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A GENERAL DESIGN ANALYSIS OF COLLABORATIVE ROBOT MANIPULATORS

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ABSTRACT

This paper explores the design fundamentals of collaborative robots (cobots) through the combined lens of functional modeling and axiomatic design analysis. Beginning with the history of cobots and robotic manipulators, the study uses the Universal Robotics 5e as a foundational case—the first commercially sold cobot. This paper starts at the customer needs level and performing a general survey to understand the overall and top most requirements for cobots. From here a comprehensive functional model of modern cobots is developed. Meaning that first a general model of a cobots black box is created which is then fleshed out by using a functional structure diagram. All of which is then complemented by a morphological matrix informed by an analysis of leading cobot manufacturers and their components. This serves as a basis for assessing Universal Robotics' implementation of axiomatic principles in creating an efficient and customizable product line.

The overall topic of axiomatic design is introduced which serves as the guiding principles for assessing a Universal Robot cobot as a general case for cobots. Next, customer needs are systematically mapped to functional requirements and physical domains, illustrating the interdependence of these domains in both functional modeling and axiomatic design. Hierarchical analysis for critical functions emphasizes the importance of independence and minimized complexity in achieving robust, adaptable systems. Critical components enabling customization—strain-based gearboxes, frameless motors, and aluminum linkages—are identified, showcasing their alignment with varying customer requirements. These identified physical domain components are qualified by their direct link to customer needs and their evaluation in the independence axiom. What is noteworthy is that this axiomatic analysis arrives at similar components and a similar structure to the functional analysis. Which essentially provides testament to the iterative refinement inherent in cobot design, arriving at an optimized state through successive design improvements. Finally an analysis of the Universal Robotics product family is completed which shows how well the critical components were leveraged to create an entire product family in a cost-effective manner. Lastly the study looks forward at what could be next for similar analysis. This covers a more indepth analysis of mass customization to see which product in the family has had the best return on investment. Additionally, it will be an opportunity to explore the information axiom something not covered in this scope of axiomatic analysis. Overall the study breaks down the design of cobots, lays the basis for the Universal Robot line as a general cobot case, and analyzes how the Universal Cobots prepped for customization in their product family.

BACKGROUND

Robotic manipulators began their implementation journey in 1961 when Unimation unveiled their 5 degree-of-freedom robotic manipulator. Meaning that this robot can translate the end tool along the 3 principal axes, and rotate about 2 axes. These initial robots used hydraulic actuators coupled with encoders to enable motion and have a very high payload capacity. Unimation started what's now considered the imperative for integrating robots within an operation. Which is determining if the task is dreary, dirty, or dangerous, where such tasks are worth automating [1].

FIGURE 1: THE UNIMATION ROBOT ARM

From here robotic manipulators continued to develop with exponential advancements. The next stage of these manipulators was to achieve 6 degrees of freedom for the end effector. This was first achieved in 1979 by the Stanford Arm which moved away from using hydraulics for actuation. This was a marked improvement as the hydraulic actuation made the Unimation #001 very bulky and prone to leaks. This smaller robot arm heralded in the beginning of smaller more adaptable arm construction for manipulators [2].

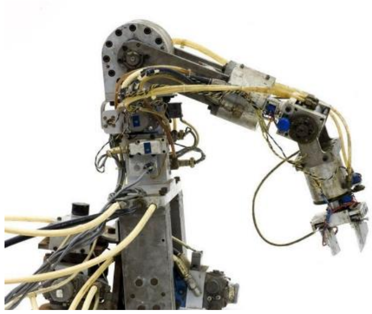

FIGURE 2: THE STANFORD ARM

The Stanford arm also brought in two critical design choices, an all electric actuation for its joints and the inclusion of brakes at these joints. Going even further the arm was capable of the earliest stages of trajectory planning [3]. This arm did not store motion in memory via a preprogramed path rather it had an onboard computer capable of planning tasks and taking in feedback from sensors mounted to the robot. This opened the door for advanced integration in the future and a starting line for how these robotic arms will continue to develop[2].

The Stanford arm also starts to mark a split in design fundaments between robotic arms and collaborative robots (cobots). Where now both manipulators with common origins specialize in various applications and therefore will deviate even further in their designs. In 1973, a development by Kuka (now a robotics powerhouse) in Germany made the first use of fully electric motors for their robotic arm. Next at Carnegie-Mellon University their Direct-drive robot integrated the electric motors directly into the joints, removing the need for tendons that would pull on the linkages of the robotic arm [6]. Both of these designs maked points in the design history that are revolutionary in that subsequent designs all inherited from these break throughs. Collaborative robots are robots designed to physically interact with humans in a workspace. The first patent mentioning them from 1997 defines them as, “an apparatus and method for direct physical interaction between a person and a computer controlled manipulator”. As such these cobots need to be ultra precise, safe, and dexterous. This bring in the creation of the first cobot which was developed at Northwestern University in conjunction with General Motors. The goal was to develop a robot capable of safety working alongside workers and that did not require a major restructuring of the manufacturing flow [4]. This cobot however only ever made it academically and was the focus of the subsequent paper written by that Northwestern research group. Additionally, their focus was on a wheeled robot, despite this many of their choice continue to cement the usage of breaks and electric motors for robots [5].

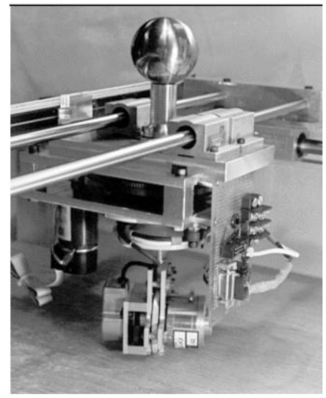

FIGURE 3: FIRST “COBOT” DEVELOPED BY NORTHWESTERN

Development continued in the industry driven by one of the major players Kuka and several other research groups. Which led to their release of the Kuka LBR III a light weight robotic arm in 2004. This is also what could be considered the first cobot as it did not require a safety cage and could interact with humans to some extent.

FIGURE 4: FIRST COBOT MANIPULATOR KUKA LBR III

The resemblance to the Standford Arm is marked, as are the amalgamation of all the prior 20 plus years of development. This arm used brushless-direct drive motors, developed on board motor controllers, feedback sensors, brakes, and could be programmed at the OS level rather than lower-level programming such as PLC [7 & 8]. Just four years later Universal Robots, now one of the largest in the industry, would sell the first cobot ever the UR5. Which was purchased to tend a CNC machine. When installed the cobot had no safety curtain and was able to be programed simply via a touch screen [9].

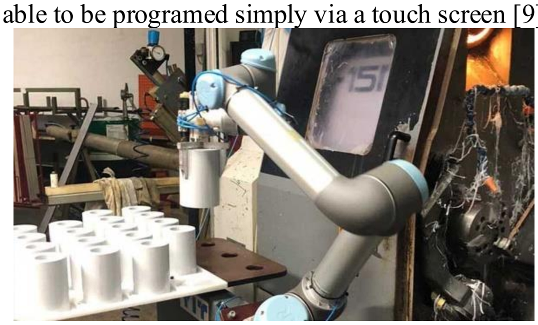

FIGURE 5: UR5 TENDING A CNC MACHINE

At this point in the journey of collaborative robots a sense of product maturity can finally be felt. Where UR5 was finally a polished product ready almost reaching the point of "plug-and-play". From here the evolution of cobots is focused on refinement and greater development in the software aspect of cobots. Fast-forwarding today looking through the full range of cobots offered by Universal Robotics show a product line of mature general cobots. This product line also will serve as a excellent analysis point of the cobots on a fundamental requirements level. Additionally, the product line will provide a case study for understanding design principles behind developing multiple customized product lines in the same family of cobots.

With the background of modern cobot arms established, it

requirements is created [10-12]. Based on that the generalized list of customer needs is as follows:

Surveyed Customer Needs
Task Adaptability
Safe Operations Next to Humans
High Load to Weight Ratio
Particular Reach in Workspace
Particular Speed
Particular Accuracy
Easy and Robust Integration
Programmability
Task Completion Autonomy

TABLE 1: CUSTOMER NEEDS

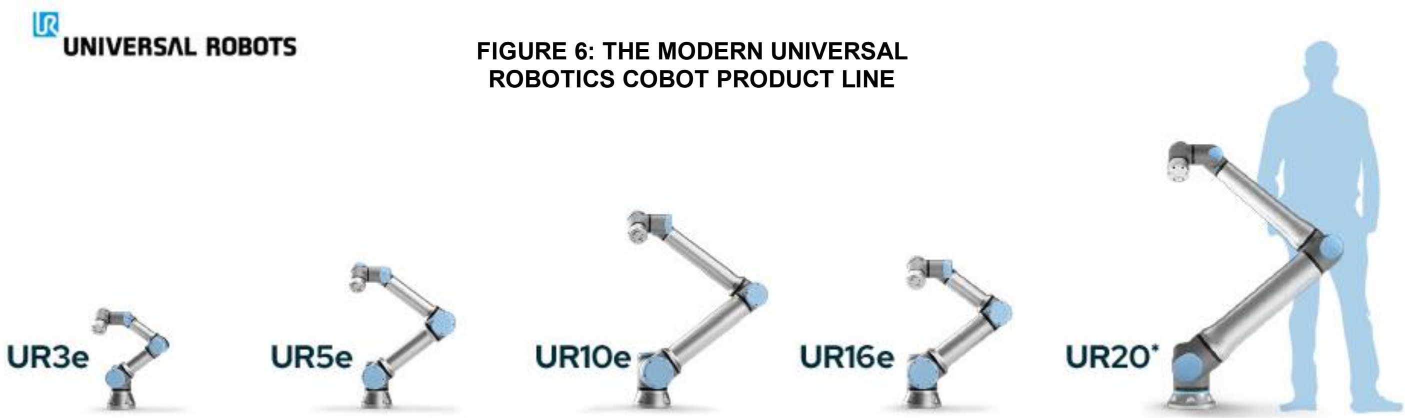

FIGURE 6: THE MODERN UNIVERSAL ROBOTICS COBOT PRODUCT LINE

also becomes possible to understand the various critical components that are critical to its hardware and software. While the components used are well documented at a general level, there is plenty of understanding to be gained from working backwards to identifying what these components are. To do so several steps of design theory can be used to understand the entire cobot. Identifying customer needs, using functional modeling, and finally morphological analysis covers an initial portion of design analysis theory. Afterwards concepts from axiomatic design can be used to relate customer needs to functional requirements to these same components. By doing so it becomes possible to understand how these product lines are intelligently developed to support their customizability.

CUSTOMER NEEDS

The primary kick off point must be at addressing the needs of a customer. Only from there can those needs be mapped to a function and eventually the functions can be mapped to components. While customer needs can be vast it is possible to use a generalized set of requirements. This assumption is found on the basis that modern cobots sold at volume are for a variety of applications and thus inherently generalized. Thereby having certain traits that are critical to all customers. Based on several articles by manufacturers and distributors a set of generalized

FUNCTIONAL MODELING

Now that needs are established the design can begin at the black box model. This is a tool which aims to represent a top level function of a product via a verb + noun pair. From here the black box takes inputs of energy, material, and information. Then it outputs the energy, material, and information. What is critical is that energy must be conserved and that the internal happenings of the black box at this level can be ignored. By starting with a black box model the fundamental function can be created which opens the ability to understand what are the expected inputs and outputs of this system.

The first item to establish is what is the function of a cobot? However, that is a interesting question to answer for a machine Given this the top level function must abide by the inherent task space ambiguity. Hence, the top level function can be identified as "perform tasks".

Next comes the energy input and output. As we have already establish modern cobots make use of electric motors. Hence the input energy is "electrical energy". This electrical energy is then converted through the black box model to its conserved output. Fundamentally electrical energy allows for the creation of torque which enables the motion thereby achieving some tasks. However, this change of electrical to mechanical conversion does not result in any mechanical energy being outputted. Since it exists solely to complete the task within the system and the mechanical energy generated converts to creating rotation. Rather what is exported is then acoustic energy from the various motion components moving and thermal energy from the motors and electrical components heating up. These forms of transformed energy do not exist entirely within the system and remain present during and after the function is complete.

Next is material input and output. Given the variability in tasks so is the variability of the material input. This is what the task is being performed on. It can be anything from steel stock in the CNC cobot application to a pan for a cooking robot, notably depending on the application it might also be zero. Thus, the input material is established as "Material for Tasks" The output thus is dependent on the input material which in this case of developing a general model could be "transformed materials"

Finally, the last would be the input and output of information from the cobot. In particular, the main input of information externally is to allow for the function to remain. So simply this can be "commands", after this proceeds through the system it exits then as "feedback". Below shows the black box model of a general cobot.

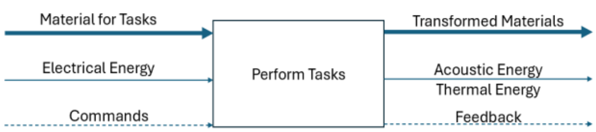

FIGURE 7: BLACK BOX MODEL OF GENERAL COBOT

This black box model establishes the top level function and the various inputs and outputs function. It now allows for the development of a function structure diagram to show the inner workings of the "perform tasks" black box.

To develop the function structure diagram the goal is to track the inputs and outputs in relation to the inner workings of black box model. For a function structure diagram to be successful it must be very clear with each of the internal works and there should be no redundancies. Additionally, it is imperative that the lines modeling the flow of the functions never intersect, thereby ensuring easy interpretation. The prerogative for the inner workings that get described is for them to be simple internal actions describable in 1-2 words.

1First the input of "material for tasks" can be analyzed, essentially material will enter the system then work will be performed on to it, subsequently the transformed material will exit the system.

Next the input of "commands" can be analyzed. The "commands" enter the system this is relayed to the actuator which then creates rotation, this passes one feedback signal. After the rotation is created it performs a transform on the material which then also provides feedback as the transform is being completed. Finally both feedbacks are joined and exported out of the system.

Lastly, the input of electrical energy can be analyzed. Here electrical energy enters the system it is then transformed into mechanical energy via the actuator. When the electrical energy is transformed into mechanical energy it also produces thermal energy which subsequently exits the system. Next the mechanical energy creates rotation which then along with the material input results in the transformed material because of "perform task". When the electrical energy converts to mechanical energy creates motion it creates acoustic energy and when the mechanical energy is used for rotation it also exports acoustic energy. Additionally, acoustic energy is likely created when the task is performed thus it is exported.

With the workings of the function structure diagram worked out the actual diagram can be developed. Note how all inputs are initially imported into the system and then the respective outputs are exported prior to becoming outputs.

Having established the function structure diagram it becomes possible to identify the various components inside of the black box model that will help achieve these goals. This

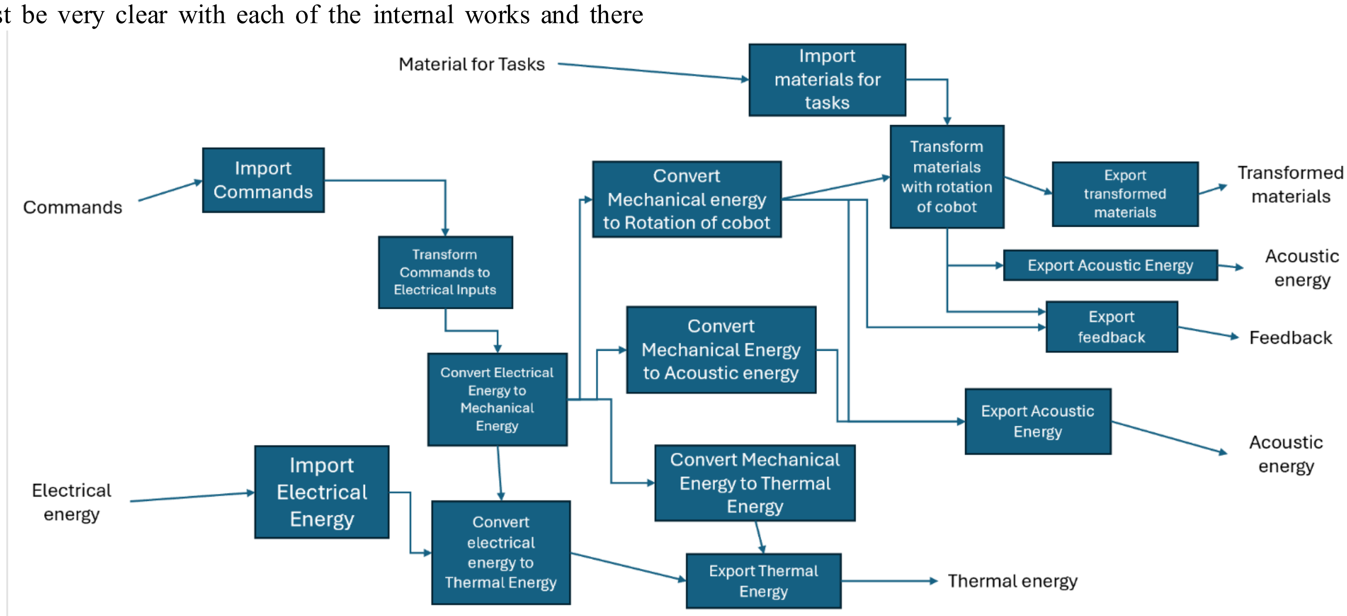

FIGURE 8: FUNCTION STRUCTURE DIAGRAM

allows for a greater understanding of where the components of a cobot manipulator are generated.

COMPONENT ANALYSIS

With the functional modeling complete it becomes time to relate the functions to components that execute them. To do so it is necessary to introduce the components that now after 50 years of development are essentially ubiquitous for cobots. What is critical to demonstrate is how a majority of cobots have adopted using the same components generally. To do so at a minimum the top 2 cobots developers by global market share were researched and surveyed to analyze whether they use similar components. These were Universal Robotics, Aubo Robotics [13]. With many companies their Bill of Materials is not directly available. So, by also identifying certain hallmarks or distinctive specifications of these manipulators they are determinable. In other cases, the manipulators are open-sourced allowing for an easier analysis. On the software side of components only higher-level aspects will be covered to avoid unnecessary granularity.

FIGURE 9: AUBO I5

ONBOARD COMPUTER

As prior mentioned, the Stanford Arm was the first to include an onboard computer for active planning and control of the manipulator. In the nearly 50 years subsequent computing power has increased greatly. With this the benefits of maintaining onboard computing have made its inclusion a standard. This is clear looking at Universal robotics touch display to interact and program the robot [14]. Similarly, Aubo maintains a touch display which serves as an onboard computer to control the robot [15].

MOTOR CONTROLLER BOARD

Motor controllers regulate the movement of each joint in a cobot, ensuring accurate execution of planned trajectories. These boards translate high-level commands from the onboard computer into precise electrical signals for motors, often incorporating feedback from encoders for error correction. In this case both ABB and UR undoubtedly maintain motor controller boards to provide direct input [16 & 17]. However, the configurations of the board can vary and its form can be circular as well depending on other design requirements.

SENSOR SUITE

Just as the Stanford arm was the first to include an onboard computer, it was one of the earliest to include several sensors for feedback into its planning and motion control. A typical cobot is equipped with sensors for position, torque, force, and vision to enhance safety and precision. Advanced sensor suites enable features like collision detection, adaptive grip, and environmental mapping. For example, force-torque sensors are common in ABB's and UR's robots, reflecting industry norms [12 & 15]. These sensors as alluded can have a variety of methods employed to generate feedback and thus can take a variety of forms which lead to different design choices required. Overall the intent remains to provide some kind of feedback to the larger system.

POWER SUPPLY UNIT

Cobots utilize modular power systems tailored to their size and application. These units provide energy for motors, sensors, and processors, often integrating backup systems for reliability. Power supply efficiency and compactness are key factors in cobot design since that increases life expectancy and decreases costs. In the case of functional modeling really this component symbolizes some means to input electrical energy into the system. In various applications the method by which power is delivered or maintained at a steady rate could change.

MOTOR

Frameless motors are prevalent in cobots due to their compact size and efficient torque generation. Integrated directly into joint assemblies, they reduce weight and improve design flexibility. This was a development mentioned earlier as a significant step towards modern cobots. The frameless motors are also responsible for speed of operations and for more quiet operations since they are brushless. Universal Robots frequently employ frameless motor designs, reflecting a broader industry trend toward lightweight systems [17]. Similarly, by just analyzing the form of the cobot produced by Aubo it is clear that they must be using inline motors that would likely also have to be frameless given the compactness of the joints. Additionally, looking at the turn-able range for the joints is also indicative of a frameless motors since they are easily able to rotate for +/-360 degrees.

GEARBOX

High-performance gearboxes, such as harmonic drives, are critical for precise motion control in cobots. These components allow for high torque-to-weight ratios and minimal backlash, key features in leading cobot designs. This again becomes clear as the defacto option given the joint break down of the UR arm [17]. For the Aubo the data sheet shows a repeatability of +/-0.05 mm a range so precise that in this form factor of the Aubo there must be a gear box present [15]. Additionally, since the speed of the robot at a joint is lower than the theoretical speed of a free spinning drive also means there must be a gearbox present. Since by increasing its torque which is needed to move the arm it will also drop the speed of the motor.

LINKAGES STRUCTURE

Cobots feature lightweight yet durable linkage structures, often composed of aluminum or carbon fiber composites. These designs prioritize ease of movement and reduced power consumption. The goal is always to be as light as possible while still maintaining the system's stiffness. For both robots it is simply inherent to the design that they contain long tubular linkages between their motorized joints. Which extends the ranges of the joints and opens more applications for the manipulators.

SOFTWARE SUITE: PATH PLANNING/ OPERATING SYSTEM/ INVERSE KINEMATICS

Cobots rely on advanced software for path planning, real-time control, and inverse kinematics. Many platforms integrate ROS (Robot Operating System) or proprietary solutions to simplify programming and operation. However, in the same breath many cobot manufacturers to enhance the plug and play appear also create their own software suite. For Universal Robotics this is Polyscope and for Aubo it is Aubope [14 & 15]. Regardless for any robot the implication is that there is a detailed software suite, and software interdependency that can be managed via open-source tools like ROS. Otherwise, manufacturers create their own basic versions that while not at the cutting edge of development still provide the needed to preform tasks.

END-EFFECTOR

The end-effector determines the cobot's task capabilities, with designs ranging from grippers to welding tools. Modular designs enable quick tool changes, improving versatility. To standardize these attachments, ISO 9409-1 specifies the mechanical interface for end-effectors, detailing dimensions, tolerances, and coupling mechanisms. Many robotic arms adhere to this standard so that they can take advantage of end-effector tools that they aren't required to develop themselves. For example this is the case for universal robotics and for a new example the Kuka cobot IIWA [18 & 19]

SAFETY SUITE / BRAKE

Lastly, what differentiates a standard robotic manipulator and a cobot is the safety suite. These components, software, sensors, and algorithms come together to ensure that a cobot can interact with a person without needing a safety wall. Integrated safety features, including brakes and force-limiting sensors, are standard in cobots to enable human-robot collaboration. These systems prevent accidents by halting motion upon detecting abnormal forces. Universal Robots maintains the industry standard in implementing safety standards like ISO/TS 15066. Similarly another major player like ABB also adheres to these standards as do many others. There are also differences in how these are implemented for example the brake design of Universal Robotics is unique [17] and features a star shaped disk that is caught by a solenoid.

OVERALL

This section has now introduced types of components commonly used in a cobot and some common examples of those component types. The goal was to qualify them as common parts that can be used as a reasonable example for later analysis. Additionally, it was an aim to show similarity between the component types for the large companies involved. Thus it becomes possible to reference the Universal Robot's line of cobots as a general case since not only do they have the largest market share, but their components align with other major players. [13]

MORPHOLOGICAL MATRIX

One common tool used to identify various potential components that satisfy the functions noted in the diagram is a morphological matrix. Alongside this the components can be directly mapped to their functional requirements and then customer needs via cascading mapping. In the case of the cobot because of the past several decades of development the mapping is clear from function to component. Analyzing the general components of the UR5e will allow for a generalized morph matrix to be completed. That structure is seen in the following

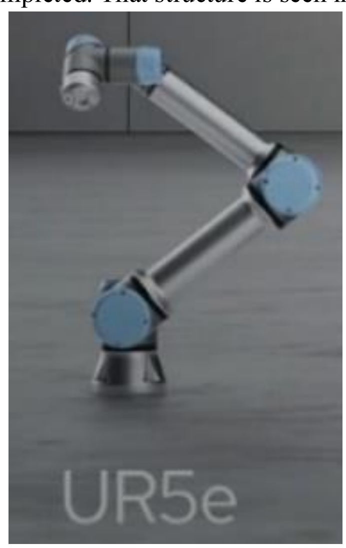

FIGURE 10: UNIVERSAL ROBOT 5E (UR5E)

morphological matrix for function to component using a reference point of this analysis as the Universal Robot 5e (UR5e).

The morphological matrix is as follows for clarity input and output types have been mapped together as part of the matrix. Note in the case of the material chain there are no standard components for the import and export of the task materials since these are application specific. Additionally, some functions while necessary to complete the function structure diagram by showing the flow of certain inputs and outputs but are not functions achieved by active components such as exporting thermal energy. In that case these functions have been excluded.

Morphological Matrix of a Cobot	
Function	**Component(s)**
Signal	
Import Commands	Onboard Computer (Generally Using Linux)
Transform Commands to Electrical Input	Motor Controller Board
Export Feedback	-Commutation -Hall Effect -Force Torque Sensors
Energy	
Import Electrical Energy	Power Supply Unit
Convert Electrical Energy to Mechanical Energy	Frameless Motor
Convert Mechanical Energy to Rotation of Cobot	-Gearbox -Linkages Structure
Material	
Import materials for tasks	Software Suite
General	
Transform materials with rotation of cobot	-Software Suite -End Effector -Safety Suite -Brake

TABLE 2: MORPHOLOGICAL MATRIX

What becomes exceedingly apparent is that certain complex functions require several components to be achieved. This is markedly different then the system having redundancies. Rather it is indicative that several of these functions could have their own entire function structure diagram for more granularity.

AXIOMATIC DESIGN ANALYSIS

Like the guiding principle for developing the morphological matrix, the focus of the axiomatic design analysis will be on the Universal Robotics cobot line. Given their market dominance and as prior shown their general components match that of other cobot, the universal robotics product line is excellent as a general example to be used for Axiomatic analysis.

Axiomatic design is a process by which the various domains of a product are mapped together. The domains focused on so far are the Customer Needs, the Functional Requirements, and the Physical Domains (components). For the functional requirements the concept of hierarchies breaks down what was prior alluded that certain functional requirements can or have to be broken down into sub-functions. Axiomatic Design also maintains two guiding principles, the Independence Axiom which emphasizes maintaining the independence of functional requirements and the Information Axiom which seeks to minimize the complexity of design up to the highest probability of success. The final aspect is the concept of "zigzagging" which describes how a designer can map between a series of Physical Domains to lower-level functional domains and descent the hierarchy [20].

Cascading domain mapping is a valuable tool for systematically linking customer needs to functional requirements and then to the components that fulfill those requirements. This process promotes a holistic view of the design, identifying dependencies and interactions between domains. It is especially useful for uncovering overlooked design challenges and optimizing the integration of multidisciplinary elements. By organizing solutions hierarchically, cascading domain mapping also aids in prioritizing critical design areas and aligning them with project goals. Ultimately, this method enhances traceability, reducing the risk of misaligned or incomplete designs [20].

The goal of this section is to analyze the modern design of a cobot from an axiomatic perspective. The prior section of functional modeling showed what the current state of cobots are and how those physical domains are currently matched to functions. Using hierarchies of axiomatic design and the design matrices will provide a means to analyze these developed design choices. Finally, this will allow for an analysis of how a customized product family of cobots such has the Universal Robotics line is developed.

CUSTOMER NEEDS MAPPING

To accomplish this first customer needs can be mapped to the functional domains to show that the selected functional domains at the top levels satisfy the customer needs, thereby justifying the functional domains.

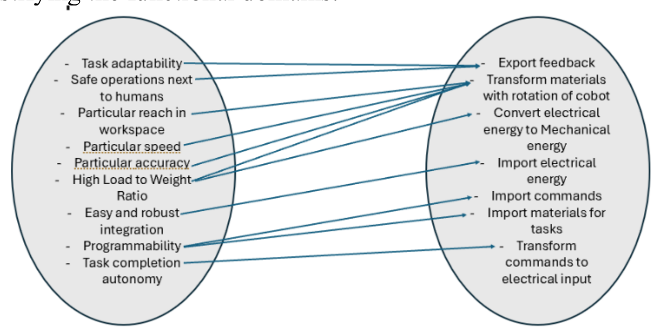

FIGURE 11: CROSS DOMAIN MAPPING OF CUSTOMER NEEDS TO FUNCTIONAL REQUIREMENTS

Given the generalized and complex nature of a cobots design as seen in the function structure diagram what is seen is that certain customer needs are satisfied by only one high level function. Juxtaposing this are more complex customer needs which require multiple functional requirements to be able to complete. This linking of multiple customer needs to a particular functional requirement alludes to customizability which will be explored later.

The next step is to identify which functional requirements have a innate hierarchy to them. Based on how the mapping of the customer needs to functional requirements has been done that can be called functional requirements which address multiple customer needs at once. These functional requirements are more complex and have several internal functions that get executed with several physical domains.

Hence the functional requirements with an analyzable hierarchical structure will be “Export Feedback [FR1] and Transform materials with Rotation of Cobot [FR2]”. FR1 satisfies the customer needs of task adaptability and safe operations next to humans. While FR2 the broader more complex task satisfies the customer needs of a particular reach in workspace, a particular speed, a particular accuracy, and with a particular payload capacity. Most interestingly these four aspects combined with the needs of task adaptability and safe operations with humans are really what separate industrial robots from cobots. In particular the four needs satisfied by FR2 are the critical factors that govern the customizability of a cobot product line.

FR1 HIERARCHICAL ANALYSIS

Looking at the functional requirement of export feedback, this is related to an entire system wide set of feedback loops that govern successful operation. This can govern the expected feedback loops for motors and continue to all parts of the system such as the force-torque sensor mounted at the end-effector. Together all the sub functionality requirements should satisfy the two stated customer needs of task adaptability and safe operations next to humans. The hierarchical breakdown is as below:

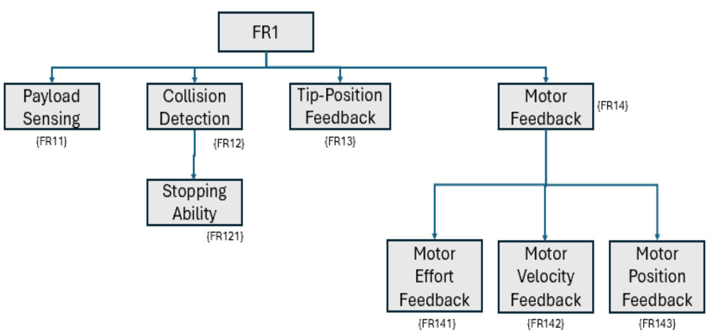

FIGURE 12: FR1 FUNCTIONAL DOMAIN

As seen FR1 breaks down into four additional functional requirements. Where the most complex of the four FR14 the Motor Feedback breaks down into three additional functional requirements. These are the minimum aspect to address motor feedback for any kind of control. They are velocity, effort (torque), and position. For the overall functional requirement now, this can be mapped to respective physical domains to complete the “zigzagging” that is typical of axiomatic analysis.

In this case the top-level physical domain {DR1} is to be considered the sensor suite. From here the subsequent DR hierarchy is as follows:

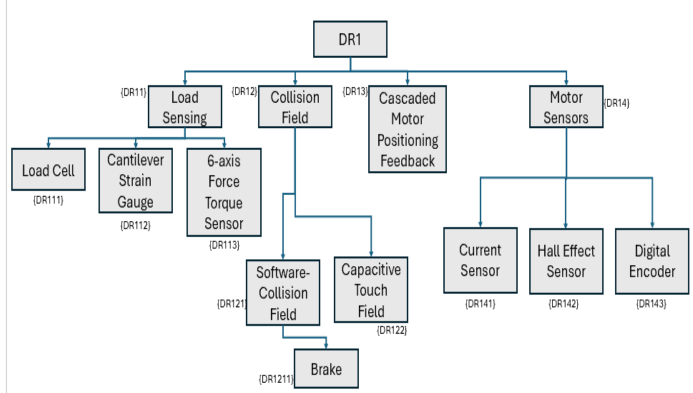

FIGURE 13: DR1 PHYSICAL DOMAIN

As expected, this domain mapping presents several physical domain options to achieve the same requirements. In particular, this makes sense for DR11 and DR12. For DR13 and DR14 the physical methods listed are considered the standard way this data is collected. For example, the sub physical domains in DR14 all come standard in advanced robotic motor controllers [21].

Having completed the Functional Domain and the Physical Domain these two can then be linked together to show how they are related. This is seen below in the expanded diagram:

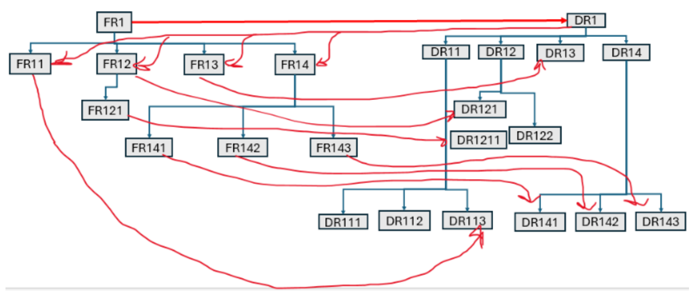

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FIGURE 14: AXIOMATIC RELATION OF FR1 TO DR1

FR2 HIERARCHICAL ANALYSIS

Similarly looking at FR2, Transform Materials with Rotation of Cobot, this process of developing the functional domain and the physical domain can be completed as follows:

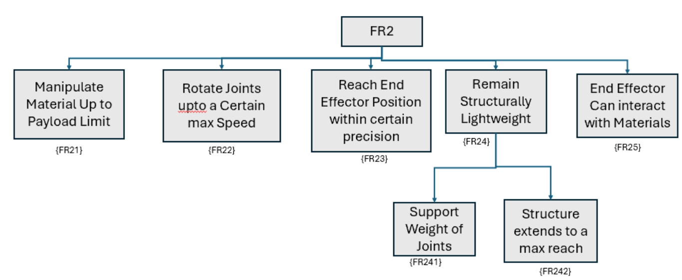

FIGURE 15: FR2 FUNCTIONAL DOMAIN

Continuing onwards with the FR2 Functional domain developed containing 5 sub-functional domains, the physical domain can be completed and then they can be linked.

The physical domain DR2 which at the top level can be described as “coordinated joint rotation” is as follows:

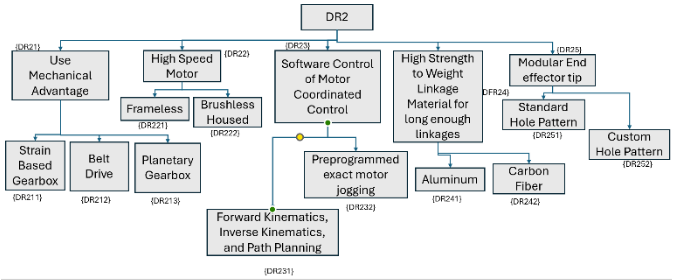

FIGURE 15: DR2 PHYSICAL DOMAIN

What is critical to note is that since FR2 is much more complex than FR1 a lot more design options are seen in its various portions of its physical domains. Additionally, FR2 inherently has more subfunctions than FR1 which increases what DR2 has to cover. Finally, the last portion of analysis is to “zigzag” through the functional domains and the physical domains.
This analysis is presented as below:

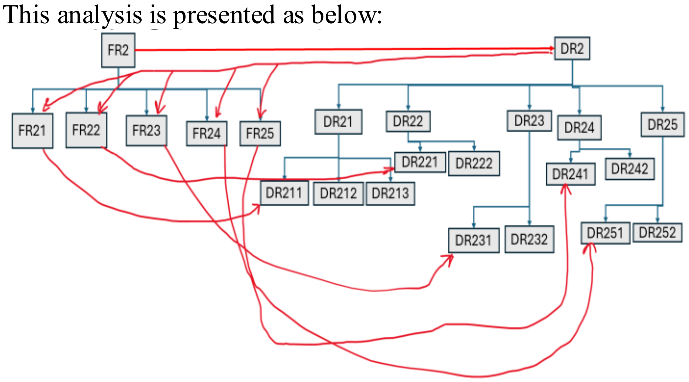

FIGURE 16: AXIOMATIC RELATION OF FR1 TO DR1

As seen above this analysis results in a clean mapping from the functional requirements to their respective physical domain solutions. Whats required for each now is a break rationale as for why these components are preferred based on a basic mechanical engineering context. For the gearbox a strain based gearbox is able to provide the lowest backlash, in the smallest form factor, with the highest ratios hence it is the preferred design choice as seen by many cobot companies. For motor selection frameless motors allow for better slimmer integration into joint assemblies and provide a high rpm. Given that cobots need to be adaptable and more intelligent than a industrial robot, cobots have to leverage complex numerical and analytical solving methods to determine for what joint angles will the end effector reach a desired position. This process is part of kinematic analysis and is the defacto method for motion planning rather than manual jogging. While carbon fiber does have a better strength to weight ratio, it falters greatly in the process domain as a harder design choice to maintain for customized versions rather than standard aluminum linkages which can grow and shrink while still meeting their requirements with minimal design changes. For the end effector as prior mentioned maintaining a standard ISO hole pattern allows for cobots to leverage existing end effector markets and thus be more attractive to customers looking to builder their own unique solutions.

With the complex mapping completed finally putting together the cascaded domain analysis is possible to ensure clarity all customer needs (CNs), functional requirements (FRs), and physical domains (DRs) will be labeled as such. Table A through Table C in the appendix defines these parameters. With all the components in down to the lowest levels and all the relevant mapping completed below is the cascaded domain mapping.

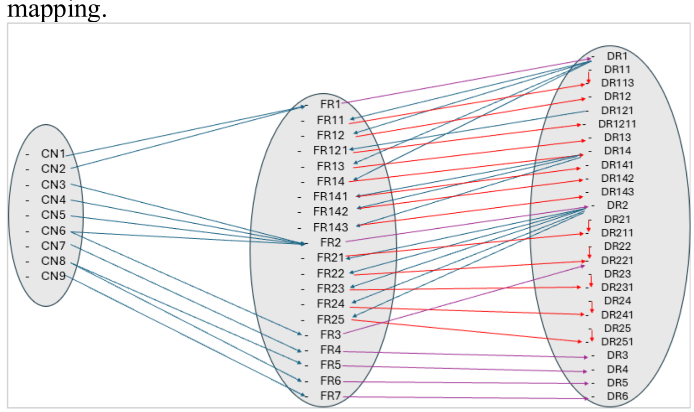

FIGURE 17: CASCADED DOMAIN MAPPING

Finally with the cascaded domain mapping completed showing how the customer requirements are satisfied by physical components the design can be assessed. Where now using the independence axiom and constructing the matrix the final design can be evaluated. Note to do so only the lowest level functions and the final physical components will be assessed. Below are the FRs to be assessed against the respective DRs.

$$FRs = \begin{matrix} \mathrm{FR11} \\ \mathrm{FR12} \\ \mathrm{FR121} \\ \mathrm{FR141} \\ \mathrm{FR142} \\ \mathrm{FR143} \\ \mathrm{FR21} \\ \mathrm{FR22} \\ \mathrm{FR23} \\ \mathrm{FR24} \\ \mathrm{FR25} \\ \mathrm{FR3} \\ \mathrm{FR4} \\ \mathrm{FR5} \\ \mathrm{FR6} \\ \mathrm{FR7} \end{matrix}$$

Next is to note the DRs that these match to and show in the matrix form that independence is almost maintained.

$$\begin{Bmatrix} \mathrm{FR11} \\ \mathrm{FR12} \\ \mathrm{FR121} \\ \mathrm{FR141} \\ \mathrm{FR142} \\ \mathrm{FR143} \\ \mathrm{FR21} \\ \mathrm{FR22} \\ \mathrm{FR23} \\ \mathrm{FR24} \\ \mathrm{FR25} \\ \mathrm{FR3} \\ \mathrm{FR4} \\ \mathrm{FR5} \\ \mathrm{FR6} \\ \mathrm{FR7} \end{Bmatrix} = \begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1 \end{bmatrix} \begin{Bmatrix} \mathrm{DR113} \\ \mathrm{DR121} \\ \mathrm{DR1211} \\ \mathrm{DR141} \\ \mathrm{DR142} \\ \mathrm{DR143} \\ \mathrm{DR211} \\ \mathrm{DR221} \\ \mathrm{DR231} \\ \mathrm{DR241} \\ \mathrm{DR251} \\ \mathrm{DR3} \\ \mathrm{DR4} \\ \mathrm{DR5} \\ \mathrm{DR6} \end{Bmatrix}$$

The only redundancy comes from FR3 which also requires the frameless motor since that is the component responsible for the conversion of electrical energy to mechanical energy as well.

Overall, really this shows that also when evaluated from an axiomatic perspective the overall design of the UR cobot is quite well done through the numerous years of iteration.

DISCUSSION OF CUSTOMIZATION OF PRODUCT LINE

After having gone fully through the design of a cobot both from a functional basis and an axiomatic basis it becomes possible to truly understand the components that are required for a sort of customizability. Additionally, now looking at the various specifications for each cobot from the UR3e to the UR20 it is now gleanable how the product family was constructed.

This can start off with what components can remain the same of the ones discussed and inputted into the matrix. These are the motor controllers, the software suite, the brakes (note these would be matched to the particular motor they need to brake), the force torque sensor, standard hole pattern, the hall effect, encoder, current sensors, and kinematic motion algorithms. These do not affect the top level customer needs that are variable of particular speeds, reaches, or payloads. Which are the main needs that require specific component changes.

Rather the 3 components that specifically are governed by the variable customer needs and thus form the basis of the product family variation are the strain-based gearbox, frameless motor, and aluminum linkage structure. One side is that the brake must be sized relative to the motor and for a motor power hungry arm a stronger psu must be used. This take away can be easily proven by just comparing 2 cobots in the product family the UR10e and the UR16e. The main difference between the two in this case is the aluminum structure otherwise the joint data remains constant for both arms. What changes is that since the length of the arm, hence its over all lever is decreased for the UR16e it has a higher payload capacity than the UR10e [19]. This is an excellent example of creating a intelligent product line. As expected, then other similar patterns do emerge upon inspection which indicate how Universal Robotics was able to leverage a set of matching gearboxes, motors, and linkages to create a product family that is able to satisfy many customers and variable needs. All while not dramatically increasing their overall costs.

FUTURE WORK ON THIS TOPIC

What comes next is to do a deep dive with the information axiom which was left untouched and use that to conduct a full customization analysis. In an idea case survey data of real customers can help create a bell curve indicating what is the overall demand of each cobot type. From there the various lines could be evaluated to see which has delivered the best return on investment for Universal Robotics. Similarly, this entire analysis could be conducted on industrial robotics which while have a similar form have vastly different internal components. It would be interesting to see if in that kind of product line a similar product family has been developed in a similar way.

CONCLUSION

In conclusion, this design analysis leverages two critical tools to explore the development of modern cobots functional modeling and axiomatic design analysis. It starts by covering the history of cobots and robotic manipulators leading up to the Universal Robotics 5e the first cobot ever sold. The first goal was to create the functional model of a general modern cobot and then using a survey of major cobot manufacturers and their current components fill in the morphological matrix. This provided a road map for qualifying the Universal Robotics cobot line as usable as an example case. From here it this analysis highlights how Universal Robotics effectively employs axiomatic design principles to create a customizable and efficient cobot product line. The overall analysis starts by mapping customer needs to functional requirements and then physical domains. These same customer needs are what serve as the basis for the functional modeling as well. Similarly, this functional modeling helps guide the hierarchical functional requirements of the axiomatic design. What is show is the critical role of hierarchical design, independence, and minimized complexity in achieving robust and adaptable systems. The mapping also reveals key components—strain-based gearboxes, frameless motors, and aluminum linkages—that enable customization to address varying customer requirements. The evaluation underscores the iterative refinement of design choices which have naturally arrived at a refined point. Future work could expand this analysis to industrial robots and incorporate customer feedback for deeper insights into product line optimization. Essentially, the key takeaways have been to provide a deep dive into the design fundamentals of cobots at a level not previously gone. While also applying techniques learned in ME6101 to provide analysis and context. It is through axiomatic analysis and the independent axiom that the critical components were justified as the critical components for customization.

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APPENDIX:

Surveyed Customer Needs	Label (CN#)
Task Adaptability	CN1
Safe Operations Next to Humans	CN2
Particular Reach in Workspace	CN3
Particular Speed	CN4

Particular Accuracy	CN5
High Load to Weight Ratio	CN6
Easy and Robust Integration	CN7
Programmability	CN8
Task Completion Autonomy	CN9

TABLE A: CUSTOMER NEEDS

Functional Requirements	Label (FR#)
Export Feedback	FR1
Payload Sensing	FR11
Collision Detection	FR12
Stopping Ability	FR121
Tip-Position Feedback	FR13
Motor Feedback	FR14
Motor Effort Feedback	FR141
Motor Velocity Feedback	FR142
Motor Position Feedback	FR143
Transform Materials with Rotation of Cobot	FR2
Manipulate Material upto Payload Limit	FR21
Rotate Joints upto a Certain Max Speed	FR22
Reach End effector Position within Certain precision	FR23
Remain Structurally Lightweight	FR24
End effector can interact with Materials	FR25
Convert electrical energy to Mechanical energy	FR3
Import electrical energy	FR4
Import commands	FR5
Import materials for task	FR6
Transform commands to electrical input	FR7

TABLE B: FUNCTIONAL REQUIREMENTS

Physical Domains	Label (CN#)
Sensor Suite	DR1
Load Sensing	DR11
6-axis Force Torque Sensor	DR113
Collision Field	DR12
Software Collision Field	DR121
Brake	DR1211
Cascaded Motor Positioning Feedback	DR13
Motor Sensors	DR14
Current Sensor	DR141
Hall Effect Sensor	DR142
Digital Encoder	DR143
Coordinated Joint Rotation	DR2
Use Mechanical Advantage	DR21
Strain Based Gearbox	DR211
High Speed Motor	DR22
Frameless Motor	DR221
Software Control of Motor Coordinated Control	DR23
Forward Kinematics, Inverse Kinematics, and Path Planning	DR231
High Strength to Weight Linkage Material for Long Enough Linkages	DR24
Aluminum	DR241
Modular End Effector Tip	DR25
Standard Hole Pattern	DR251
Power Supply Unit	DR3
On-board Computer	DR4
Software Suite	DR5
Motor Controller	DR6

TABLE C: PHYSICAL DOMAINS