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Axiomatic Design of a linear motion robotic claw with interchangeable grippers

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Abstract

Reykjavik University's electronic lab has a five-axis CRS Robotics A255 arm used in laboratory exercises that are in need of an improved claw. The current claw limits the robot arm operation duration and dexterity due to its bulk. In addition, the grippers don't provide a stable grip as it is applied. Axiomatic Design principles were employed to design a claw to be much lighter, more compact and with more precise grip. The new design replaces the current pneumatic actuators with a servomotor. Interchangeable grippers with carefully designed geometries provide better adaptability on oddly shaped objects. The new design allows a simple preloading mechanism to provide the optimal grip force for a complete and capable manipulation solution.

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Keywords: Axiomatic design; Robot arm; Claw

Nomenclature

C_n	Constraint n
CA_n	Customer Attribute n
DP_n	Design Parameter n
DC_n	Design configuration n
DR_n	Design requirements n
FR_n	Functional Requirement n

1. Introduction

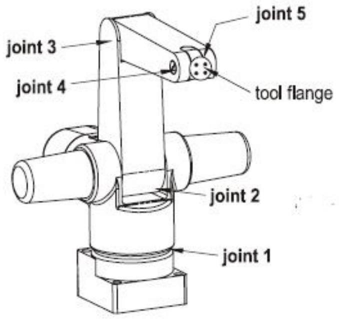

Fig. 1. The CRS Robotics A255 5-axis Arm used for teaching automation courses [1].

The five-axis CRS Robotics A255 Arm (Fig. 1) in the Reykjavík University (RU) electronics lab is used as part of industrial robotics courses. One project in the course requires the students to create a robotic bartender who can open, lift, and pour drinks out of bottles. The robot has several end-effectors to choose from, one of which is a claw designed and built by students in an earlier design course. Unfortunately, this claw turned out to be too heavy for the robot arm's actuators, resulting in unexpected cutouts after 30 seconds. A request for new, lighter and more capable end-effector was made by Indriði Sævar Ríkharðsson, the industrial robotics instructor, to the course "Design" in the Applied Engineering curriculum. This claw needed to be better suited for the CRS robot arm's specifications (Table 1). Due to its inclusion in the curriculum, Axiomatic Design was employed to guide the design effort on the claw.

1.1. Background

There are many various designs of robot claw-type end-effectors to choose from. Industrial claws often use pneumatic actuators and have powerful grip but minimal displacement for

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Table 1. Main physical characteristics of CRS Robotics A255 Arm. [1]

Physical characteristics	Value	Unit
Number of axes	5	—
Output voltage of robot arm	12	V
Nominal payload	1	kg
Reach (joint 1 axis to tool flange)	559	mm
Repeatability	±0.05	mm

a very specific operation [2]. These pneumatic actuators are almost exclusively made from metal and are quite heavy, making them unsuitable for the current arm.

The bartender task needs a gripper that can expand to grip objects 100 mm in width. One servomotor-based design from Robotiq has such a capability but is priced from 1000–18000 USD [3]. Unfortunately, is beyond what the instructor can afford.

The most common claws for amateur use are RC servo powered, often with a linkage system to convert the rotational torque into linear motion of the claw. Many of these designs are lightweight but don't offer the desired displacement of 100 mm. In addition, many of the claws move in an arc motion changing the gripping point for objects of different dimensions. Due to alignment errors, the inexpensive claws are often not capable of gripping and holding more than 500 g.

The selection of claws that meet the project's needs is very sparse between the 30 USD "hobbyist" claws with parallel grippers in linear motion e.g. the LG-KT gripper made by Lynxmotion [4], and the multi-thousand dollar professional claws that have hand-like grippers, extreme precision, and strong gripping force e.g. the RB-Rbq-01 gripper hands made by Robotiq [3].

The current claw (Fig. 2) uses two pneumatic actuators: one is the main closing actuator and a second allows the claw to close more slowly. The grippers have a displacement of 80 mm but move in an arc which makes gripping and holding odd-shaped objects unreliable. With the current pneumatic actuators, the claw has a mass of 1100 g, which is more than the robot arm full extended capacity. Operators often get only get 1–2 minutes of use before the robot arm overheats and shuts down. The robot must operate a minimum of 150 minutes (the length of the laboratory session) to be considered acceptable.

2. Design process

The Axiomatic Design process [5] of the claw started by analyzing the customer's needs[1] then refining them into desired functionality. Proposed concepts were created and selected, followed by a deeper analysis and optimization of the proposed solutions. The final step was to recheck the design against the customers needs.

2.1. Top-level requirement generation

The standard Axiomatic Design process involves capturing Customer Attributes (CAs) which are mapped to the Functional Requirements (FRs). These FRs are then mapped to the design parameters (DPs). Each mapping is represented by a design matrix which shows the relationships between the two domains [5]. The FR-DP matrix is often considered the most critical and will the only one considered in this paper.

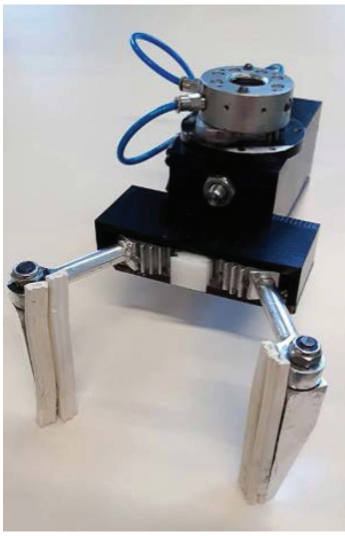

Fig. 2. Existing non-linear pneumatic claw (claw). The coupling for the A255 is located at the top.

The goal of any CA is to capture what the customer needs, rather than what they say. A great deal of discipline is needed to avoid recording the CAs directly from the customer, especially an expert who is able to provide detailed specifications. Another common pitfall is to take these CAs and copy them directly as FRs as shown in Bragason et al. [6]

Indriði listed his needs for the new claw in detail to the team. These notes were filtered and organized to generate customer attributes (CAs) for consideration. He was satisfied with the current geometry and mounting point but the weight had to be no more than half of the current one. This is due to his main complaint that the robot arm was overheating due to the load placed on its motors at full extension. The robot arm's fully extended load capacity is 1000 g including the claw; the maximum capacity is 2000 g when folded up. The goal was to design a claw within the arm's loading capacity to perform the desired task reliability. This became the top level CA_0: "A lightweight robot end-effector which can pour a beer bottle." From CA_0, a top level FR_0 emerged: "Move smooth bottle-shaped objects by gripping them." After looking at various technologies for making a robot end-effector, a design concept was chosen: DP_0: "Servomotor claw with compliant high-friction grippers moving linearly."

With the top-level mapping complete, the team continued the "zig-zag" process by decomposing these top-level design intents into more manageable elements. As per AD standard practice, the decomposition started with the CAs.

2.2. Customer attributes

Detailed CAs were generated during the zig-zag based upon the new knowledge gained generating DP_0. Some customer requests which were unsuitable for FRs became constraints as described in Section 2.3.

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[1] partially described in the previous section

CA_1 Controllable with electrical signals from the robot.
CA_2 Must be able to hold a beer bottle
CA_3 Gripper fingers must move smoothly in a path that can be easily modeled in terms of displacement and force application.
CA_4 Compatible with robot arm coupling.

2.3. Constraints

Constraints affect multiple parts of the design but are not functional requirements. They often define the boundaries of the design space. The following constraints were defined within the scope of a project that could be accomplished in a standard 12-week academic semester with the available budget from the customer.

C_1 Total cost can not exceed 500 USD.
C_2 Must be operational continuously for the entire class (150 minutes).
$\text{C}_{2.1}$ Total mass of the claw must be under 550 g.
$\text{C}_{2.2}$ Power needs of the actuator must match the power supply chosen.
C_3 Similar geometry as the current claw.

2.4. Initial Functional Requirements (FRs)

Functional Requirements must focus on (and preferably begin with) an action or transformative verb. In addition, they must be something that can be validated [5,7] This is critical due to the need for "functionality" which is always derived from some sort of activity or conversion. In addition, proper FR designations are "solution agnostic", allowing for a variety of solutions to be considered. Proper AD application and therefore optimal design becomes difficult when this rule is overlooked [8]. For brevity, we have included the third level decomposition which focuses on the gripper movement path in FR_2. This decomposition was actually performed after all domains had completed their second level decomposition.

FR_1 Rotate actuator into position.
FR_2 Lift 1000 g smooth rounded objects.
    $\text{FR}_{2.1}$ Create controlled clamping force on objects.
    $\text{FR}_{2.2}$ Convert clamping force into frictional fixture forces.
FR_3 Slide grippers in a planar-linear path.
    $\text{FR}_{3.1}$ Roll wheels on rails.
    $\text{FR}_{3.2}$ Rotate servo hub connected to the linkage.
FR_4 Interface mechanically with robot coupling.

2.5. Initial Design Parameters (DPs)

Once detailed FRs have been generated, the process of describing physical instantiation begins with the creation of Design Parameters DPs. Proper DPs are focused (and preferably begin with) a noun or a quantity [5,7]. During this phase, the necessary actuator torque and linkage geometry had not been calculated, so placeholder variables were placed in the DPs.

DP_1 Electrical connectors from robot coupling to electrical servo motor
DP_2 Moving grippers with high friction material.
    $\text{DP}_{2.1}$ Force sensor control-loop
    $\text{DP}_{2.2}$ High-friction lining on grippers

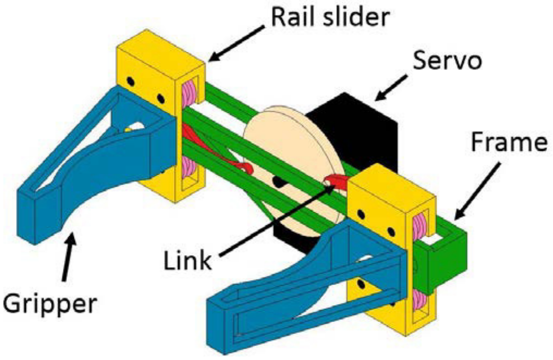

Fig. 3. The initial concept used rollers on flat tracks.

DP_3 Grippers on bearing driven by linkage
    $\text{DP}_{3.1}$ Opposed roller bearings in contact with a flat rail
    $\text{DP}_{3.2}$ Servo of torque τ connected to gripper linkage of length l_g
DP_4 Coupling mates to mounting platform.

With the completion of the initial FR-DP mapping, the AD process instructs the designer to build a design matrix. This matrix is a Cartesian product of all possible combinations of elements in a domain (FRs and DPs) showing where elements are coupled i.e. affect each other [9,10]. A matrix with only diagonal elements is "uncoupled" and satisfies Axiom 1 "to maintain the independence of the functional requirements." [5]. This configuration can be easily optimized due to the allowance to customize any specific FR or DPs without affecting others. A diagonal matrix indicates a "decoupled" or "path dependent" solution, which can still be optimized, but the ordering of parameter choice selection becomes important. All other design matrices are "coupled" and may be able to find a workable solution but will resist modification and optimization [5].

$$\begin{Bmatrix} \text{FR}_1 \\ \text{FR}_2 \\ \text{FR}_{2.1} \\ \text{FR}_{2.2} \\ \text{FR}_3 \\ \text{FR}_{3.1} \\ \text{FR}_{3.2} \\ \text{FR}_4 \end{Bmatrix} = \begin{bmatrix} X & X & X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & - & - & X & X & X & 0 \\ 0 & | & X & 0 & 0 & X & X & 0 \\ 0 & | & 0 & X & 0 & X & X & 0 \\ 0 & 0 & 0 & 0 & X & - & - & 0 \\ 0 & X & 0 & 0 & | & X & X & X \\ 0 & 0 & 0 & 0 & | & X & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \text{DP}_1 \\ \text{DP}_2 \\ \text{DP}_{2.1} \\ \text{DP}_{2.2} \\ \text{DP}_3 \\ \text{DP}_{3.1} \\ \text{DP}_{3.2} \\ \text{DP}_4 \end{Bmatrix} \quad (1)$$

3. Final Concept

3.1. Revision from a design review

After the first attempt of using Axiomatic Design procedures to design a new robot claw, the design (Fig. 3) was presented at an in-class design review. The coupled design matrix (Eq. 1) was concerning to the student reviewers due to the coupling created in $\text{FR}_{3.1}$ and $\text{DP}_{3.1}$ from the roller bearing concept. The worry was that off-axis torques from the gripping motion or the coupling interface would derail it. After much discussion, the design was revised with a new concept that used recirculating sleeve bearings on a pair of cylindrical bearing rails.

These elements were implemented in a new decoupled design matrix (Eq. 2) The design of the robot claw (Fig. 4) was ready for prototyping.

3.2. Functional requirements

- FR$_1$ Rotate actuator to position.
- FR$_2$ Lift 1000 g smooth rounded objects.
  - FR$_{2.1}$ Create controlled clamping force on objects.
  - FR$_{2.2}$ Convert clamping force into frictional fixture forces.
- FR$_3$ Slide grippers in planar-linear path.
  - FR$_{3.1}$ Slide bearings on precision cylindrical shafts.
  - FR$_{3.2}$ Rotate servo hub connected to linkage.
- FR$_4$ Interface mechanically with robot coupling.

3.3. Design parameters

- DP$_1$ Electrical connectors from robot coupling to electrical servo motor
- DP$_2$ Moving grippers with high friction material.
  - DP$_{2.1}$ Contact switch signals servo additional displacement on compliant gripper fingers.
  - DP$_{2.2}$ Gripper contact area has a coefficient of friction of greater than 1.
- DP$_3$ Grippers on bearing driven by linkage
  - DP$_{3.1}$ Parallel bearing rods with re-circulating sleeve bearings
  - DP$_{3.2}$ Servo of torque τ connected to gripper linkage of length l_g
- DP$_4$ Coupling mounts to mounting platform.

$$\begin{Bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \\ \mathrm{FR}_{2.1} \\ \mathrm{FR}_{2.2} \\ \mathrm{FR}_3 \\ \mathrm{FR}_{3.1} \\ \mathrm{FR}_{3.2} \\ \mathrm{FR}_4 \end{Bmatrix} = \begin{bmatrix} X & X & X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & - & - & 0 & 0 & X & 0 \\ 0 & | & X & 0 & 0 & 0 & X & 0 \\ 0 & | & 0 & X & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X & - & - & 0 \\ 0 & 0 & 0 & 0 & | & X & 0 & 0 \\ 0 & 0 & 0 & 0 & | & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_2 \\ \mathrm{DP}_{2.1} \\ \mathrm{DP}_{2.2} \\ \mathrm{DP}_3 \\ \mathrm{DP}_{3.1} \\ \mathrm{DP}_{3.2} \\ \mathrm{DP}_4 \end{Bmatrix} \quad (2)$$

3.4. Design details

Now that the general concept for the claw was chosen, the next step was to determine the optimal geometry. One factor must be considered regarding the specific geometry of any end-effector on the A255: the claw must not collide with the A255 during operation, especially in the safe start position (Figure 5). For simplicity, the previous coupling geometry was kept to ensure the end-effector was compatible with the A255. Figure 6 shows the final geometry.

The frame is milled from a block of HDPE [11]. The robot arm coupling mounts to the mounting platform on the frame. In the center of the frame, there is a mounting place for the servo [12] with threaded holes for fastening. Wherever possible, cut-outs were created to reduce mass. On each side of the frame, there are mounting holes for the precision shafts [13]

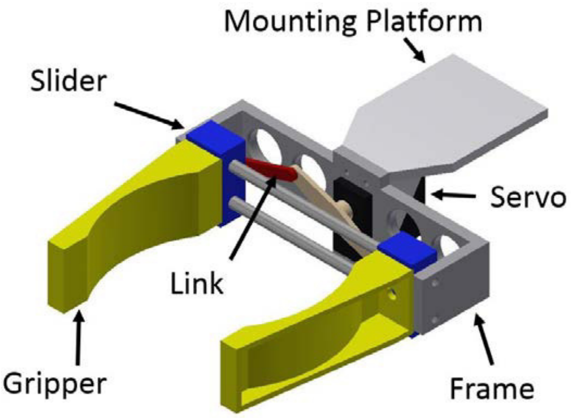

Fig. 4. The final design constrains gripper travel using a pair of bearing shafts.

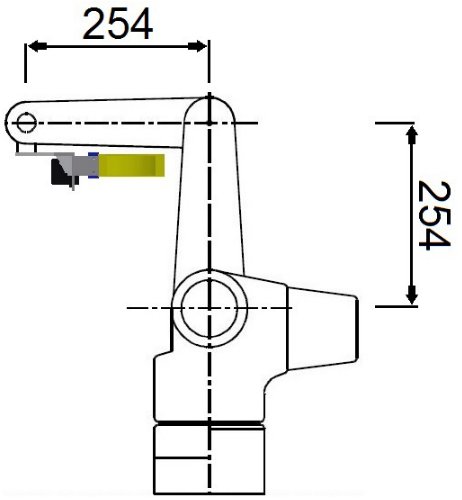

Fig. 5. Claw and coupling geometry must not collide with the arm in safe start position (units in mm).

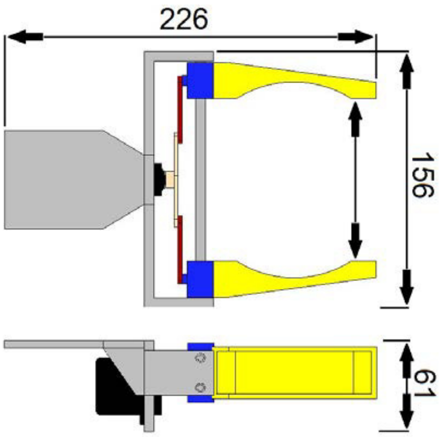

Fig. 6. Dimensions of the final design (units in mm)

The servomotor used is an analog high torque servo made by Power HD [12] used in RC cars and aircraft. It was chosen for its balance of torque, size, and price. The servo is rated 17 kg cm at 6 V while only having a mass of 63 g and price of 20 USD.

The linkage system consists of two linkages that connect to each end of the servo hub and to each slider assembly. They are made of aluminum [14] to provide a solid transformation of the rotational movement of the servo to the linear movement of the sliders in both directions. Details of how the torque, displacement, and force were made to match the requirements are detailed in Section 4

Shafts that hold the sliders and mount on the claw frame are SKF 6 mm precision shafts [13]. These hardened steel shafts are designed to be compatible with the linear recirculating ball bearings [13]. Each HDPE [11] slider has two SKF linear bearings [13] which mount on the precision shafts [13]. They are made from HDPE [11] to save weight but still has decent strength. The front face of the slider has a specially made groove for the gripper arm to rest and uses a single bolt to fasten the gripper arm. The gripper arms are made from HDPE [11] chosen for high rigidity and resistance to yielding. The grippers are mounted on the slider in a special groove; only one bolt must be adjusted to fasten or remove the gripper. The grippers are lined with 2 mm thick rubber with a coefficient of friction on glass surfaces of approximately 2.

4. Gripper arm force and stress analysis

An analysis of force on the gripper arms are shown in Equations 3–6. d is the horizontal distance from the center of the slider to the center of the servo hub, τ is the torque from the servo, L is the length of the linkages, r is the radius of the servo hub, h is the height from the center of the slider, α is the angular position of the servo hub, and F is the resulting force to the gripper arms (Fig. 7).

$$d = \sqrt{L^2 - (r\sin\alpha + h)^2} - r\cos\alpha \tag{3}$$

$$F_3 = \frac{\tau(r\sin\alpha + h)}{rL}\cos\left(\alpha - \frac{\pi}{2} - \cos^{-1}\left\{\frac{r\sin(\pi-\alpha) + h}{L}\right\}\right) \tag{4}$$

$$F_5 = \frac{\tau(r\sin\alpha + h)}{rL}\sin\left(\alpha - \frac{\pi}{2} - \cos^{-1}\left\{\frac{r\sin(\pi-\alpha) + h}{L}\right\}\right) \tag{5}$$

$$F = F_3 - F_5 \tag{6}$$

Through this analysis, it was discovered that the hub's cosine displacement must be at least 100 mm to avoid jamming.

Autodesk Inventor was chosen to perform FEM analysis on the claw before prototyping. Displacement and stress analysis with a 12.5 N gripping force resulted in 0.88 mm displacement and 2.3 MPa Von Mises stress (Fig. 8). A buckling analysis was performed on the linkage and resulted in 110 N buckling force; this result is more than sufficient for the design. Inventor was also capable of estimating the mass and displacement: the mass should be 391 g, which is 35% of its predecessor weight and the displacement would be 65% of the total width, making it a fairly compact design.

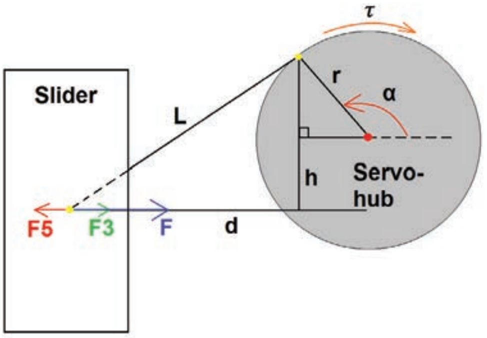

Fig. 7. Free body diagram of the gripper arm forces and the rotation of the servo.

Table 2. Calculated values of physical characteristics of the final claw.

Physical characteristics	Value	Unit
Torque of servo motor	1.66	N m
Output voltage of robot arm	12	V
Angular speed of servo	0.1336	rad s^{-1}
Gripper arms max velocity	0.195	m s^{-1}
Friction coefficient, gripper arms vs glass	2	—
Max clamping force of gripper	24.45	N
Clamping force of gripper holding a bottle	20	N

5. Prototype

Once the analysis and CAD design were complete, the next step was to manufacture a prototype claw.

The manufacturing and assembly process of the project was performed in the RU metal working facilities. The grippers and sliders were milled with 3-axis CNC mill. The frame was milled manually in a 3-axis mill due to its complex geometry and fixturing. Linear bearings were press fit into the sliders to keep tolerances in check and the grippers fixed to the sliders with bolts and short threaded rods. On the contact face, the grippers were lined with the chosen rubber. The servomotor was mounted to the frame and secured with screws, on the servo output shaft the hub is mounted and between it and the sliders, linkages are mounted. The CRS Robotics A255 arm coupling connector will be fastened to the mounting platform on the frame so the arm will be able to connect automatically to the claw.

During manufacturing, bearing alignment issues were discovered that created large frictional forces during translation. These issues were never completely resolved, so a fully functioning claw was never tested. In a future iteration, the claw's manufacturing and assembly process will be re-examined to avoid the misalignment error.

6. Conclusion

Axiomatic Design principles assisted in optimizing the claw design to fit the customer needs. The customer initially re-

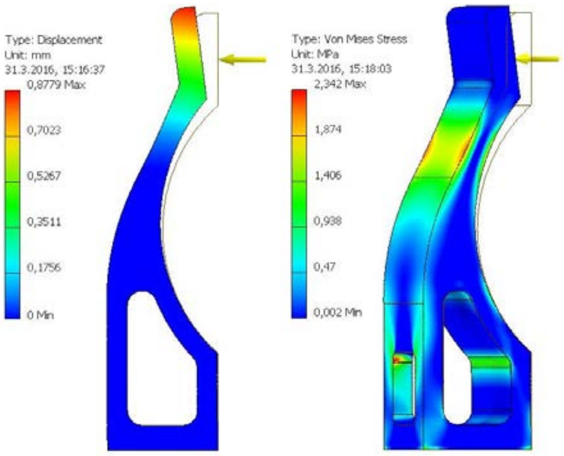

Fig. 8. FEM visualization of Von Mises stresses within grippers.

quested a lighter and more precise tool to grab and hold objects CA_0: "A lightweight robot end-effector which can pour a beer bottle." These attributes were mapped to FRs to pinpoint his needs: FR_0: "Move smooth bottle-shaped objects by gripping them." After looking at various technologies for making a robot end-effector, a design concept was chosen: DP_0: "Servomotor claw with compliant high-friction grippers moving linearly."

Though the implementation was unsuccessful due to manufacturing issues, we believe this paper to be a valuable example of Axiomatic Design being employed on a challenging electro-mechanical problem. Due to the generation of Functional Requirements, Design Parameters, and design matrices, the authors were able to catch reliability issues (due to coupling) before the construction began. Future efforts will build upon the designs described here to further improve the gripper employed in the automation course.

Acknowledgments

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References

[1] CRS Robotics Corporation. A255 Robot System User Guide. 5344 John Lucas Drive Burlington; 2001.

[2] Festo. Parallel grippers [Webpage search result]; 2016 [cited 2016 Mar 15]. Available from: `https://www.festo.com/cat/en-in_in/products_010804`.

[3] RobotShop inc. Available grippers [Webpage search result]; 2016 [cited 2016 Mar 15]. Available from: `http://www.robotshop.com/en/catalogsearch/result/?q=gripper&order=stats_sales_order_count&dir=desc`.

[4] Lynxmotion. Little grip Kit (with servo) [Webpage]; 2016 [cited 2016 Mar 15]. Available from: `http://www.lynxmotion.com/p-160-little-grip-kit-with-servo.aspx`.

[5] Suh NP. Axiomatic Design - Advances and Applications. Oxford University Press; 2001.

[6] Bragason G, Þorsteinsson S, Karlsson RI, Grosse N, Foley JT. Heat-activated Parachute Release System. In: Thompson MK, Giorgetti A, Citti P, Matt D, Suh NP, editors. Procedia CIRP, 9th International Conference on Axiomatic Design (ICAD). vol. 34. Procedia CIRP. Florence, Italy: Elsevier ScienceDirect; 2015. p. 131–136. Available from: `http://www.sciencedirect.com/science/article/pii/S2212827115008203`.

[7] Cochran DS, Li J, Vanover K, Foley JT. A System Design of a Rural Hospital Operating Room. In: 26th CIRP Design Conference. Stockholm: CIRP; 2016. p. 6.

[8] Thompson MK. A classification of procedural errors in the definition of functional requirements in Axiomatic Design theory. In: Thompson MK, editor. 8th International Conference on Axiomatic Design (ICAD 2014). vol. 32. CIRP. Worchester, MA: Axiomatic Design Solutions, Inc.; 2013. p. 1–6. Jun. 27–28.

[9] Cochran DS, Foley JT, Bi Z. Use of the Manufacturing System Design Decomposition for Comparative Analysis and Effective Design of Production Systems. International Journal of Production Research. 2016;p. 24.

[10] Benavides EM. Advanced engineering design - An integrated approach. Woodhead Publishing; 2012.

[11] British Plastics Federation. Polyethylene (High Density) HDPE [Webpage]; 2016 [cited 2016 Mar 15]. Available from: `http://www.bpf.co.uk/plastipedia/polymers/HDPE.aspx`.

[12] HuiDa RC International INC. Power HD HD-1501MG Specification Sheet. 1707, Huashang Building, Xiapu district, Huizhou, Guangdong, China; 2016. Available from: `http://www.chd.hk/UploadFiles/Att/2016012216551596.pdf`.

[13] SKF group. Linear bearings and units with SKF factory pre-lubrication. SKF Group; 2013. Available from: `http://www.skf.com/binary/30-149566/4182_2-EN_linear-ball-bearings-and-units.pdf`.

[14] Callister WD, Rethwish DG. Materials Science and Engineering. Eighth ed. John Wiley & Sons, Inc.; 2011.