University of Illinois at Urbana-Champaign

ME270 Design for Manufacturability

ME 270
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Kartik Bokka, TA

Team Project Final Report

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1 Introduction

1.1 Product Description

The WatchDog is an interactive novelty alarm clock that deters the user from overusing the snooze button. After the alarm has been snoozed once, the WatchDog is programmed to begin barking and running at the end of the snooze cycle to ensure the user must get out of bed to turn off the alarm. The WatchDog is a complex electro-mechanical system in which an Arduino controls both the alarm clock functionality and the rotation of two small servo motors. These servos were attached to eight-bar linkages (Jansen mechanisms) that were created using laser cut acrylic and held together with dowel pins and retaining rings. These linkages allow the WatchDog to move with fluid, canine-like motion thus adding to the aesthetic value of the design. The Arduino circuit and servos are housed within a segmented, 3D-printed torso that is held together with snap fits. The two endcaps of the torso are attached to a dog-like head and tail to add to the friendliness of the design.

1.2 Product Interest and Need

Research done in 2014 by the health innovation company Withings shows that about 70% of American hit the snooze button in the morning with 57% admitting to hitting it more than once. Evidently, oversleeping is a problem for even those who use traditional alarm clocks. As the WatchDog is not a traditional alarm clock, but rather a novel one which coerces the user to get out of bed to turn off the alarm after the first snooze cycle, it ensures that users are awake and moving instead of rolling over for more sleep. While most alarm clocks are drab boxes which wake disoriented users to a cacophony of harsh tones, the WatchDog brightens the morning of anyone who uses it with its playful design and whimsical barking alarm. Other alarm clocks that use more coercive techniques to get users out of bed include the Northwest Flying Alarm Clock and Clocky, the Runaway Alarm Clock. The Northwest Flying Alarm Clock launches a small plastic propeller from its base when the alarm goes off, and this propeller must be retrieved and reconnected to the base to shut off the alarm. However, it is possible to lose the flimsy propeller and the flexible plastic is prone to breaking during impact with objects in the room, which would prevent the user from turning off the alarm. Clocky, like the WatchDog, begins moving away from the user when the alarm goes off. Unlike the WatchDog, however, Clocky is rather clunky and uninspiring, opening it to the possibility of being kicked or thrown by disgruntled users. The friendly design of the Watchdog makes it more enjoyable to wake up to, thus preventing such cruelty.

2 Methods

2.1 Prototype Fabrication

The prototype for the WatchDog (see Figure 1) was built using a combination of purchased parts from McMaster Carr, RobotShop, and the ECE shop, as well as parts printed using the LulzBot Mini 3D-printer and acrylic parts custom printed with a laser cutter. A simplified bill of materials can be seen in Table 1 below, showing the source of each group of parts. This report will examine closely the methods used to design and fabricate the body and linkage system of the WatchDog.

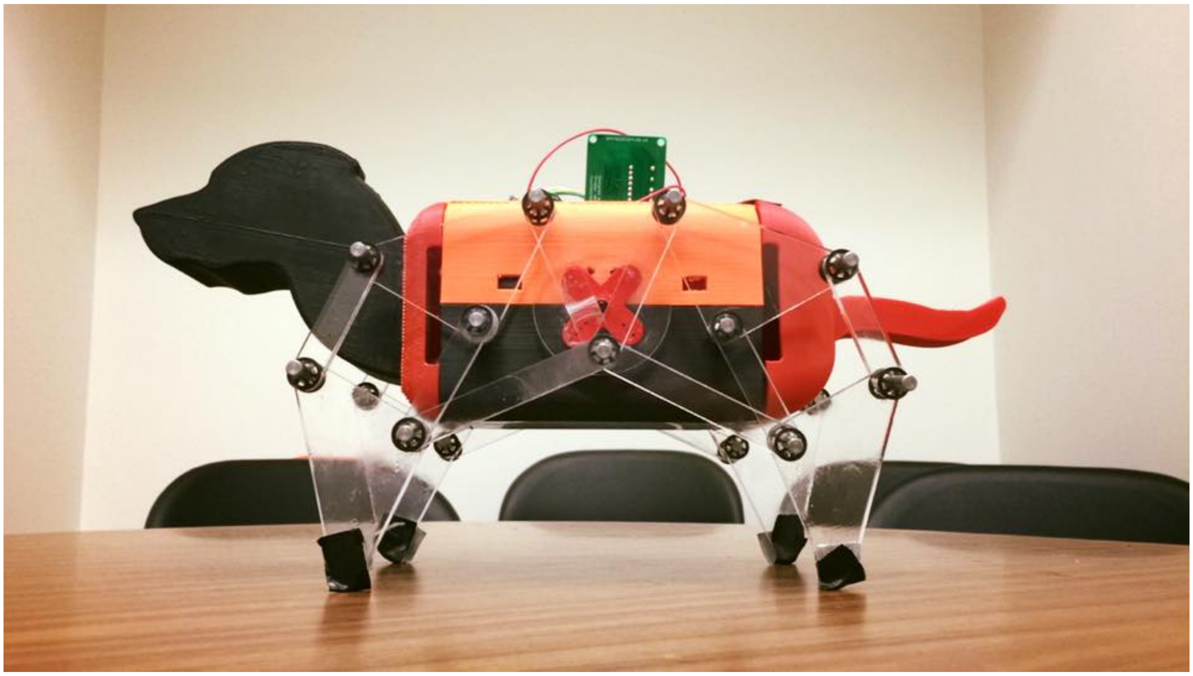


Figure 1: The WatchDog prototype

Table 1: Simplified Bill of Materials

Quantity	**Part(s) Description**	**Source/material**
1	Body, head, and tail	3D Printed HIPS
1	Circuitry/Arduino	ECE shop
2	Servo Motor	RobotShop
2	Linkages	Laser cut 0.25” acrylic
22	3/8" Low-Strength Dowel Pins	McMaster Carr
44	3/8" Self-Locking External Retaining Rings	McMaster Carr

2.1.1 Body Fabrication

The purpose of the body on the WatchDog is to house the electronics and to mount the linkage system. It comes in two parts, top and bottom, which snap together using snap locks. The body was designed using Creo Parametric 3.0 before being 3D printed. This design was iterated upon once, as can be seen in Figure 2 below.

The first body prototype was constructed as a proof of concept for the cantilevered snap lock design which was utilized. The snap locks were designed to lock in place when the two body halves are forced together. They were also designed to come apart with a small amount of force allowing easy access to the electronic parts. Issues that were not foreseen in the first body prototype was that the mating edges which are brought together by the snap locks did not align well. In order to fix this, extra tabs were added to the top half of the body which aligned to the mating bottom half of the body. This not only properly aligned the mating edges, but also improved the strength of the snap lock fit. The CAD model of this design iteration can be seen in Figure 3 below.

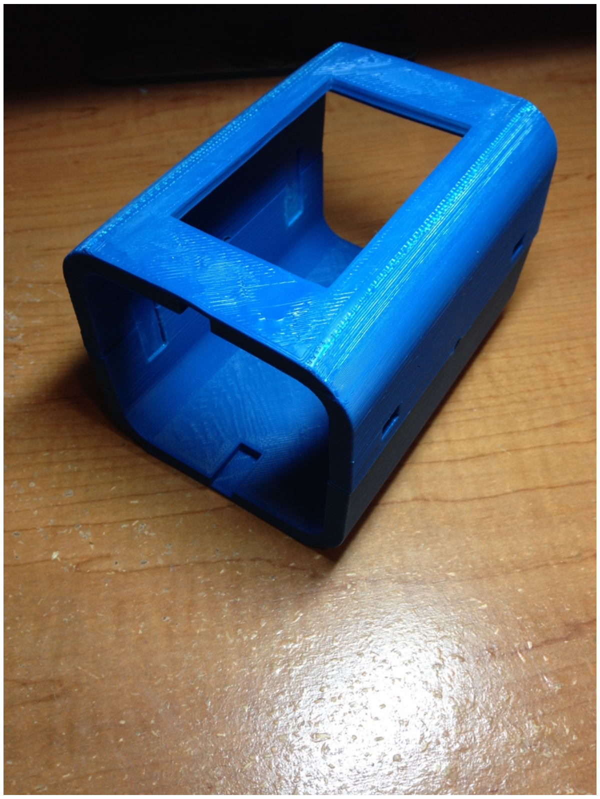
2.1.2 Linkage Fabrication

The linkage system used in the WatchDog is a modified Jansen linkage which is driven by two continuous-motion servos, one on each side. The lengths and tolerances for each link were calculated using Jansen linkage ratios and adjusted for the scale of the WatchDog. The links were laser cut from a 12x24" sheet of 0.25" acrylic, and fastened together using the dowel pins and retaining rings purchased from McMaster Carr.

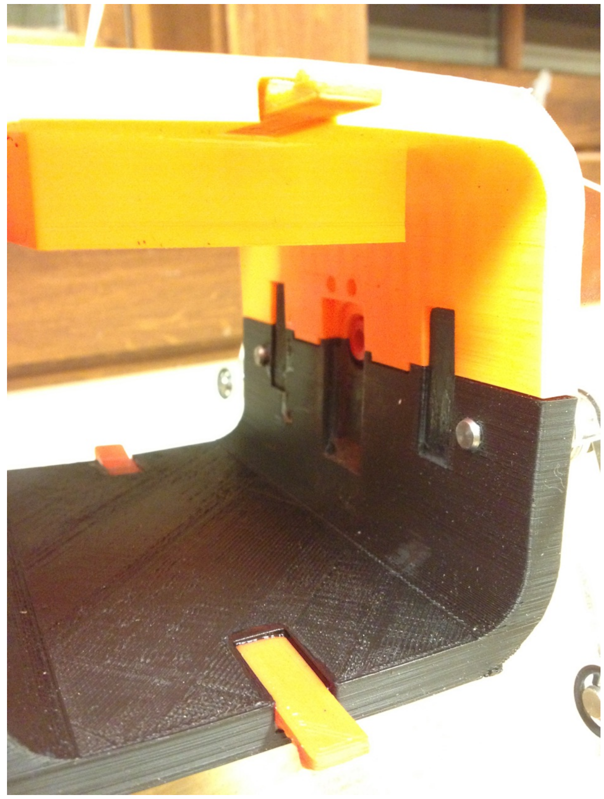
The largest issue that arose when constructing and testing the linkage system was that the torque of the motor was limiting, particularly as we had to switch out our original (unintentionally) non-continuous-motion servos with continuous-motion ones with lower torque than we initially anticipated. In order to ensure no loss of driving torque from the servo motors, the linkage system was well lubricated with WD-40 to reduce the amount of friction between acrylic links. This successfully ensured that the linkage system would rotate and provide the WatchDog with an adequate walking motion which is a major design particular for this project. For the manufactured product, higher-torque servos that were programmed to resist motion when not activated would improve the motion capabilities. Another improvement that could improve the motion is the addition of *feet* linkages on the bottom so there is more surface area in contact with the ground and therefore better stability.

2.2 DOE Methodology

To create a product that could really end up a significant distance from the user in the time it takes for them to get up and turn it off, it was desirable for us to program for the fastest achievable servo speeds. In order to determine the settings for fastest servo speed in rpm, we performed 2^3 factorial experimentation on the prototype for the input variables of joint lubrication, servo angle offset, and servo time offset. Lubrication was affected by the quantity of WD-40 we used on the joints, which would presumably help to reduce torque load, but might have some unexpected effects beyond a certain point. Servo angle offset and time offset are Arduino programming considerations, with angle offset being the displacement that the Arduino attempts to impose on the continuous-motion servo in a single program loop, and time offset (or delay) the amount of time that the Arduino inserts as *padding* between loops. Because angle offset has a complex interplay with the velocity dynamics of the servo, and time offset with the computation time of loops in the Arduino, the effects



(a) First Body Prototype



(b) Final Body Prototype

Figure 2: Prototype Iteration

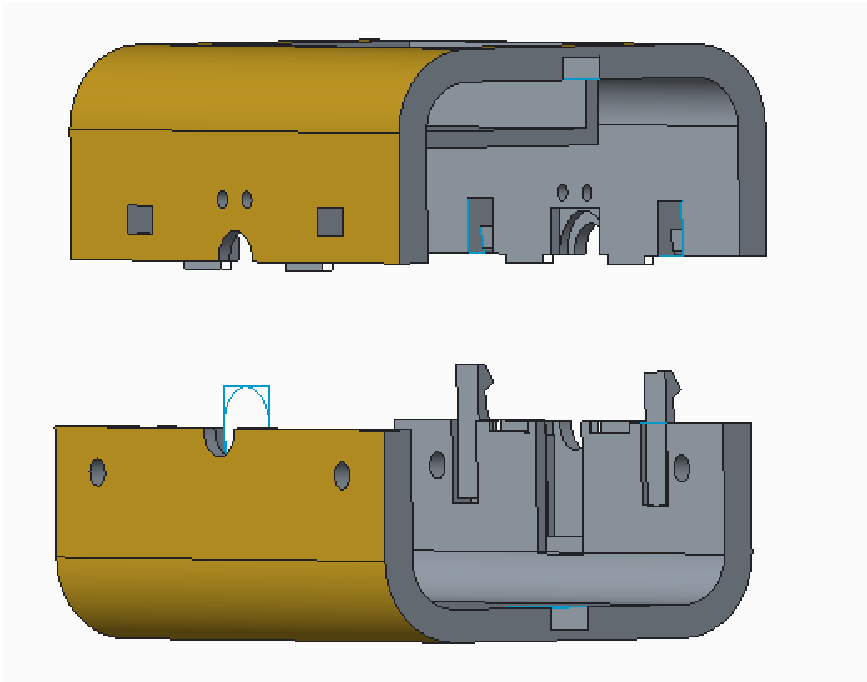
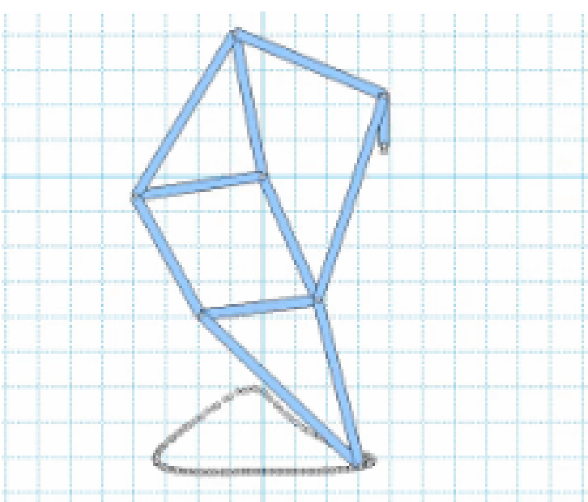
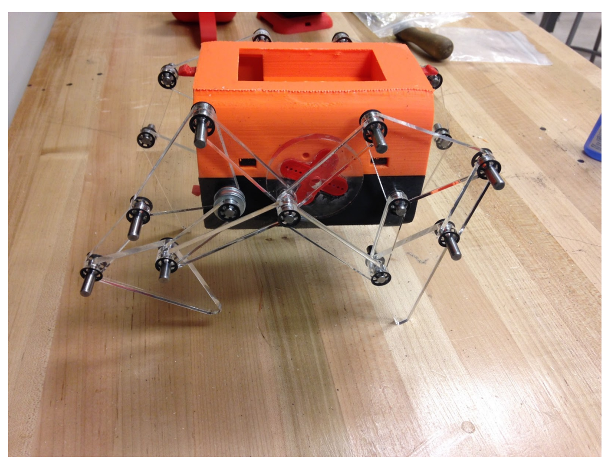


Figure 3: Cantilevered snap lock design utilized to join body pieces



(a) Jansen linkage design



(b) WatchDog linkage prototype design

Figure 4: Linkage Iteration

of these variables are hard to predict and are thus a fair subject for DoE testing. Performing the eight tests with one replication and subsequently determining the significant main and noise effects with the method of cumulative probability graphs, we were able to find the characteristic equations for the output variables, which allowed us to determine the settings for the input variables that would provide the fastest servo speeds.

2.3 DFA Methodology

Design for assembly (DFA) analysis was performed on the WatchDog to investigate areas in which the assembly time or number of parts could be reduced. The assembly time was estimated using tabulation approximations that are common with DFA analysis. Each part operation has an estimated assembly time associated with it based on the handling and alignment time added to the insert and secure time. Handling and alignment times are first calculated by estimating the part fetch time (based on the distance to reach for the part), alpha and beta symmetry (based on the symmetry of the part with respect to the axis of insertion), part size, and handling difficulty. Next, the time it takes to insert and secure the part must be estimated based on criteria such as general placement, hole or pin alignment difficulty, part size, and fastening method. By combining these two times, an approximation can be made for the assembly of each part operation. An important parameter to describe the assembly of a product is DFA index:

$$\text{DFA Index} = N_m t_m / t_a$$

where N_m = Theoretical minimum number of parts, t_m = Minimum assembly time per part = 3 second, and t_a = Estimated total assembly time. This DFA index is an indicator the assembly efficiency, where a higher DFA index corresponds to a higher assembly efficiency.

2.4 Costing Methodology

In order to determine the costs involved in manufacturing the WatchDog, cost analysis was performed. The result of cost analysis depends on several different variables. One of the most important factors affecting cost is the manufacturing process chosen for the creation of the product. The materials used in this manufacturing process, as well as the chosen manufacturing location, also can significantly affect manufacturing costs. After the desired options for each of these factors are chosen, cost analysis can be performed with the use of aPriori. Two resulting cost values are of interest. The first of these is the fully burdened cost (FBC). This is the total cost of manufacturing each individual product unit. Another important value is the total capital investment, the money spent in order for the manufacturing of the product to be possible. This includes the costs of various parts and machinery required to create the product. For example, the cost of creating molds for an injection molding process would be a capital investment cost. By comparing the calculated FBC and capital investment costs for several different manufacturing options, the optimal manufacturing methods can be determined.

3 Results and Discussion

3.1 DOE

The variable settings used for the DoE testing for servo speed are in Table 2, and the design matrix in Table 3.

The significance of main and noise effects was determined by cumulative probability graphs, shown in Figures 5 and 6, by finding which effects deviated from the approximately linear (and thus normally-distributed and random) effects about zero.

Once the significant effects were found, the characteristic equations for output variable value and variance could be derived. They are, respectively:

$$y = 42.14 - 0.54x_1 - 0.34x_1x_2 - 0.79x_2x_3$$
$$s_Y^2 = 9.37 - 11.00x_1$$

The residuals were then found by subtracting the predicted value for each test based on the characteristic equation from the actual average value, and the ranked residuals were plotted on a cumulative probability graph to ensure a roughly linear relation that would verify the validity of the characteristic equations. The plot of the residuals, Figure 7, yielded a line of best fit with an r-squared of 0.954, a high value that indicates reasonable linearity and a valid model. The ranked effects and residuals are given in Table 4.

3.2 DFA

DFA analysis was performed on each part in the WatchDog assembly, to determine which parts could be eliminated and replaced for ease of assembly. Preliminary analysis showed that the parts which took a considerable amount of assembly time were the dowel pins and retaining rings, as can be seen in Figure 8 below.

In order to reduce the assembly time and number of parts, this method of fastener was eliminated and a new design was implemented, as seen in Figure 9 below. These pegs are able to easily snap between linkages and reduces the required fastener parts by a factor of three.

DFA analysis on the final production model of the WatchDog can be seen in Table 5 below. The parts which take the most amount of assembly time are the components in the linkage system. Without changing the entire system, however, these components have been optimized for assembly time after the introduction of the peg fasteners. It was found that the total assembly time is 137.8 seconds, and the DFA index is 0.174. The minimum number of parts required for this design was found to be 8. However, none of these parts (such as the dog head and tail) can be eliminated without harming the aesthetic qualities of the WatchDog design.

$$\textbf{Total Assembly Time} = 137.8\text{s}$$
$$\textbf{DFA Index} = 0.174$$

3.3 Cost Analysis

Due to the complex geometry of our parts, we decided that injection molding was the obvious choice for the manufacturing process of the final product. ABS was then selected as the injection material due to its unique balance of high strength and low cost. ABS is also much lighter than the acrylic used in the linkage system of the prototype. This reduced weight would decrease the torque on the walking mechanism motors, allowing the dog to walk more easily. Using injection molding and ABS as the respective manufacturing process and manufacturing material, aPriori cost analysis was performed for production in the US, Mexico, and China. The resulting FBC and capital investment costs for each of these locations are shown in Table 6

Table 2: Input Variable Settings for DoE

Variable		**Low**	**High**
x_1	lubrication	low	high
x_2	angle offset	1°	90°
x_3	time offset	50 ms	200 ms

Table 3: Design Matrix for DoE

Test	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	y_1	y_2	y_{avg}	stdev	var
1	-1	-1	-1	1	1	1	-1	38.5	44.0	41.3	3.9	15.1
2	-1	-1	1	1	-1	-1	1	39.3	45.0	42.2	4.0	16.2
3	-1	1	-1	-1	1	-1	1	41.0	47.0	44.0	4.2	18.0
4	-1	1	1	-1	-1	1	-1	40.0	44.5	42.3	3.2	10.1
5	1	-1	-1	-1	-1	1	1	40.0	43.0	41.5	2.1	4.5
6	1	-1	1	-1	1	-1	-1	40.0	43.0	41.5	2.1	4.5
7	1	1	-1	1	-1	-1	-1	41.0	44.0	42.5	2.1	4.5
8	1	1	1	1	1	1	1	41.0	43.0	42.0	1.4	2.0

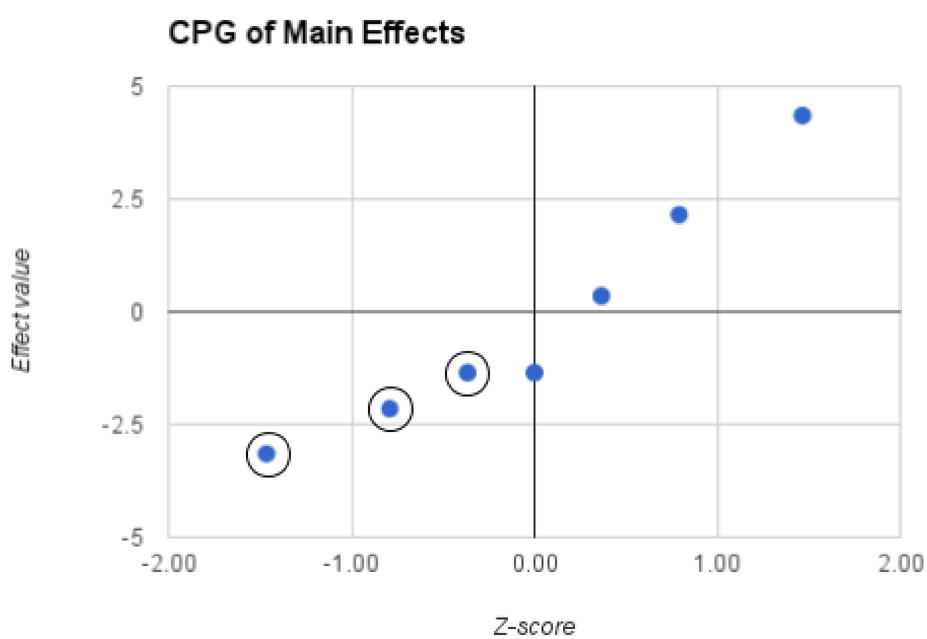


Figure 5: Cumulative probability graph of ranked main effects with significant effects circled

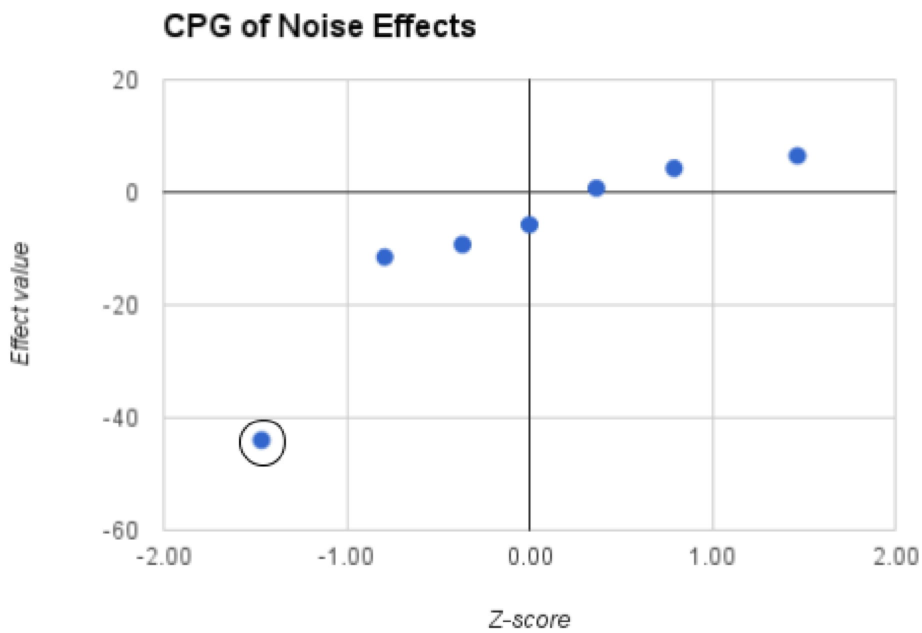


Figure 6: Cumulative probability graph of ranked noise effects with significant effects circled

Table 4: Ranked Main and Noise Effects and Residuals

Rank	**Main Effects**	**Noise Effects**	**Residuals**
1	-3.15	-44.00	-1.23
2	-2.15	-11.50	-0.98
3	-1.35	-9.25	-0.31
4	-1.35	-5.75	0.02
5	0.35	0.75	0.19
6	2.15	4.25	0.34
7	4.35	6.50	0.44
8	–	–	1.52

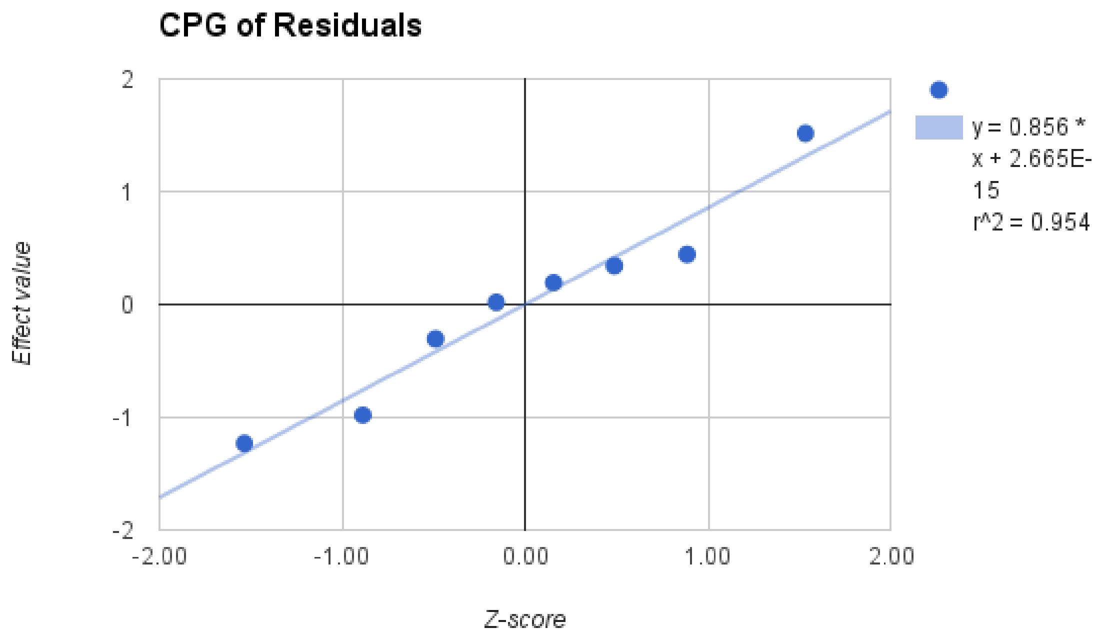
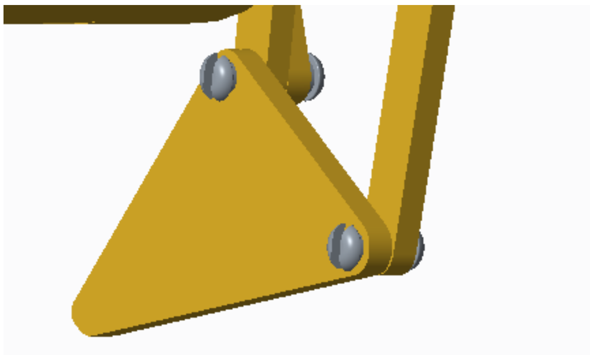
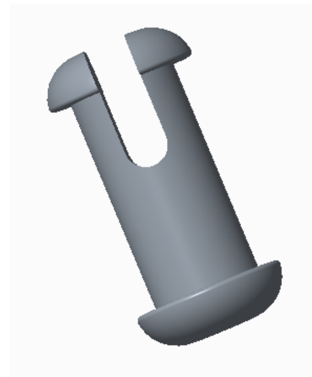


Figure 7: Cumulative probability graph of residuals with line of best fit with r-squared value of 0.954

Figure 8: Dowel pin and retaining rings used to fasten together linkage system



(a) Completed peg-fastener system



(b) Individual snap-fit peg

Figure 9: Peg-fastener design for linkage system

Table 5: DFA assembly operations and total assembly time calculations

Op#	**Times Iterated**	**Part Description**	**Required?**	**Handling Alignment Times(s)**	**Insert Secure Times(s)**	**Total Time(s)**
1	1	Bottom Body Half	Y	2	0.5	2.5
2	1	Circuitry	Y	2.5	0.5	3
3	1	Top Body Half	N	2.5	0.8	3.3
4	4	1" Pegs	Y	1.5	1.1	10.4
5	2	Drivewheel	Y	2.5	1.1	7.2
6	16	Straight Links	Y	1.5	1.4	46.4
7	8	Triangle Links	Y	2.5	1.7	33.6
8	6	0.5" Pegs	Y	2	1.1	18.6
9	2	0.75" Pegs	Y	2	1.1	6.2
10	1	Tail	N	2.5	0.8	3.3
11	1	Head	N	2.5	0.8	3.3

Table 6 shows that China had the lowest manufacturing costs by far, with a fully burdened cost of $13.25, and a total capital investment of $79,052.19. Because of these low costs, China was chosen as the ideal manufacturing location with the goal of minimizing the price of the final product and increasing its profitability.

4 Conclusion

Through good teamwork, effective project management, and application of skills we learned in this class and earlier classes, we developed an electro-mechanically complex product which is unique and which we believe to be highly marketable. Our functional prototype of the WatchDog product–the construction of which, over several iterations, made up the bulk of our project time–clearly demonstrated the major components and their interplay as well as its appeal to our intended market, as our creation drew a lot of interest from our peers in the final stages of construction. In addition to fabricating the prototype, we considered an ideal final design for large-scale manufacturing. We took into account manufacturing concerns through methods such as DoE, DFA, and geometric cost analysis to be sure that the final product would be easily produced and profitable on a large scale, concluding that it would in fact. Truly, with so much in its favor as a novel consumer product, the WatchDog speaks–or barks, as it were–for itself.

Table 6: Manufacturing Costs

		USA		Mexico		China	
Component	#	**ΣFBC**	**ΣCap. Inv.**	**ΣFBC**	**ΣCap. Inv.**	**ΣFBC**	**ΣCap. Inv.**
Bottom Half Body	1	$2.49	$31,186.37	$1.35	$11,646.6	$1.13	$8,071.20
Top Half Body	1	$2.46	$26,178.02	$1.32	$10,411.7	$1.10	$7,369.00
End Cap & Head	1	$2.28	$26,506.89	$1.26	$11.295.2	$1.03	$8,168.10
Tail End Cap	1	$0.55	$24,733.52	$0.31	$9,844.10	$0.27	$6,954.27
Tail	1	$1.12	$13,163.04	$0.63	$5,832.36	$0.54	$4,263.91
Drive Wheel	2	$2.96	$19,650.33	$1.02	$7,756.24	$0.78	$5,488.68
Link C	4	$2.76	$11,867.62	$1.12	$5,188.00	$0.68	$3,781.07
Link K	4	$2.76	$12,263.49	$0.92	$5,372.04	$0.72	$3,915.87
Link BED	4	$4.40	$12,825.35	$1.52	$5,646.88	$1.16	$4,117.92
Link J	4	$2.76	$12,215.62	$0.92	$5,353.93	$0.68	$3,904.44
Link F	4	$2.76	$11,867.91	$1.12	$5,188.11	$1.68	$3,781.14
Link GHI	4	$2.88	$12,737.87	$1.04	$5,599.87	$0.80	$4,083.28
1/2” Inch Peg	12	$7.56	$11,257.12	$2.16	$4,904.44	$1.56	$3,574.00
3/4” Inch Peg	4	$3.92	$11,276.27	$1.12	$4,911.67	$0.80	$3,578.55
1” Inch Peg	4	$4.16	$11,590.54	$1.32	$5,067.13	$0.96	$3,695.63
Clock Cover	1	$1.30	$13,389.08	$0.46	$5,905.57	$0.36	$4,305.13
	Σ	$47.12	$262,709.04	$17.59	$109,923.97	$13.25	$79,052.19