University of Pittsburgh
Swanson School of Engineering

Mechanical Design II
Professor Stephen Ludwick

Design Project #5

Rube Goldberg "Beverage Pouring" Mechanism

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1. Project Definition

The goal of this project is to design a "Rube Goldberg" type mechanism with the final goal of pouring a "summer beverage". As per the typical Rube Goldberg design, the mechanism will contain several steps in a chain reaction. The design should be based on sound engineering principles and therefore should work if it were to be manufactured. The only constraints are that the design must contain at least one compound gear train and one spring element.

2. Functional Requirements

1. Successfully pour a beverage.
2. Contain at least one compound gear train
3. Contain at least one spring element
4. All elements must be purchasable or obtainable in some other way (i.e. the mechanism could be manufactured)

3. Simplified Sketch

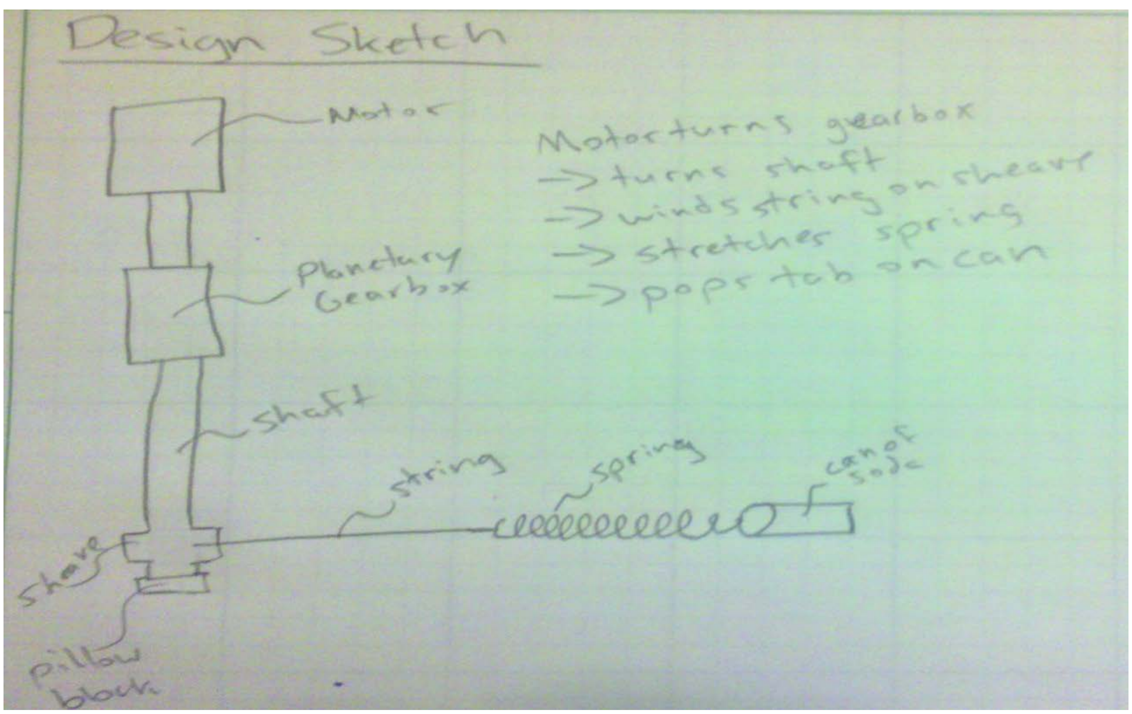


Figure 1. Simplified sketch of what the final design will look like provided all calculations work out.

4. Parts Specification

Based on my initial design of this mechanism it will be necessary to buy several parts. First, and the most important, will be the gears. These will determine the specifications necessary for the other parts. The chosen gear is a planetary gear box with a gear ratio of 58:1. This will significantly reduce the speed of the motor and increase the torque. The motor chosen was a NEMA 17 motor with output rpm of 3000 and output torque of 5.06in-lb. Next a tension spring was selected which is strong enough to withstand the force from the gearbox as well as the force to pop a tab on a can. Also, it was necessary to buy a sheave to wrap up a string which will be attached to the spring. A pillow block is necessary at the opposite end of the shaft coming out of the planetary gearbox. Finally, a custom made holder for the can of soda was designed. All that is left is to select your favorite canned beverage.

5. Design Specifications

In order for this design to be successful several tolerances must match up. First, the max rpm accepted by the planetary gearbox must be greater than the max output rpm of the motor. Second, the torque output of the motor must be less than the max torque input into the gearbox. Third, the torque outputted by the gearbox must be sufficient to pop the tab on a can. Fourth, the spring must be able to withstand the forces from the pop tab as well as from the sheave which winds the string attached to one end of the spring. Here is a picture of the design to make the design specifications easier to understand.

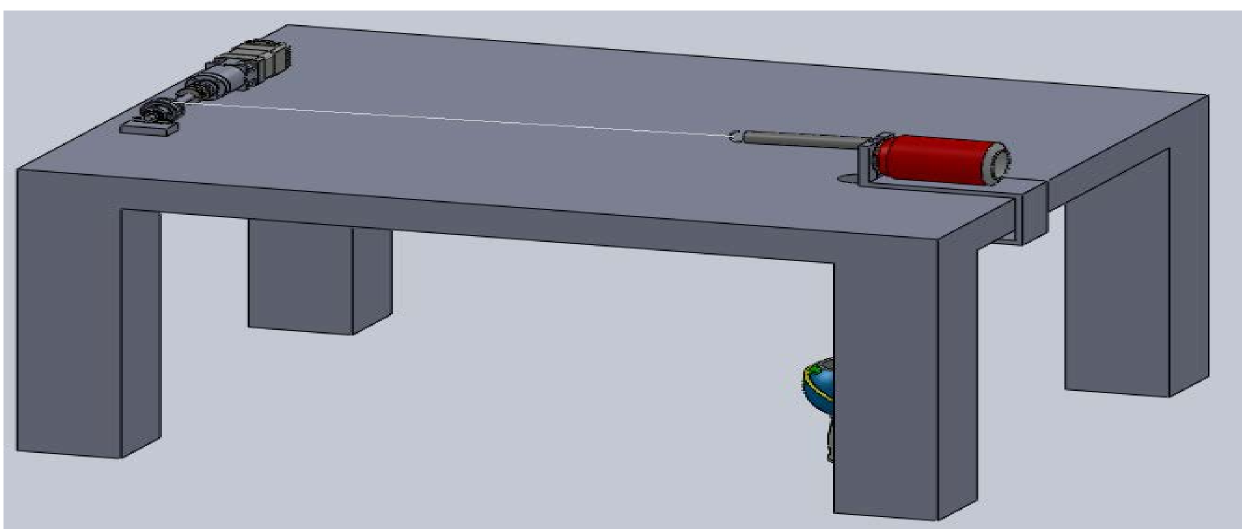
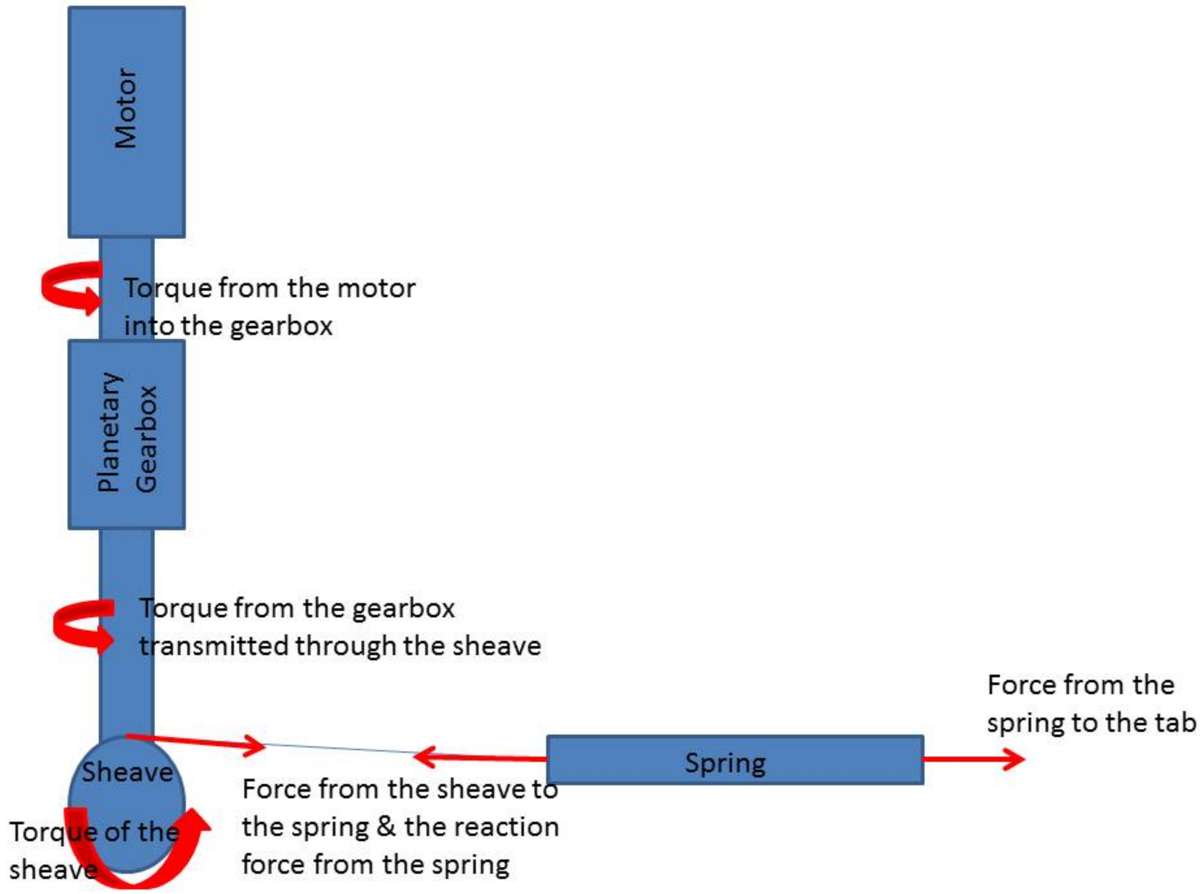


Figure 2. Complete assembly of the mechanism

6. Calculations

FBD



Assume the force needed to pop a tab is 10lbf = 44.5N

NEMA 17 Motor Specs:

max RPM = 3000

Torque = 5.06in-lb = 0.5717 N-m

First, we will calculate the power coming out of the NEMA 17 motor.

$$P = \mathrm{T} * \omega = (0.5717 N \cdot m) * \left(3000 \frac{rev}{min}\right) * \left(2\pi \frac{rad}{rev}\right) * \left(\frac{1}{60} \frac{min}{sec}\right) = 179.6\, W$$

IMS Planetary Gearbox Specs:

Gear Ratio: 58:1

Max rpm in: 3000

Constant Torque Out = 7.5N-m

Efficiency = 75%

N_{sun}=15, N_{planet}=20, N_{ring}=55

Now, we can calculate the power and torque coming out of the gearbox knowing that the power into it equals 179.6W and the efficiency of the gearbox is 75%.

$$P_{out} = 0.75 * \ P_{in} = 0.75 * 179.6 = 134.7W$$

$$\omega_{out} = \frac{\omega_{in}}{58} = 51.7rpm$$

$$\text{T}_{out} = \frac{P_{out}}{\omega_{out}} = \frac{134.7W}{\left(51.7\frac{rev}{min}\right) * \left(2\pi\frac{rad}{rev}\right) * \left(\frac{1}{60}\frac{min}{sec}\right)} = 24.7N \cdot m$$

But the manufacturer, IMS specifies a constant output torque of 7.5 $N \cdot m$ so we will use that value.

Now we can determine the maximum force acquired from the gearbox through a sheave with a pitch radius of 15mm.

$$For\ a\ pulley: \text{T} = F * r$$
$$\Rightarrow F = \frac{\text{T}}{r} = \frac{7.5N \cdot m}{0.015m} = 500N = 112.4lbf\ This\ is\ more\ than\ enough\ to\ crack\ the\ tab$$

Now we can begin calculations on the spring:

Spring Specs:

L_0=150mm

k=0.33N/mm

F_i=9.81N

d=1.8mm

$$y_{max} = \frac{F_{max} - F_i}{k} = \frac{44.5N - 9.81N}{\frac{0.33N}{mm}} = 105mm$$

$$L = L_0 + y_{max} = 150mm + 105mm = 255mm$$

Now we can check for failure of the spring.

We have Spring Steel (ASTM A228):

From Table 10-4: m=0.145, A=2211 MPa-mm^m

$$S_{ut} = \frac{A}{d^m} = \frac{2211MPa - mm^m}{1.8^{0.145}} = 2030.37MPa\ (Eq. 10 - 14)$$

$$S_{sy} = 0.45 * S_{ut} = 0.45 * 2030.37 = 913.67MPa\ (Table\ 10 - 7)$$

$$D = OD - d = 18mm - 1.8mm = 16.2mm$$

$$C = \frac{D}{d} = \frac{18}{1.8} = 10$$

$$K_B = \frac{4C + 2}{4C - 3} = 1.14$$

Shear stress under service load:

$$\mathrm{T}_{max} = \frac{8 * K_B * F_{max} * D}{\pi * d^3} = \frac{8 * 1.14 * 44.5 * 16.2}{\pi * 1.8^3} = 398.7MPa$$

$$\Rightarrow \eta_s = \frac{S_{sy}}{\mathrm{T}_{max}} = \frac{913.67}{398.7} = 2.3$$

For gear analysis we will use the Lewis Bending Equation.

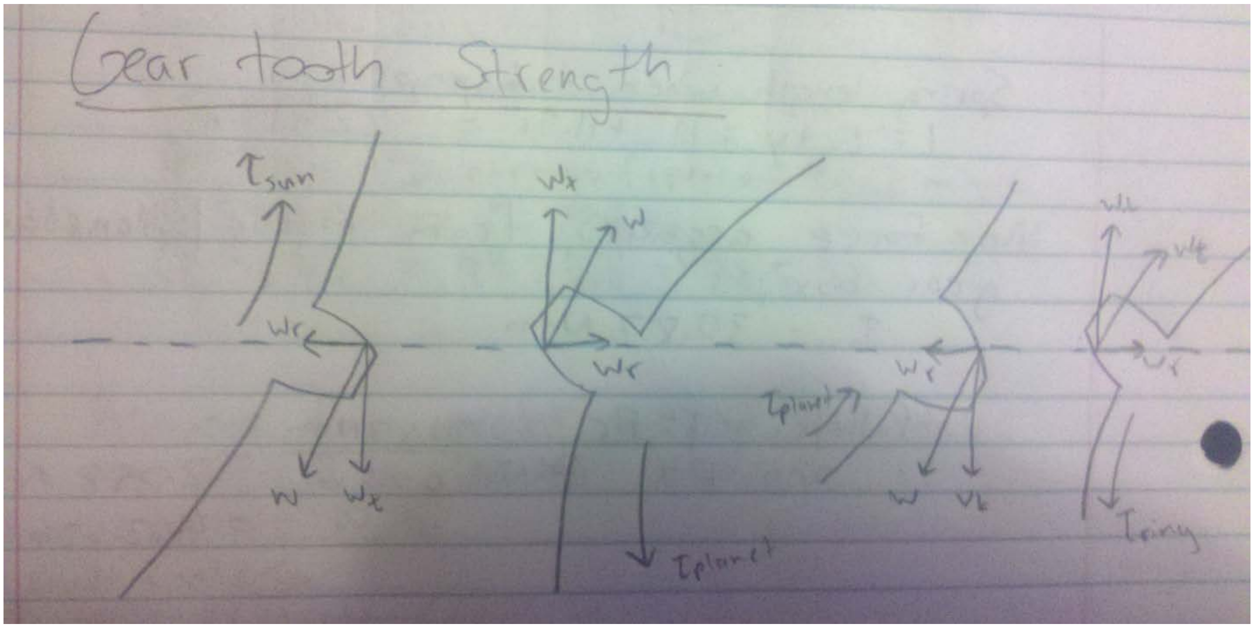


Figure 3. FBD of the gears in the planetary gearbox

First we will do the sun gear:

Gears are grade 1 through hardened steel with allowable bending stress of 45kpsi=$3.1x10^8$ Pa

$$W_{t,allow} = \frac{m * F * Y * \sigma_{all}}{K_v}$$

$$m = \frac{d}{N} = \frac{10mm}{15\ teeth} = 0.67mm$$

$$V = \pi * d * n = \pi * 0.01m * 3000 \frac{rev}{min} * \frac{1}{60} \frac{min}{sec} = 1.57 \frac{m}{sec}$$

$$\Rightarrow K_v = \frac{6.1 + V}{6.1} = \frac{6.1 + 1.57}{6.1} = 1.26$$

$$F = 10.3mm = .0103m$$

$$Y = 0.290\ (Table\ 14 - 2)$$

$$W_{t,allow} = \frac{0.00067m * 0.0103m * 0.290 * 3.1x10^8 Pa}{1.26} = 492.1N$$

$$W_t = \frac{T}{r} = \frac{2T}{d} = \frac{2 * 0.5717N \cdot m}{.010m} = 114.3N$$

$Since\ W_t < W_{t,allow}\ this\ gear\ will\ not\ fail\ due\ to\ bending\ stress.$

Now for the planet gears:

$$W_{t,allow} = \frac{m * F * Y * \sigma_{all}}{K_v}$$

$$m = \frac{d}{N} = \frac{16mm}{20teeth} = 0.8mm$$

$$V = \pi * d * n = \pi * 0.016m * 3000\frac{rev}{min} * \frac{1}{60}\frac{min}{sec} = 2.5\frac{m}{sec}$$

$$\Rightarrow K_v = \frac{6.1 + V}{6.1} = \frac{6.1 + 2.5}{6.1} = 1.41$$

$$F = 10.3mm = .0103m$$

$$Y = 0.322\ (Table\ 14 - 2)$$

$$W_{t,allow} = \frac{0.0008m * 0.0103m * 0.322 * 3.1x10^8 Pa}{1.41} = 329N$$

$$W_t = \frac{T}{r} = \frac{2T}{d} = \frac{2 * 0.5717N \cdot m}{.016m} = 71.5N$$

$Since\ W_t < W_{t,allow}\ this\ gear\ will\ not\ fail\ due\ to\ bending\ stress.$

Now for the ring gear:

$$W_{t,allow} = \frac{m * F * Y * \sigma_{all}}{K_v}$$

$$m = \frac{d}{N} = \frac{42mm}{55\ teeth} = 0.76mm$$

$$V = \pi * d * n = \pi * 0.01m * 0\frac{rev}{min} * \frac{1}{60}\frac{min}{sec} = 0\frac{m}{sec}$$

$$\Rightarrow K_v = \frac{6.1 + V}{6.1} = \frac{6.1 + 1.57}{6.1} = 1$$

$$F = 10.3mm = .0103m$$

$$Y = 0.415\ (Table\ 14 - 2)$$

$$W_{t,allow} = \frac{0.00076m * 0.0103m * 0.415 * 3.1x10^8 Pa}{1} = 887.8N$$

$$W_t = \frac{T}{r} = \frac{2T}{d} = \frac{2 * 0.5717N \cdot m}{.042m} = 27.2N$$

$Since\ W_t < W_{t,allow}\ this\ gear\ will\ not\ fail\ due\ to\ bending\ stress.$

7. CAD

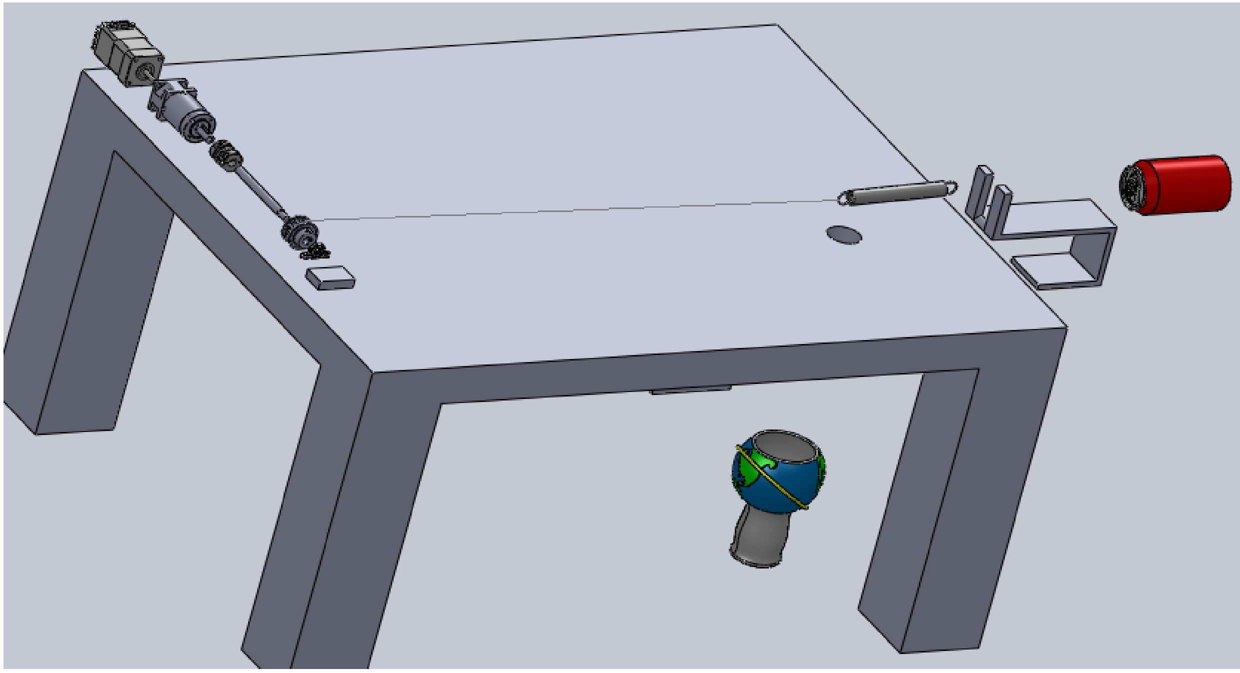


Figure 4. Exploded view of the mechanism

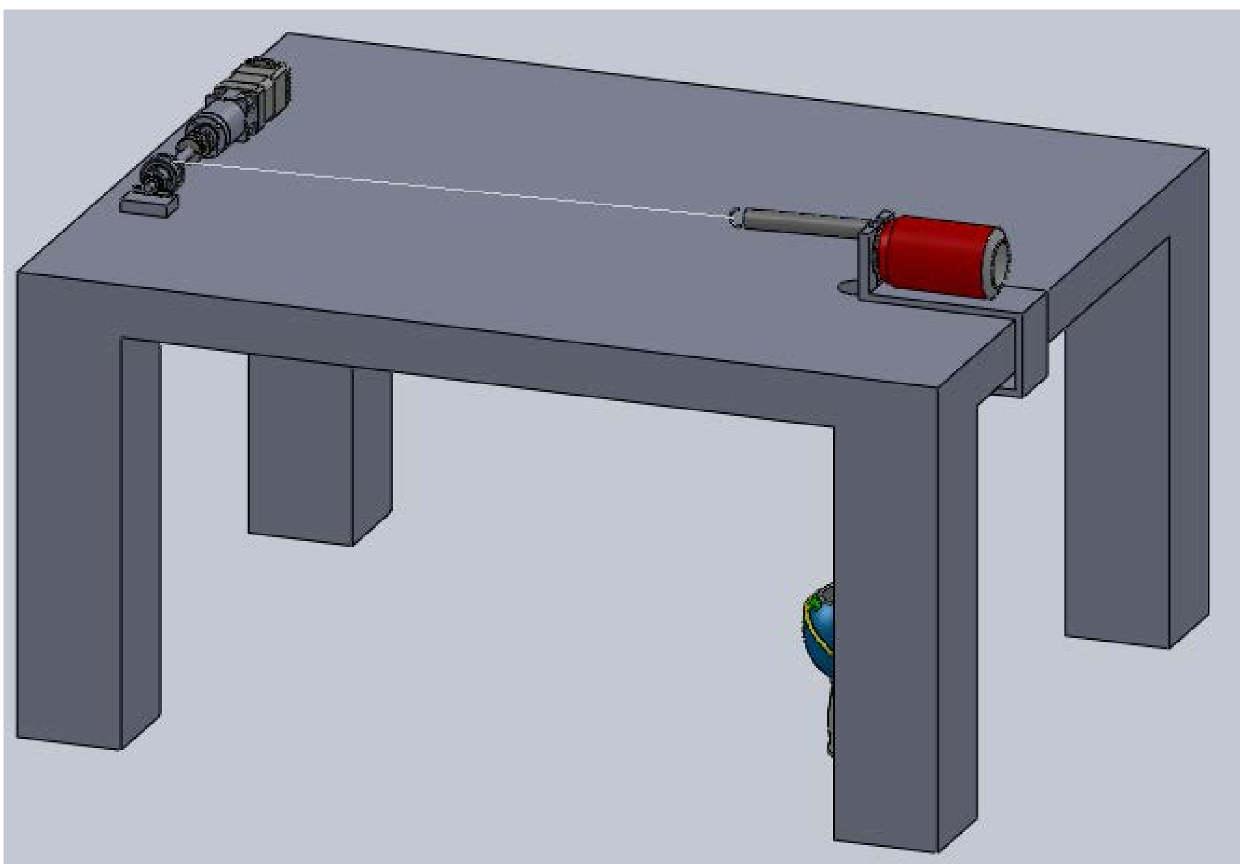


Figure 5. Complete CAD of the mechanism

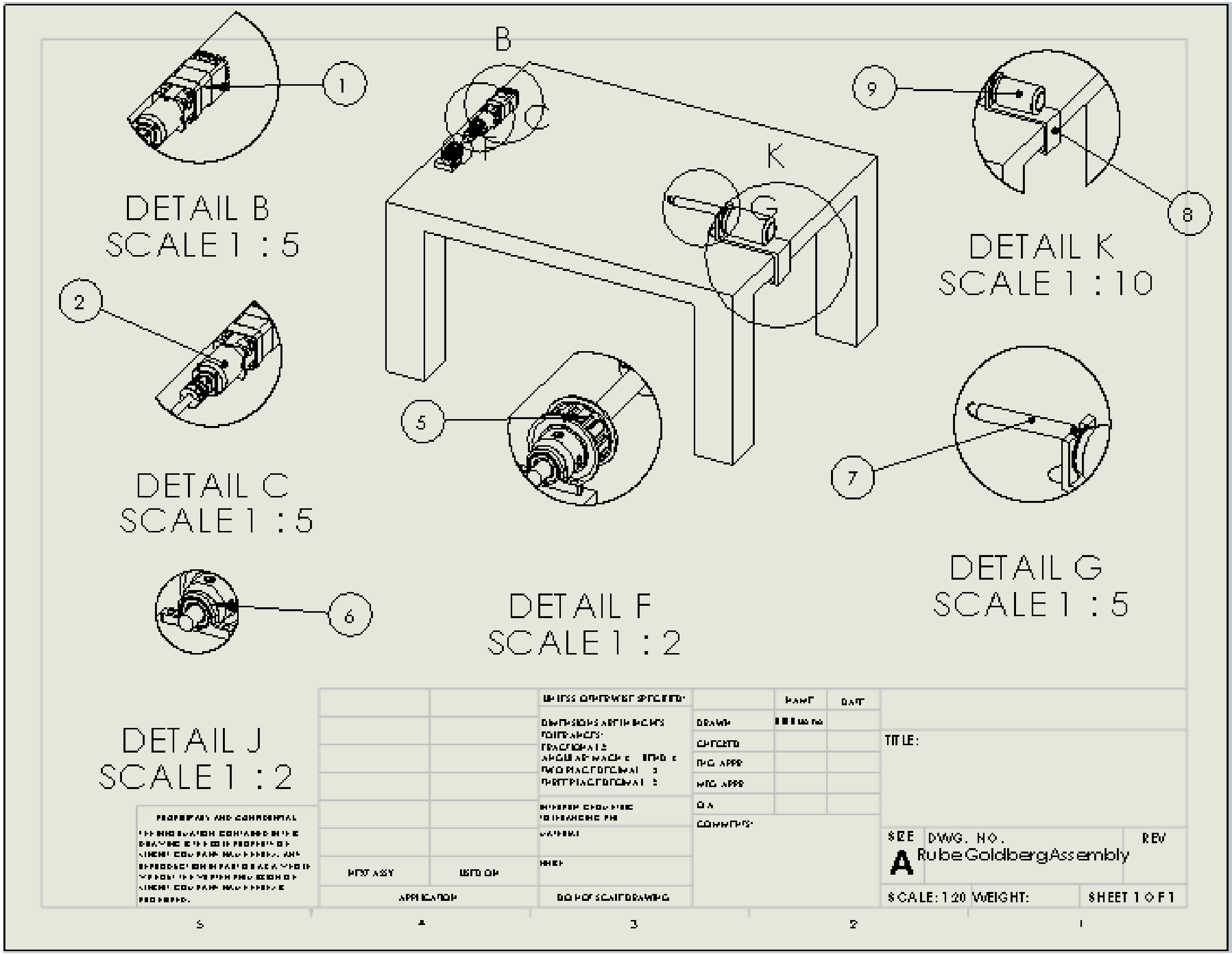


Figure 6. Drawing of the CAD assembly with detailed views of all the components

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6627T3	NEMA 17 Motor	1
2	Planetary Gear Box	58:1 Ratio	1
3	Coupling	Slit style, clamping	1
4	Shaft	10mm Diameter Steel	1
5	Pulleys	30mm Pitch Diameter	1
6	8600N13	8mm Bore Pillow Block	1
7	Spring	Extension Spring	1
8	Can Holder	Custom Part	1
9	Can	12oz beverage of your choice	1
10	Table	Any old table around	1
11	UFO cup	Canned beverage receptacle	1

Figure 6. BOM according to the assembly drawing seen in Figure 7

8. BOM

Vendor	Part #	Description	Cost Per 1	Quantity	Total Cost
McMaster-CARR	9640K14	Steel Extension Spring	$4.88	1	$4.88
McMaster-CARR	6627T3	NEMA 17 Frame Motors with Integrated Driver and Motion Controller	$454.55	1	$454.55
IMS Gear	PM 42 LN	58:1 Planetary Gearbox	$384.20	1	$384.20
TackleWarehouse.com		25lb test fishing line	$8.49	1	$8.49
sdp-si.com	A 6A 4M10DF12510	30mm pitch diameter pulley	$11.62	1	$11.62
McMaster-CARR	8600N13	8mm bore pillow block	$14.28	1	$14.28
Anywhere	N/A	Beverage Can	$0.75	1	$0.75
Anywhere	N/A	Cup	$0.25	1	$0.25
OnlineMetals.com		Mild Steel 1018 ; Cold Finish Round; 0.5" diameter; Cut to 12"	$2.34	1	$2.34
				Total Cost	$881.36

9. Conclusion

In conclusion, this Rube Goldberg was successfully design to withstand any forces it may see as well as theoretically be successful. The design was not actually built so I am unable to determine for sure if it will work. Otherwise, given the calculations seen earlier and the specifications of the components/the solid model of the mechanism it would be a safe assumption that this Rube Goldberg mechanism would be successful.

Works Cited

[1] "IMS:Gear." IMS Gear. 13 July 2011. http://www.imsgear.com/

[2] "McMaster-Carr." McMaster-Carr. 20 Jan 2011. 5 June 2011. http://www.mcmaster.com/

[3] *MISUMI, the Catalog Company of Machine Components ECatalog*. Web. 15 July 2011. <http://us.misumi-ec.com/>.

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[5] *Precision Mechanical Components Timing Belts Pulleys Spur Gears Couplings Bearings Sprockets Retaining Rings Brakes Helical Gears Clutches Universal Joints*. Web. 15 July 2011. <http://sdp-si.com>.

[6] Shigley, Joseph Edward., Charles R. Mischke, and Richard G. Budynas. *Mechanical Engineering Design*. New York, NY: McGraw-Hill, 2004. Print.

[7] *Tackle Warehouse - Bass Fishing Shop for Fishing Rods, Reels, Swimbaits and Lures*. Web. 15 July 2011. <http://www.tacklewarehouse.com/>.