The Axiomatic Design of The Walker.

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Ezra Bailey-Kelly[2], *Hilmar Þór* Pétursson[1], *Kjartan Bjarmi* Árnason[1], and *Kristian Sande* Sjølyst[3]

[1] *Reykjavik University, Menntavegur 1, Reykjavik 101, Iceland*
[2] *University of Nebraska-Lincoln, 1400 R St, Lincoln, NE 68588, United States*
[3] *University of Southeast Norway, avd Porsgrunn, Kjølnes Ring 56, 3918 Porsgrunn, Norway*

Abstract. Robotics as a field has been steadily growing worldwide for the past decades. With this growth, the demand for simplicity and modularity in robots has increased dramatically. Using the Axiomatic Design process, this paper aims to demonstrate the possibilities of increased modularity through the use of wirelessly connected parts. To demonstrate this a singularly modular robot called The Walker was designed. This design is compromised of several individual parts, each of which could be considered a robot in its own right. Each part was designed to carry its own power supply and microprocessor as well as the wireless transmission chip required to communicate with the other parts.

1 Introduction

The Walker was originally a hexapod that was redesigned to function solely on wireless communications between all of its six legs. The objective of this redesign was to have the possibility of attaching the legs to surfaces of reasonable size and weight, such as a common plate and transform it into a hexapod. The possibilities of truly wireless communications between different parts of a robot can be quite interesting. This connection can eliminate the risk of a malfunction in one part transmitting to others. It simplifies replacing parts considerably. In this particular case, it allows the attachment of robotic appendages to objects that were not designed for it. This project was designed and created during the twelve weeks of the class T-411-MECH at the University of Reykjavík.

1.1 Axiomatic design theory

When designing and creating The Walker. The theory of Axiomatic Design was used. The theory can be roughly broken down into the following two axioms.

Axiom 1 - Independence

- "Maintain the independence of the functional requirements"
- Enforce modularity

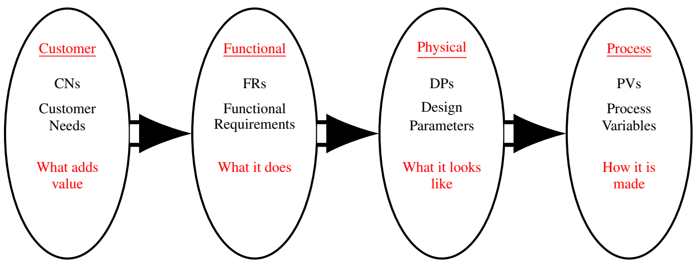
Axiom 2 - Information

- "Minimize the information content of the design"
- Pick the simplest, most reliable solution

Nomenclature:

CN Customer needs
FR Functional Requirement
DP Design Parameter
C Constraint

Using these axioms, the top-level customer needs (CN) were broken down into functional requirements (FR) and design parameters (DP). This process follows the Axiomatic Design domains that are visualized here below.



A great synopsis for this procedure was written in the paper The Axiomatic Design of Chessmate [1]:

> "Rather, the focus was placed on developing comprehensive FR and DP lists, then evaluating the coupling between them. This coupling is symbolized in a design matrix, which is a Cartesian product of all FR and DP combinations" [2, 3]. Where there is an interaction between an FR and DP, this is denoted by a non-zero coefficient, or in the case

of the value being unknown, simply a placeholder variable X. Minor levels of coupling, often considered higher-order effects, are annotated with x to show their lessened effect. A diagonal matrix is "uncoupled" and satisfies the Independence Axiom: "to maintain the independence of the functional requirements (FRs)" [4]. Such a design can be easily optimized by adjusting a particular 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 have a usable local solution but usually resist modification and optimization [4]. Needless to say, the focus is on minimizing coupling wherever it may appear.

1.2 Customer Needs

The target customer of this project is any individual or institution that has an interest in the modularity and creation of robotics. As this is a research project the top level customer needs are defined by the project team as such.

CN_0 A wirelessly connected walker system that can attach to any base of reasonable size and weight.

CN_1 The system needs to be capable of walking in relatively rough terrain without falling over.

CN_2 The system needs to be able to do so with bases of several different shapes.

2 Existing designs

Hexapod builds are fairly common builds among professionals and hobbyist alike. As a result of this, it was a simple matter to find and examine several builds. Most builds followed the same design patterns as can be observed in the Capers II build [5]. There were a few bulkier versions that appealed more for this project such as the Golem [6] Which can be observed in figure 1. There were however no builds found that corresponds completely with the idea behind The Walker.

What makes The Walker different from the Hexapod builds that were examined, is the modularity with which it was designed. The fact that each leg will be its own self contained module. It will be capable of attaching several legs to any base and make it a walking robot.

An example of a hexapod is in figure. 1.

3 Design

First and foremost in the design process at this stage was to identify the top-level functional requirements and design parameters that correspond with the customer needs.

Figure 1: The Golem[6]

When looking at CN_0 it becomes apparent that the top-level functional requirement FR_0 and design parameter DP_0 have to be the independence of each leg. And working from that hypothesis the rest of the functional requirements and design parameters were conceived.

FR_0 A robot made out of smaller synchronised leg modules

DP_0 A fully functional leg module.

When designing The Walker. it was decided to constrain the design to fit in with the robotics design competition that is held annually at the University of Iceland. The exact specification for this year's contest was unavailable at the time of design. As such the rules from the past years were examined and a list of constraints were created.

C_0 It needs to be able to move autonomously, without direct user input.

C_1 It can not weigh more than 15Kg

C_2 The final price must be under 60.000isk

Keeping these constraints in mind the first level FR-DP mapping was made. This map can be observed in table 1.

Table 1: First draft for the top level FR-DP mapping.

ID	Functional Requirement	ID	Design Parameter
FR_1	Each leg module must be able to think for itself	DP_1	Micro-controller in each module
FR_2	Each leg module must be able to move on its own	DP_2	Motors place in each module
FR_3	There must be constant communication between the legs modules	DP_3	Communication specific chip on each module
FR_4	Each leg must be able to draw power independently from the others	DP_4	Individual battery system placed in each module
FR_5	Must be able to keep balance in a rough and uneven terrain	DP_5	Pressure sensors on the bottom of each module
FR_6	Stability on surfaces with different friction coefficients	DP_6	A high friction tip, such as rubber. At the end of each module
FR_7	The ability to attach to different bases	DP_7	A clamping system at the end of each module
FR_8	Each leg must know where it is placed on the base	DP_8	A numerical system of placement with regards to the base. Programmable into each module.
FR_9	Adjustable for bases of different sizes and shapes	DP_9	Software must be written to adjust to several shapes and sizes of bases

From this mapping, a design matrix was developed as shown here below.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \\ FR_8 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X & X \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \\ DP_8 \end{Bmatrix}$$

This matrix is de-coupled and should be optimized better. Further improvements were planned to be done after experimenting with this design.

4 Experiments

With the first level mapping ready, the first design was created using Solidworks. The design was then printed using an Ultimaker 3D printer. The result from this first design can be observed in figure. 2.

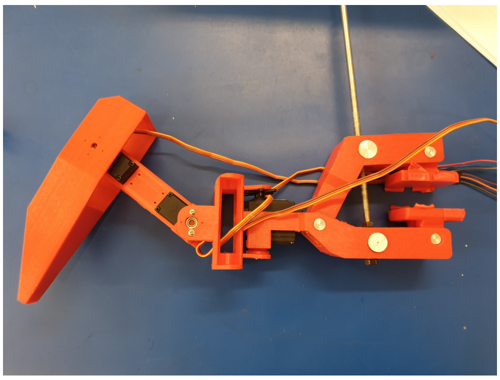


Figure 2: First design of a leg module

After the work had begun on designing the leg module. Things became clearer and many questions were answered. The leg module was created with three servos and two 18650 batteries attached to it. A screen was then added to it along with dip switches to simplify access to the software of the module.

It became apparent that for communication between modules it would be required to have a centralized server. The decision was taken that the leg module would have an ESP32 microcontroller because of the integrated Wi-Fi component. The ESP32 would then communicate with a BeagleBone Black that will act as the centralized server for The Walker. Realistically any Linux system can run the server as long as it is connected to the same Wi-Fi network as the ESP32s. The BeagleBone Black launches an access point allowing the design to be outside of an external Wi-Fi network. With this decided, the software side of the project was commenced in full force. A master-socketed server with port-forwarding was made to run on the BeagleBone Black that allows new connections to be established to the master-socket and forwards it to a new port and communicates to it there. This method proved to work exceptionally well and was expanded upon when the shipment of new servos arrived and new modules created.

After creating the module the first level mapping was revisited and it was realized that FR_1, FR_2, FR_3 & FR_4 were part of the same functional requirement. They all revolve around making each leg module an independent piece. Therefore they should all be a subcategory of the FR_1 Make each leg module independent and it's subsequent DP_1 No outgoing wires from the module. Following this train of thought, it became obvious that the Axiomatic Design would need to be revised. The functional domain was then revisited and expanded further. As can be observed in table 2.

Table 2: Revised Top level FR-DP mapping

ID	Functional Requirement	ID	Design Parameter
FR_1	Make each leg module independent	DP_1	No outgoing wires from the module
FR_2	The walker must be able to walk despite variances in terrain.	DP_2	Sensors and high friction tips on each leg.
FR_3	The walker must be compatible with different bases.	DP_3	Clamps to attach each module to a base and physical buttons to adjust the software.

Table 3: Second level FR-DP mapping

ID	Functional Requirement	ID	Design Parameter
$FR_{1.1}$	Microcontroller for each leg	$DP_{1.1}$	The ESP32 was chosen as the brain for each module since it also has integrated Wi-Fi.
$FR_{1.2}$	A centralised server for smoother communication	$DP_{1.2}$	Beaglebone black will act as the centralised server between each module
$FR_{1.3}$	Battery pack for each module	$DP_{1.3}$	Two 18650 batteries will be on each leg.
$FR_{2.1}$	Each module capable of moving itself	$DP_{2.1}$	Three LX-16A Metal Gear Servos placed in each module.
$FR_{2.2}$	Capable of walking in uneven terrain	$DP_{2.2}$	Pressure sensitive resistor placed at the bottom of each leg.
$FR_{2.3}$	Can walk on surfaces with different friction coefficients	$DP_{2.3}$	A high friction rubber tip will be placed at the bottom of each module.
$FR_{2.4}$	Capable of sensing holes or high drops	$DP_{2.4}$	The servos know their own positions and will retract if exceeding a threshold.
$FR_{2.5}$	Capability of sensing the speed by which each module moves	$DP_{2.5}$	An accelerator will be placed in each module.
$FR_{3.1}$	Attachment to bases of different sizes and shapes.	$DP_{3.1}$	A clamp attachment at the end of each module.
$FR_{3.2}$	Each module knows it's placement, and the shape of the base.	$DP_{3.2}$	The software is written to be easy to adjust for this.
$FR_{3.3}$	Simple to change the base and the placement of each module on it	$DP_{3.3}$	An Oled display on each module, accompanied by three pushbuttons for simple control of the software.

4.1 FR_1 Each module independent

The clear cut goal of making each leg as independent as possible fit into the tenant of axiom 1. And is crucial to achieving the designated DP_0. Second level decomposition of this functional requirement revealed an uncouple matrix and can, therefore, be said to be an optimized system.

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \end{Bmatrix}$$

4.2 FR_2 Capable of walking in different terrains

The capability of walking can be said to be the most important aspect of a robot called The Walker. But it was decided to place it second after the requirement of independence. This is due to the extreme importance placed on independence and modularity in this design. The deconstruction of FR_2 revealed a lot of the physical requirements of the system as can be observed in table 3. This deconstruction reviled a decoupled system with one dependency. It is, however, a non-consequential dependency and is, therefore, more effective to leave it as it is, rather than finding a convoluted solution.

$$\begin{Bmatrix} FR_{2.1} \\ FR_{2.2} \\ FR_{2.3} \\ FR_{2.4} \\ FR_{2.5} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{2.1} \\ DP_{2.2} \\ DP_{2.3} \\ DP_{2.4} \\ DP_{2.5} \end{Bmatrix}$$

4.3 FR_3 Compatible with different bases

Functional requirement three is perhaps the most difficult to achieve. This is due to the large array of different shapes and sizes that bases can take. Attuning the software to all possibilities is almost impossible, but an effort is made to be able to attach to all the most common shapes and sizes. The deconstruction of FR_3 revealed a decoupled system. This is due to $DP_{3.3}$ being directly connected to $DP_{3.2}$. This is however believed to be optimized to its fullest capabilities.

$$\begin{Bmatrix} FR_{3.1} \\ FR_{3.2} \\ FR_{3.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & X \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{3.1} \\ DP_{3.2} \\ DP_{3.3} \end{Bmatrix}$$

5 Conclusion

The design of the leg module went through several phases and change quite considerably from its original version seen in figure 2. These changes included a simplified clamping system, a completely different tibia, and femur as well as a completely revamped centralized housing for the batteries and microcontroller. These changes resulted in a more compact and visually pleasing design as can be observed in figures 3 - 5. With this design, the FR_0 was met in its entirety and can there

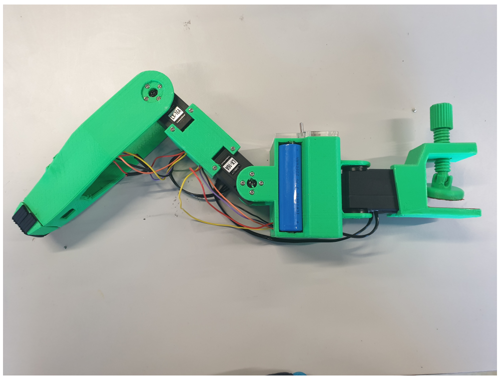


Figure 3: The finalised design

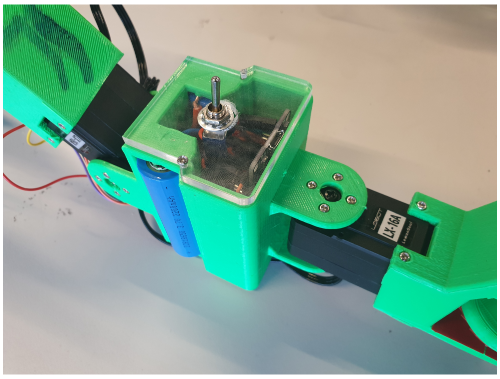


Figure 4: Finalised center housing

Figure 5: The Walker, Version 1

Overall the design and execution worked as a proof of concept for the wireless module design and fulfilled FR_0. There were however some problems with the functionality of the modules as a hexapod and as such FR_1 and FR_2 were not adequately fulfilled. The biggest culprit for these errors was the time constraint surround the 3D printing of the modules. Do this constraint the research team was unable to effectively program a fully functional walking gait. The time constraint also led to a problem regarding the battery holders, where a small impact on the legs resulted in a quick disconnection of the module. The servos are also proving to be on the worse side of things, getting consistent results on them seems to be almost impossible. Whether there are any problems with the server code or the code on the ESP32 excluding the walking gait remains unknown since testing out all the kinks is impossible until we get a rudimentary walking capability working.

5.1 Future work

The team has assembled a list of future improvements that would be optimal to create a fully functional walking system.

- Create a more secure Battery pack.
- Better walking gaits.
- Attach more professional motors
- Integrate more sensors.
- Compliant joints.
- Self screwing clamp system.
- Accelerometer on each leg.

5.2 Summary

The project was a success as a proof of concept for the possibility of wirelessly connected modules. The design of the Walker met all of the requirements from FR_1 There were however several problems from FR_2 & FR_3 but they mostly stemmed from the teams' inexperience with hexapod design and execution. Further work will be made on this project in the coming weeks and hopefully, The Walker will be fully functional.

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