook mechanism, shown below, is designed to provide the circular motion. It is driven by a small motor attached to the side of the casing along the axis of one of the holes. The motor raises and lowers the hook. The hook is spring loaded so that when it comes in contact with the inclined plane it will stay in contact with the creased portion of the top back tab.

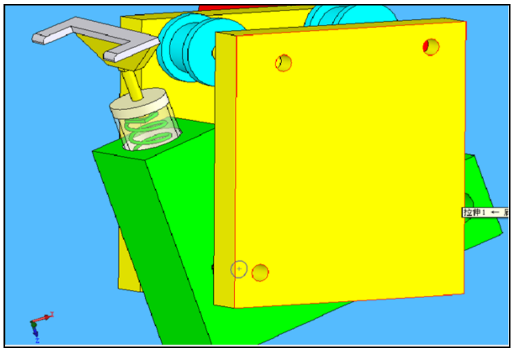


Figure 23: Stage 4 Hook Mechanism

The arc that the hook will follow had to be calculated exactly so that it will guide the creased portion of the top back tab exactly where it needs to go. In order to ensure this, some simple analysis was done. The top tab is 51mm long. The hook must be the height of the top tab and must be offset by a certain distance in order to stay in contact with the tab until it is folded. The point of contact cannot be on the creased portion of the top tab. A sketch showing the arc the hook will follow is pictured below.

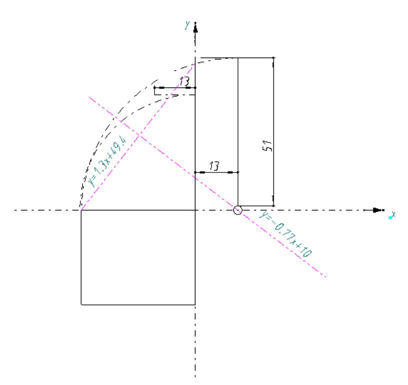


Figure 24: Sketch of Hook Motion

We implemented a shoe-horn type concept into the stage 4 hook mechanism to guide the creased portion of the top tab into its proper position. The guider is actually the front gate of stage 3 mold extended upward. The spring loaded hook will fit inside the inclined plane of the guider. The “shoe-horn guider” is shown below.

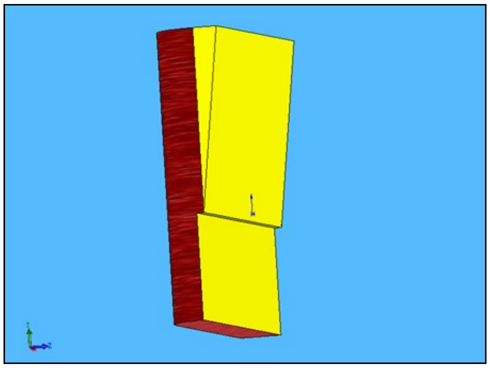


Figure 25: Shoe-Horn Guider

After the hook pushes the creased portion of the top back tab into place, the box is completely loaded and folded. The hook retracts, the hook mechanism moves up and away from the box, and the gate opens so the conveyor can transport the box onward.

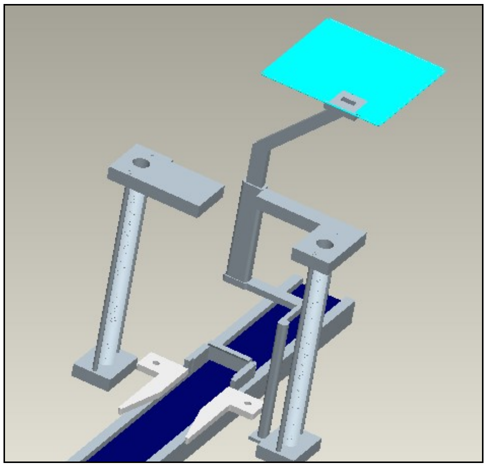


Figure 26: Elevating Screws

A step motor turns the screws and the bracket, which is attached to the screws' threads, moves up and down accordingly. The speed at which the bracket can move depends on the thread size and the speed of the motor. Because our design requires fast and repeatable action, this solution may prove to be too slow. A more conventional mechanism such as a linkage could be designed to achieve the desired effect and may prove to be more suitable for our design.

The vibration of the springs used to settle the paper-clips in the box is achieved by two springs on either side of the stage 3/stage 4 mold as pictured.

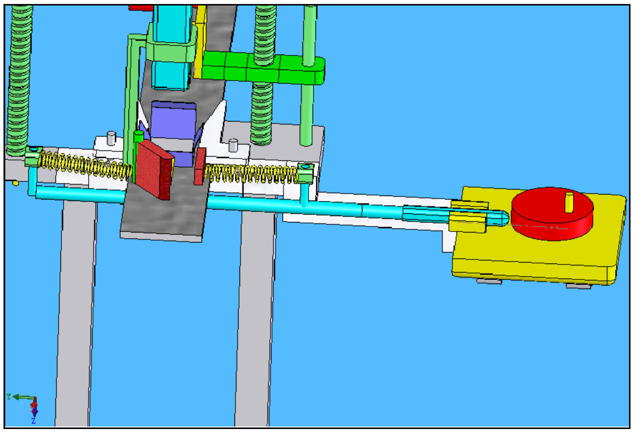


Figure 27: Vibration Springs

As shown above, an offset cylinder driven by a step motor pushes a rod to which the springs are attached. The frequency at which the springs shake the mold depends on the rotational speed of the offset cylinder.

The motion of the front-side door of the stage 3/stage 4 mold is easily achieved with a linkage very similar to the one used in the stage 1 mechanism. 90-degree rocker motion is required, so the same linkage could actually be used but must be scaled appropriately.

4.5 Combining the Stages – The Complete Machine

Once the mechanisms were designed, the task of combining them remained. We designed a common frame for the stages 1 and 2 mechanisms as well as for the stages 3 and 4 mechanisms. While the shape of the frame will almost definitely change as the machine is further developed, the locations which come in contact with the mechanisms are precisely measured. The entire machine is shown below.

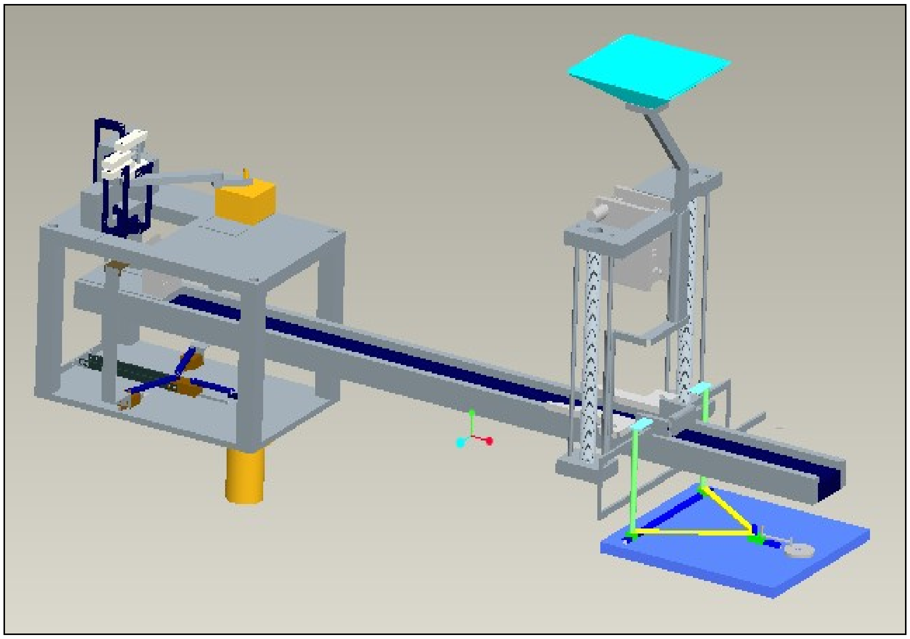


Figure 28: Entire Machine

Chapter 5 - Conclusions

Though our team initially set out to design and manufacture a prototype of the automated packaging machine, we quickly found that the time we had in Wuhan would not be sufficient. However, we are very pleased with the results of our work. We now have a solid conceptual design of the automated packaging machine and have built a strong foundation for further development of this project. While time did not permit the thorough analysis necessary to properly select materials and build the prototype, we achieved results in the form of an animated CAD model of the entire machine. We studied our process and pinpointed several of the most likely modes of failure in our machine as well.

The single most likely mode of failure for all stages of our machine depends on material selection. Material selection will be the paramount concern for anyone who chooses to develop this project further. Because of the multitude of small parts working in a common space, any bending or fracture during the machine's operation could cause part interference or even failure. A strong, lightweight material should be selected.

Modes of failure specific to the individual mechanisms include:

1) In the stage 1 mechanism, the box may fall out of the linkage unless the coefficient of friction between the linkage and the box is high enough or another mechanism serves to stabilize the box.
2) The slider-crank mechanisms and the hooks in the stages 2 and 4 mechanisms must be coordinated properly for the mechanism to work correctly. This will require accurate synchronization of the step-motors used in the mechanism.

To determine if our design is good, we will compare the efficiency of our design and the preexisting packaging/loading method. The efficiency is comprised of cost, speed, reliability, and size. Unfortunately, we do not have any cost data to compare or size nor do we have any idea of the current dimensions of the working area to compare sizes. Currently our machine can't match the speed of the 12 women packaging them manually and it is inherently more unreliable because machines need outside help to know if they make mistakes. Unless our machine is repeatable, it will either suffer in reliability or the customer will have to pay someone to watch it. This should not be discouraging because we feel this process is perfect for automation because of its series of repeated actions and motions.

With additional time, a completed design ready for prototyping would be a very realistic possibility. With only five and half weeks to design a machine from scratch, we felt this time constraint hampered our ability to run a thorough stress analysis for each component of our machine and prevented us from making an informed decision on material selection. With continued work on our design to increase the speed, thorough analysis of the stresses each component experiences, and determination of the modes of failure of our machine, we could revolutionize the loading/packaging industry. Our machine's small size and its ability to complete packaging operations of this complexity without the assistance of a human are unprecedented in the commercial world.

Chapter 6 – Acknowledgements

First and foremost we would like to thank Prof. Rong for giving us this great opportunity to visit a foreign country, immerse ourselves in an exotic culture, and work on a professional style project. As our advisor he was there to help us focus our work, answer any questions we had, and arrange travel accommodations. Next, we would like to thank Professors Wu, Yuan, and Liu, our advisors at Huazhong University of Science & Technology. They offered us valuable insight and clearly laid out the goals of our project. In addition to offering help regarding the project, they also made sure our stay in Wuhan was as trouble free as possible and arranged weekend trips for us to explore the surrounding areas. Last, we would like to thank our project partners at HUST, Wen Liu, Yang Jin, and Yan Xuekai. Without their innovative ideas and problem solving techniques we would never have completed our work. Not only were they good, hardworking project partners, but also great friends. They would take us around Wuhan, help us communicate with the local populace, and really allowed us to see how college students live on the other side of the world.

It is nearly impossible to individually thank everyone involved with the project or our stay in China. To those we did not formally thank, including all HUST students, HUST faculty, and WPI Faculty, who aided in the successful completion of this project, we would like to extend our sincerest appreciation to you.

Chapter 7 – References

1. Norton, Robert L., Design of Machinery, McGraw Hill, 3rd Edition, 2005
2. http://www.kluge.biz/smallboxmachine.htm
3. http://www.newenglandbelting.com/ConveyorApplications.asp