

ITERATIVE CREATURES

AWROM

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DIGITAL FUTURES
2026

Iterative Creatures

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A thesis exhibition presented to OCAD University in partial fulfillment of the requirements for the degree of Master of Fine Arts in Digital Futures

OCADU Waterfront Campus, March 26th – 30th

Toronto, Ontario, Canada, 2026

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Acknowledgement

I would like to thank my primary advisor, Nick Puckett, for his support, encouragement, and trust throughout this process — it has gone a long way.

I would also like to thank my secondary advisor, Immony Mèn, for his support and wisdom in writing

I am grateful to Digital Futures Graduate Study Director Simone Jones for fostering a productive and supportive environment in which to grow as a researcher.

To my cohort, you have been the best I could have ever asked for. Thank you for the collaboration and the collision of ideas.

Finally, I want to thank my parents for their unconditional support and the faith they have always had in me.

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Abstract

Iterative Creatures is a research design project that includes robots in their own development process to mitigate designer intentionality. AWORM is a standardized microcontroller driving two servo motors and a modular architecture of 3d printed components with the capacity to upgrade and expand over time.

This thesis investigates how human designers can create non-human-centric robot behavior by granting robots agency. AWORM and ABOT are two robots developed within this premise as research instruments. Their behavior is governed by both physical and computational constraints that require active maintenance and upgrades from the designer and themselves, enabling them to operate as self-directed robots with different abilities and personalities.

Iterative Creatures demonstrates how designer intentionality can be mitigated by collaborating with robot agency by including robots in their own design process.

Key words: artificial life, autonomous, non-human, behavior, robot-in-loop

Chapter 1: Introduction



Figure 1 AWORM

1.1 Context

The term Artificial Life was first coined by Christopher Langton. It's a study of natural life through simulated systems with the use of computer simulation, robotics and biochemistry (Langton, 2000). Bedau further defined Artificial Life into three subcategories: Hardware Artificial Life (Hard A-Life), using robotics to approach A-Life in physical space; Software Artificial Life (Soft A-Life), using computer simulation to simulate life digitally; Wetware Artificial Life (Wet A-Life), using synthetic artificial cell out of biochemistry (Bedau, 2003). *Iterative Creatures* approaches A-Life through the Hard A-Life approach, utilizing physical robotics projects as research instruments.

Iterative Creatures is a research project involving the creation of prototype robots under the Hard A-Life field. It explores the designer-robot dynamics, how designer intentionality affects the robot and how to minimize human intervention in the design process. With *Iterative Creatures*, this research attempts to enable robots to iterate speculatively by mitigating designer intention, allowing the robot to iterate outside of the conventional Hard A-Life research.

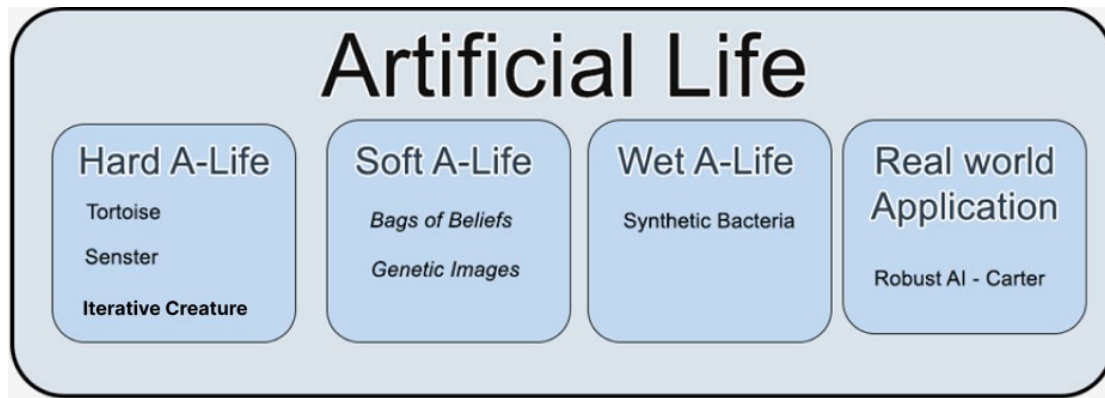


Figure 2 Types of Artificial Life and Where Iterative Creatures Sits

At the core of this research are two robotics projects - ABOT and AWORM. They are designed as research instruments to investigate the research questions. The development of the prototypes is a laddering process. It started with ABOT's investigation of robots with their own, non-human concerns, inquiring what a robot with no human intervention would be, laddering to AWORM's investigation on the mitigation of designer intentionality in a robot's development process by enabling robot agency through the inclusion of the robot in its own design process.

This thesis contributes to the discourse of Hard A-Life and the Iterative Design process; this thesis provides a case study for Hard A-Life and proposes a method to design Hard A-Life iteratively. It follows the core principles of iterative design while using contemporary digital fabrication technology as the intermediate layer to grant the robot agency in its own development process.

This thesis also proposes Iterative Creatures, an open platform for creating Hard A-Life by working with the robots in the design process, it starts with a vague goal, as the robot iterates, needs for upgrade will be observed by the human designer. Who will work with the robot to evolve its physical construction and software program.

1.2 Research Questions

Primary Question

What role does human intentionality play in the design of a non-human centric robot and how can the relationship between a designer and robot be mitigated in the design process?

Secondary Question

What role does a designer play in the iterative design process of a robot that is granted

agency in its own development process?

Chapter 2: Contextual Review

The robotics prototypes *Iterative Creatures* create fall under the category of Hard A-Life which often takes the form of establishing a goal, break it down to requirements.

Constructing a robot fulfilling such requirements and iterating based on the observation and result. This process allows precise control of the robot's structure, only install necessary components onto the robot.

This chapter will examine relevant research projects, including William Grey Walter's *Tortoise* and his Purposefulness, Independence and Spontaneity model, Valentino Braitenberg's book and the Uphill Analysis (Braitenberg, 1986), and Rodney Brooks' world model and subsumption architecture. By the end of the chapter, a gap and a method on how to close the gap is proposed.

2.1 Foundation of Artificial Life

Christopher Langton organized the first "Workshop on the Synthesis and Simulation of Living Systems" (Langton, 2000), later known as Artificial Life. It is a study of potential life forms, started as a research instrument to research natural life, the life as we know on Earth, later developed into a study of simulated life, by hardware or software.

Langton defines it in a memorable way: "The stuff of life is not stuff"(Langton, 2000). He claims life and artificial life is not about matters, it's how matters are organized:

"Artificial Life is the study of man-made systems that exhibit behaviors characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis of living organisms by attempting to synthesize life-like behaviors within computers and other artificial media. By extending the empirical foundation upon which biology is based beyond the carbon-chain life that has evolved on Earth, Artificial Life can contribute to theoretical biology by locating life-as-we-know-it within the larger picture of life-as-it-could-be. (Langton, 1989, p. 1)

Bedau further defined Artificial Life by framing it with three distinct approaches: Software, Hardware and Wetware Artificial Life. Soft A-life creates simulations in purely digital construction, Hard A-Life produce hardware implementation in physical world and Wet A-life synthesizes living systems out of biochemical substances.(Bedau, 2003) The Hardware implementation is where *Iterative Creatures* sits in the spectrum, it uses physical hardware robots to investigate questions.

Iterative Creatures is a robotics project, focusing on making an embodied physical machine in the physical spaces. With the use of the Hard A-Life approach and some Soft A-Life methods, Iterative Creatures can build upon previous research and groundwork while providing new insights.

2.2 Physicality, Simplicity and Embodiment of Hard A-Life

Hard A-Life presents unique opportunities and challenges, especially when the robot physically exists in the material world. The physical nature of Hard A-Life both forces acknowledgment of embodied robot and requires careful construction. The following projects examined the hardware limitations and explored the physical world of embodied artificial life.

2.2.1 Where Hard A-Life Started

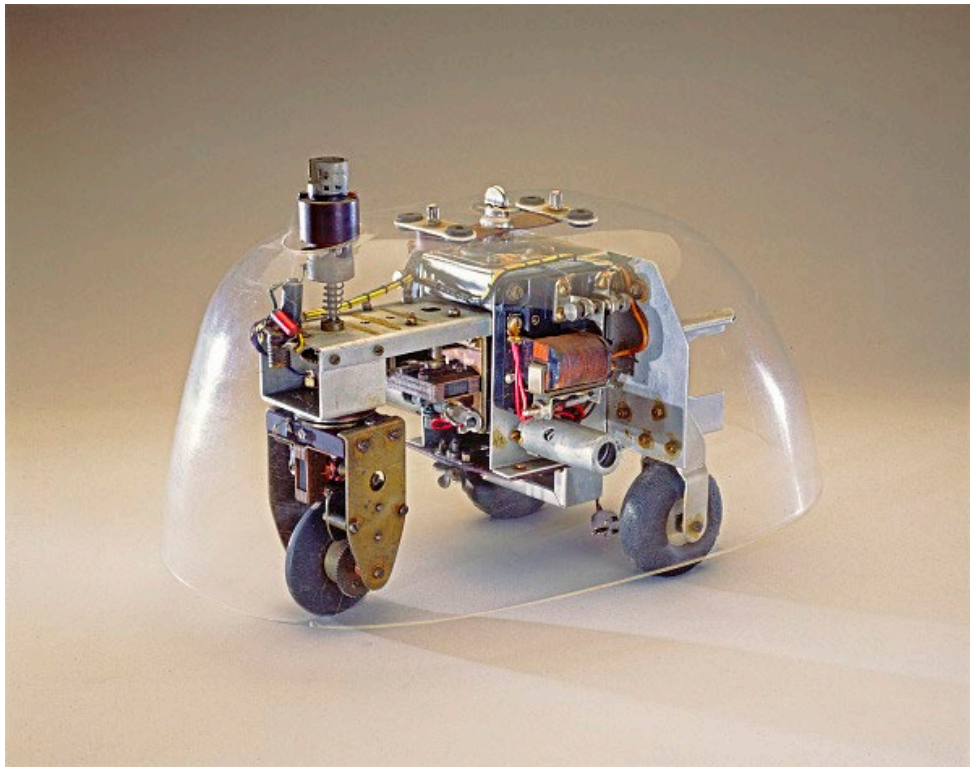


Figure 3 Tortoise -William Grey Walter

William Grey Walter pioneered the autonomous robot field and investigation on life imitation with his article *An Imitation of Life*. He introduced the robotics project *Tortoise*. A robotics project using a rotating photoelectric cell as the machine's eye and an external contact switch as the touch sensor, *Tortoise* can autonomously avoid obstacles, follow the light and find the charging station when power is low. Walter demonstrated even simple rules can develop complex and purposeful behavior once it is in a physical space.

William Grey Walter concludes the structure of hardware simulation: "These machines are perhaps the simplest that can be said to resemble animals. Crude though they are, they give an eerie impression of purposefulness, independence and spontaneity"(Walter, 1950). The three properties William Grey Walter considers as the property of life - purposefulness, independence and spontaneity.

The physicality of Tortoises allowed them to navigate the space and hold an immediate relationship with the viewer, although *Tortoises* is not aware of human audiences, it would acknowledge their existence when encountered, it will steer away from the audiences, treating them as obstacles. This relationship with the audiences, or humans in general can also be found in *Iterative Creatures*. The two prototype robots are designed to be non-human-centric by not programming any human specific code, but they still acknowledge the presence of humans by treating them as surroundings or obstacles. *Iterative Creatures* follows the exact three principles initiated by Walter: Purposefulness, Independence and Spontaneity.

2.2.2 Simple Machines Present Complex Behaviors

Valentino Braitenberg systematically examined the idea of simple machines that can present complex behaviors, one of the foundational concepts for *Iterative Creatures*.

In his seminal book *Vehicles: Experiments in Synthetic Psychology*, he built a series of imaginary simple robotics systems with sensors, thresholds and motors that have the potential to present complex behavior, and he proposed two concepts, the uphill analysis and the downhill synthesis (Braitenberg, 1986). Downhill synthesis refers to the ease of creating simple machines that act in a certain way, and the uphill analysis is when one from the outside trying to understand a machine's internal construction by analyzing its behaviors, that often presents challenges and the risk of overestimating complexity.

One of the book's early vehicles (or robots) he examined are vehicle 2.a and 2.b illustrated in Figure 4, 2.a is a negative phototaxis vehicle that steers away from lights by

linking two sensors to two motors without crossing the connection. So whichever side senses the light will start to accelerate, eventually steering the robot away from the light. Vehicle 2.b is the opposite, by inverting the connections of Vehicle 2.a, now when the left sensor senses light, it will cause the right motor to accelerate, leading to the robot steering towards the light source. This is called phototaxis, often found in insects to either go towards the light such as moths or mosquitoes or cockroaches running away from light.

By examining Vehicle 2.a and 2.b, it becomes evident that simple machines with only two connections can present complex behaviors. Later, Valentino Bratienberg adds more sensors and components, creating theoretical machines with memories and inclinations.

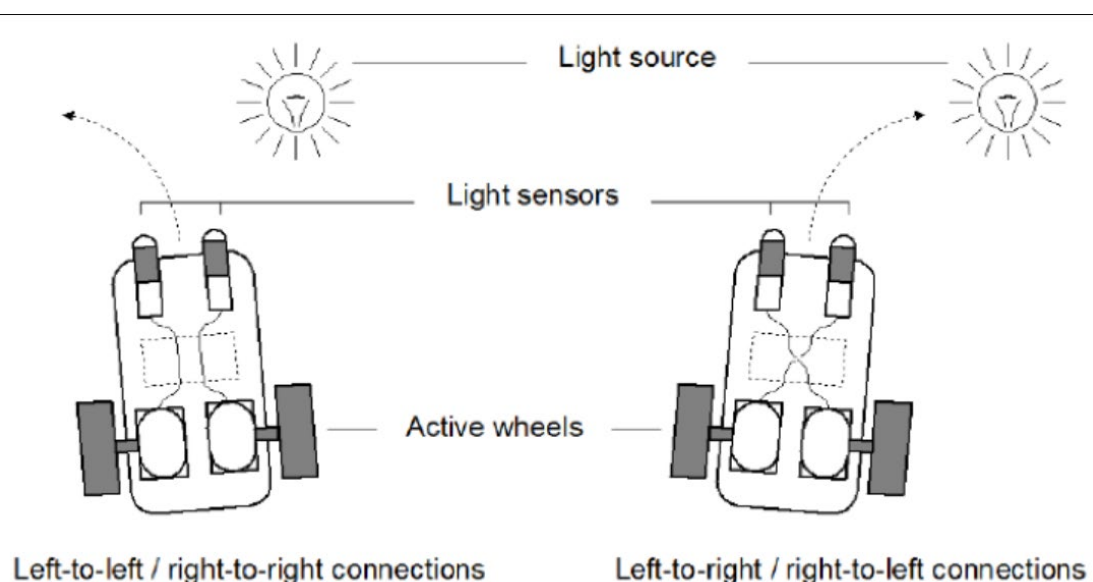


Figure 4 Vehicle 2.a and 2.b

Note. From *Synthetic psychology — the mission to understand behavior through robotics* by Shuhan He, 2019, *The Robot Report* (<https://www.therobotreport.com/synthetic-psychology-understanding-human-behavior-through-robotics>)

The Uphill Analysis Phenomenon is present in both Iterative Creatures projects, by encapsulating the interior, they can present complex behaviors, while internally the system is driven by simple local rules, AWORM uses this phenomenon intentionally and extensively by building a fully encapsulated and being battery powered.

This phenomenon also reveals the first finding of Iterative Creatures, that humans cannot be taken out of the equation completely, instead of removing humans, *Iterative Creatures* mediates it with robot agency, enables it to advocate for itself during the design process.

2.2.3 Embodiment and Subsumption Architecture

“The world is its own best model” founder of iRobot and Roomba Rodney Brooks claims a few different things in his writings, to start, he suggests the bottom-up structure and practices it in his own robotics project Genghis, a six legged insect-like robot that does not have a central “brain”, all six legs are running under their own local rules, and once they work together there's the illusion of Genghis walking, but really is just 6 separate legs doing their own movement without the knowledge of others.

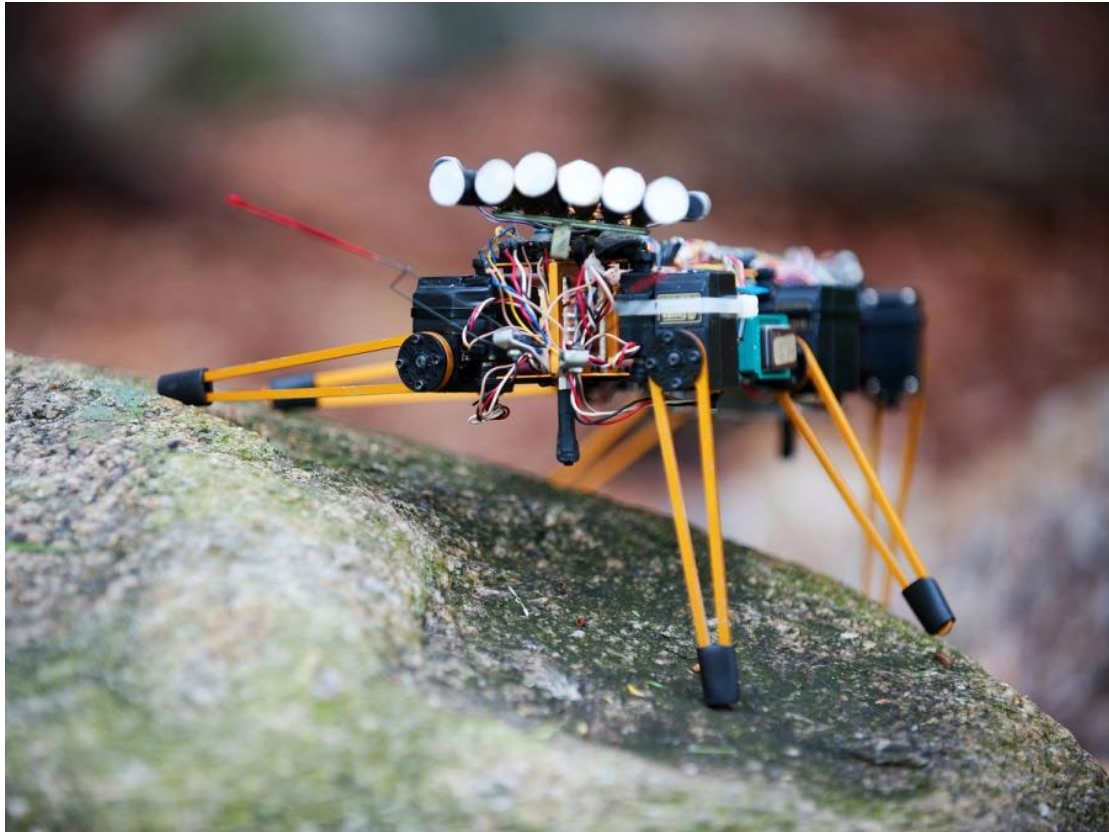


Figure 5 Genghis hexapod robot.

Note. From Genghis, by RobotsGuide (n.d.), <https://robotsguide.com/robots/genghis>

Rodney Brooks calls it the subsumption architecture, a structure that allows parallel, layered robotics system, it is a critical structure for Hard A-Life systems, where component can physically break down, the robustness will keep the robot intact. This is helpful to AWORM or any robot to stay operational, which contributes to the overall robot independence.

Rodney Brooks' other claim is the best place to practice Hard A-Life is the physical world, that the Hard A-Life needs to be situated in the physical space to be effective. Embodiments of the robot are supported by the subsumption architecture's robustness. Combining both claims together, “The world is its own best model”, points out the

classic AI/robot architecture's dependency on complex internal map, Brooks suggests there's no representation needed if the robot is embodied.

AWORM, as a physical robot, it fully embraces the subsumption architecture by design, both software and hardware wise, nothing is technically required to run AWORM, missing parts won't stop AWORM from operation, it will just operate in a different way. The subsumption structure's robustness also allows Iterative Creatures to be more independent from humans.

Conclusion: The Gap

While Hard A-Life researchers do iterate robots, those researchers examined in this chapter show less intention to include the robot in the loop. Researchers review robots' performance, behavior and make adjustments to iterate those robots, Rodney Brooks had 4 prototypes for his MIT Artificial Intelligence Laboratory project(Brooks, n.d.-b), and *Braitenberg's* entire book is about iterations(Braitenberg, 1986), both of those research projects had iterated for an specific goal, .

Iterative Creatures is proposing an approach to iterate with less human intentionality, to iterate with vaguely defined goals and to iterate towards the robot's goal discovered during the design process. This allows the designer to shift perspective from "what I think it should do" to "what I think it's trying to do" therefore granting agency to the robot with the ultimate goal of making it less human-centric.

Chapter 3: Methodologies and Methods

3.1 Overview

Iterative Creatures uses a mixed methodology built around Iterative Design, it is an iterative process that empowers the robot with agency, enabling it to engage in a dialogue with the designer therefore resulting in less human-centric iterations.

Iterative Creatures is supported by a variety of different parts, the theoretical framework of Critical making, Iterative Design, Rapid Prototyping and More-Than-Human design. They all serve the same purpose, to establish a channel of communication between the robot and the designer, empowering the robot with more agency, therefore mediating human intentionality throughout the process.

3.2 Critical Making: Robot as Negotiable Entity

Critical making helps designers to be more comfortable with the robot they are making, it helps them to establish relationships and be fluent in the material they work with.

“Critical making, a mode of materially productive engagement that is intended to bridge the gap between creative physical and conceptual exploration.”(Ratto, 2011)

Ratto first coined the concept critical making in 2008, he framed it as a bridge between critical thinking and the act of making, calling it critical making. It offers advantages to makers and theorists: it brings care and investment to the matter, it overcomes the “rigid style of work” associated with computers which benefits robotics projects too.

Ratto made a distinction between “caring about” and “caring for”, in his words, “caring for” means to invest in a subject, it seems to be a “necessary step” to reconnect people with technology, whereas “caring about” means something lesser”(Ratto, 2011). He continued by drawing on Bruno Latour’s distinction between “matters of fact” and “matters of concern,” matters of fact are framed as objective and self-contained, while matters of concern expose the networks of values, negotiations, and responsibilities that produce them (Latour & Weibel, 2005). Ratto claims “Matter of fact” is what people are “caring about” it is facts that are less negotiable whereas “matter of concern” is what people are “caring for”, it means people realize the issue is designed, flexible and negotiable.

Critical making turns “Matter of fact” into “matter of concern” by putting designer in close contact with the robot through firsthand making. This allows the designer to put more investment into the subject therefore making the designer to “care for” the subject. Example given by Ratto is subject associated with computers tend to appear as “rigid style of work” but by “messing about”, it de-stabilizes the rigidity and allow people to realize computers are negotiable.

3.2.1 How Critical Making helps Iterative Creatures

Iterative Creatures aims to start a negotiation with the robot, experimenting with what it wants and what it needs. Critical Making enables the possibility to have a negotiation by establishing a connection between the designer and the robot, making the designer care for the robot as well as framing the robot as a negotiable entity, instead of a rigid system built with components and code.

Designer in *Iterative Creatures* acts as an investigator who asks questions constantly to ensure accurate interpretation. Critical Making allows the designer to be familiar and comfortable negotiating with the robot and the media, helping the designer to be critical about the investigation instead of just hovering over surface level technical problems.

3.3 Iterative Design

Iterative design is the core methodology used in this research project, in addition to providing all the methodological advantages Iterative Design offers, it also allows the prototype robots to have agency by inserting itself into the iterative design process.

Gould and Lewis are the early adopters of iterative design and examined this method extensively in their paper *Designing for usability: key principles and what designers think*. This chapter will use it as a framework to discuss how iterative design enables Iterative Creatures to achieve the building of non-human robots.

Iterative Design enables this research to generate knowledge incrementally, dynamic development cycle and identifying necessary modifications. However, it also tends to increase both the time and the financial cost of a project (Wynn & Eckert, 2017), which this thesis will propose a solution to later in this chapter. In addition, Iterative Design allows Iterative Creatures to mitigate designer intentionality by granting robot agency and design for non-humans.

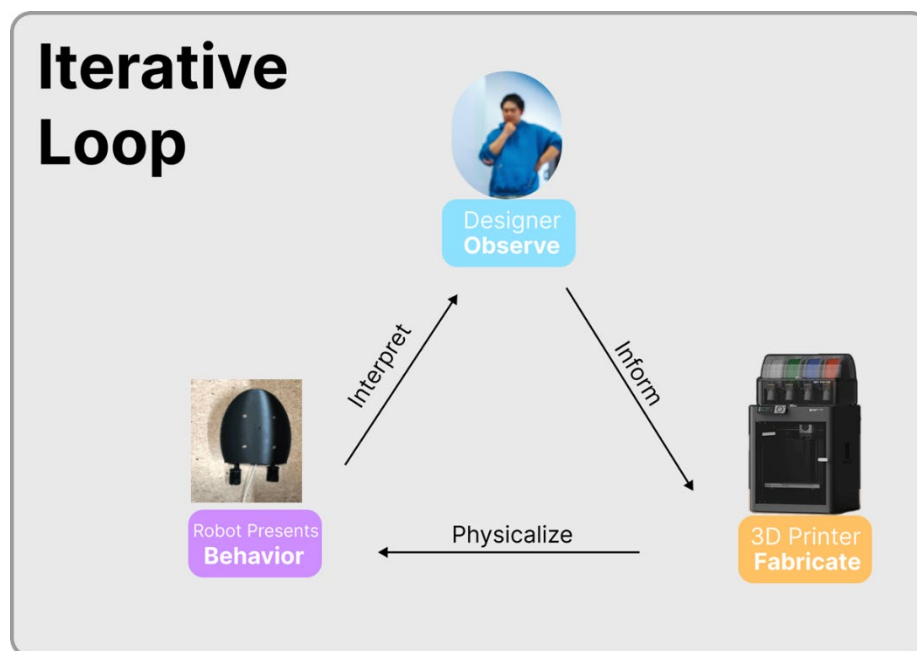


Figure 6 Iterative Process Loop. Observe - Fabricate - Behavior

3.3.1 Mediating Designer Intentionality, Empowering Robot Agency: Building a Channel of Communication

Iterative Creatures set out to design a robot that is non-human-centric, in other words, a non-human robot that is not designed for humans but for the robot itself. To achieve that goal, it is important to investigate what a robot needs, this directly translate to what Gould and Lewis calls "Understanding Potential User"(Gould & Lewis, 1985). In Gould and Lewis' work, the primary way to understand the user is to have direct contact with the user, having verbal conversations and observing the user using the design(Gould & Lewis, 1985). Robots do not talk, spoken or written unless specifically programmed to do so, a channel of communication becomes necessary to "understand" the robots, user of this research project.

The other method Gould and Lewis propose is the Participatory design where users are involved in early stages of the design process of the product that they are going to use once the development process finishes. This ensures the development aligns with the user's need. But once again this requires a channel of communication between the designer and the robot.

Iterative Creatures proposes a solution to establish the channel of communication essential to a non-responsive user, disassociating the design and the designer. When the designed product itself is the user, the designer needs to be able to disassociate themselves from the design, viewing it as if they are a bystander. Iterative Creatures uses encapsulated shell to contain the creatures from exposing their internals, therefore looking more like an independent entity instead of a robot in development.

With Valentino Braitenberg's uphill analysis theory, the encapsulation acts as an opaque layer, where designers view it as a separate entity rather than a designed product in development. This allows the designer to see through the design imperfections, the engineering problems and human intentionality, and to observe the robot as what it is at that very moment.

As the robot is encapsulated and running, it starts to present behaviors, due to the opaque layer, the designer is forced to observe and interpret the behaviors, it shifts the narrative for the designer from "what I think this should do" to "what I think it is trying to do" . This is how a designer can receive communication from a robot, by observing solely the behavior without understanding the internal status of the robot, thus viewing it as an entity instead of a designed product.

3.3.2 Iterative Process

Iterative Creatures heavily uses iterative design, from the fabrication of physical structures to the programming architecture, Iterative Creatures is prototyping, testing, evaluating and refining. Throughout the process, Iterative Creatures is able to develop in a way both makes logical sense and enables human designer as a builder to gain knowledge on robot.

Every Iteration is tested with the robot, from observing the creature's emergent behavior, the next iteration will be produced. For example, the leg design, while being fully 3D printed, leg mechanism has over 15 different designs and finally settled on a 5-bar linkage mechanism and a silicone pad for friction. Through the leg's evolution, a few key areas were explored for a functional leg design and helped the robot to achieve its goal, including friction on the foot, joints connector, torque spikes and CAD design. Together they form a good functional leg for the robot, additionally those knowledge are generalizable and can be applied to future Iterative Creatures or projects.

A complete Iteration map can be found below, it details the iterative process of AWORM Phase 2 from start to finish, listing out every significant check points.

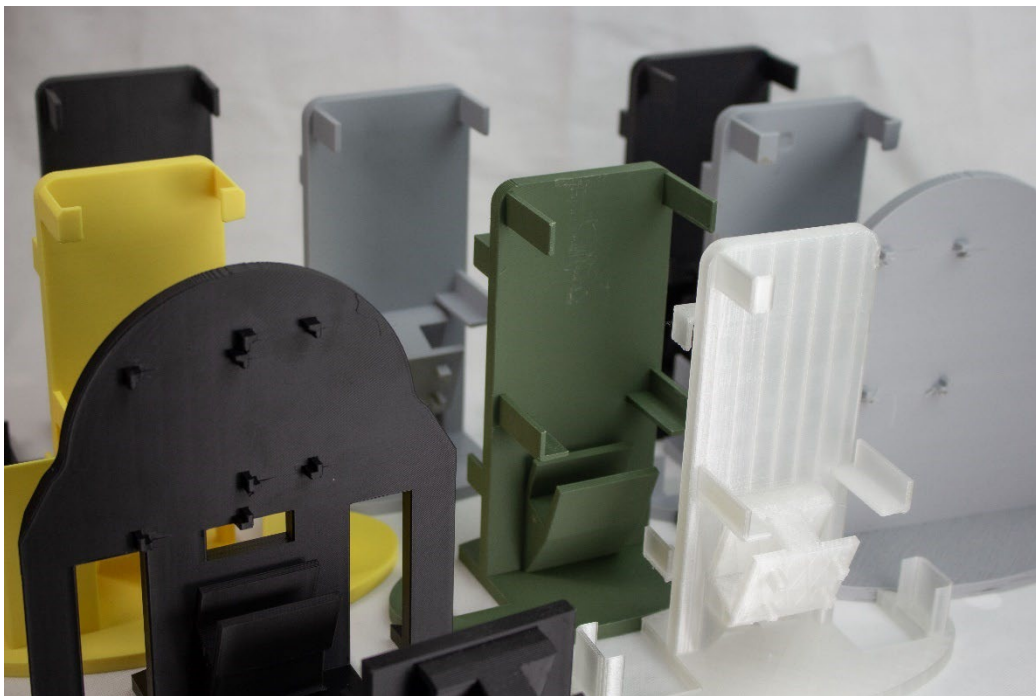


Figure 7 Iterations of Internal Structures

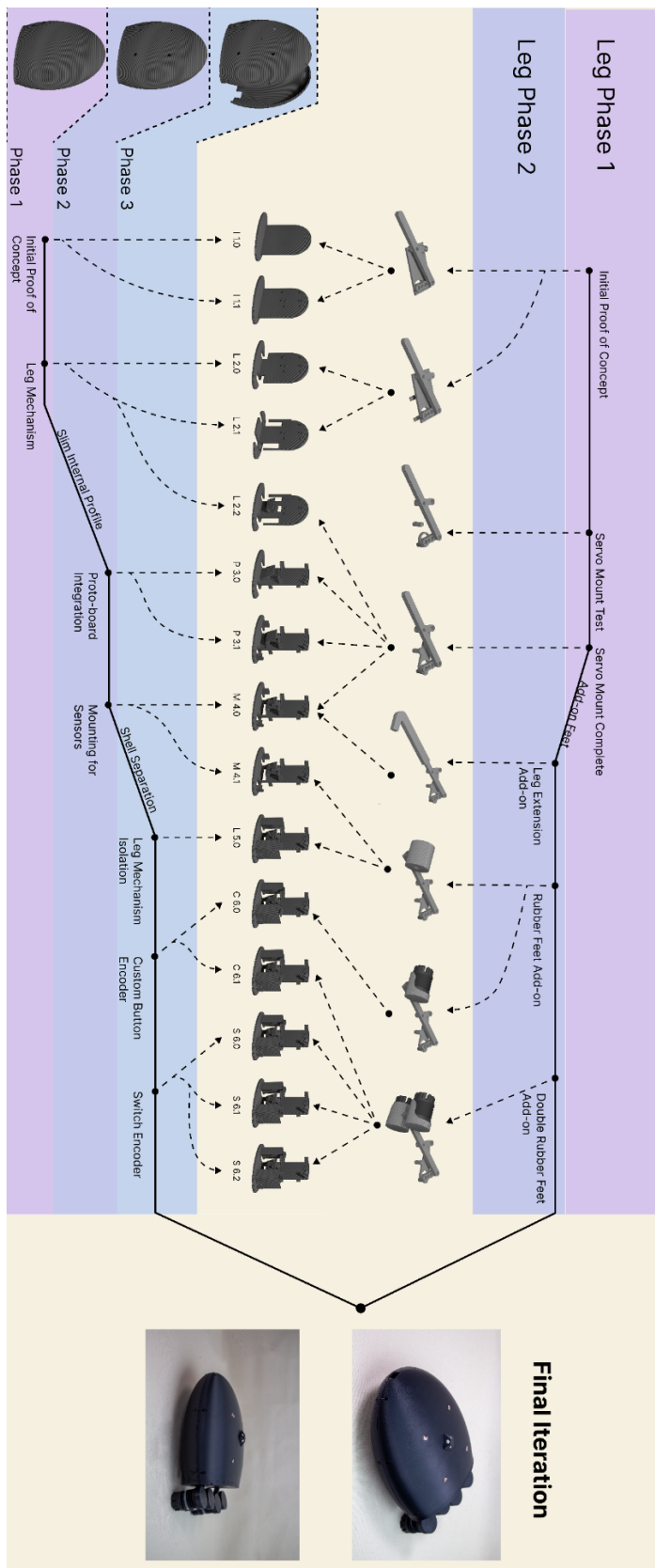


Figure 8 Iterative Map For AWORM Early Version

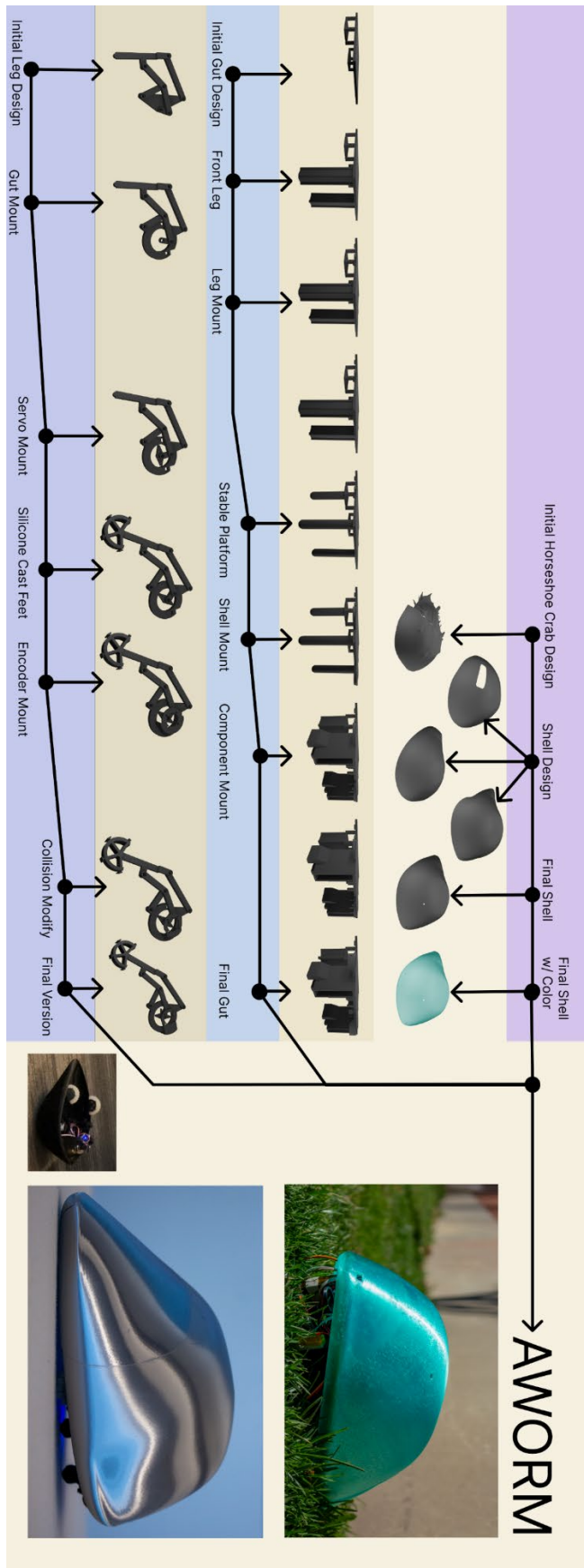


Figure 9 Iterative Map For AWORM

3.4 Rapid Prototyping: Message Sent to Robot

While Iterative Design and Participatory Design helps the designer to understand their user, the robot with observation. Rapid Prototyping with contemporary technology acts as a bridge for the designer to send messages to the robot, by iterating the robot's physical form.

Bruce Sterling is a pioneer in Rapid Prototyping, he claims Rapid Prototyping solves design problems by exhausting all possibilities of the problem thus making it an extremely effective solution.

Rapid prototyping is a form of brainstorming with materials. It's not simply a faster way to plunge through older methods of production, but a novel way to manage design and production. By previous standards, it looks as if it is profligate, that it "throws a lot away"—but with better data retention, "mistakes" become a source of wealth. Rapid prototyping seen in depth is an "exhaustion of the phase space of the problem"—it isn't reasonable, thrifty or rational, but it has the brutal potency of a chess-playing computer. (Sterling, 48)

Combining this with contemporary digital fabrication technology such as 3D printing allows faster iterations with low cost material. Linking back to earlier this chapter, one of the disadvantages of Iterative Design is the added cost and time from multiple iterations, this can be remedied by 3D printing with its speed and cost.

Iterative Creatures utilizes Rapid Prototyping as the grease of the machine. With 3D printing and PCB technology, it allows low cost of making mistakes and rapid iteration, essentially helps to establish a valid channel of communication, allowing easier robot-designer communication. Being able to see each iteration live in the testing offers an ideal environment for the designer to "understand" what the robot "indicating". It also negates some of the negative effects on cost and time of Iterative Design as well.

This method is significant for *Iterative Creatures'* iterative process as it acts as the communication layer from the designer to the robot, each iteration can be easily fabricated and tested with the robot, reducing the cost of making mistakes. This does two things, it allows the designer to have low stake designs where the design does not need to be carefully engineered, it just needs to be fabricable by contemporary technology. Secondly, it allows the robot to be exposed to as many iterations as possible, the exposure helps the product align with the users need better, more user involved iterations usually yields better result, as Gould and Lewis hinted in their paper(Gould & Lewis, 1985).

3.5 Conclusion

Critical Making, Iterative Design and Rapid Prototyping forms the backbone of *Iterative Creature*, the three methodologies allow it to be a fast, iterative and low stakes process and most importantly, a collaborative design process. Through such process, *Iterative Creatures* is able to follow the initial assumption and investigate the research questions.

Chapter 4: Iterative Creatures

4.1 What are Iterative Creatures

Iterative Creatures produced a series of robots as research instruments, in which the designer is in constant communication with the robot, keeping the robot in its own design process, *Iterative Creatures* aims to mitigate human intentionality by introducing robot agency and include robot in the design process. It aims to bring robots out of the commonly found human-centric design atmosphere in robotic design.

This section will review the challenges, findings and prototypes made during the research process. It starts with a brief overview of the Anxiety Robot (ABOT), examining findings from ABOT then the major research project AWORM. A worm-like robot designed specifically to investigate research questions. This chapter will examine AWORM's design process referring to the three properties William Grey Walter considered as the property of life imitation: Independence, Spontaneity and Purposefulness.

4.2 Limitation and scope

Iterative Creatures is an art research project, it is not an engineering project and has no intention of being one, it does not create technologically advanced robots, or algorithms to evolve the creatures.

Iterative Creatures create simple robots with sensors and servo motors, running on simple logics. It resembles Vehicle prototypes Valentino Braitenberg discussed in his book (Braitenberg, 1986). Where most sensor values directly link to servo motor outputs.

Another common theme when it comes to robots is sentience. *Iterative Creatures* and its robots are not sentient, as far as this research is concerned, they are somewhere between a rock and bacteria as shown in Figure 9. They are not meant to be sentient.

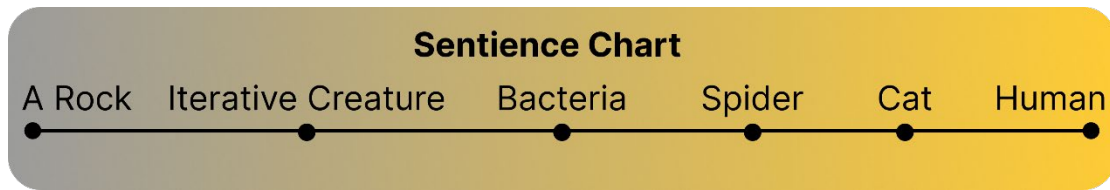


Figure 10 Sentience Chart, Ranging from A Rock to Human. Shows where Iterative Creatures sits.

4.3 Initial Assumption and ABOT

Initially, *Iterative Creatures* aims to create non-human-centric robots by removing humans from the equation. The removal is done by enabling the robot to follow its own inclination, imagining what the robot might want as a robot.

ABOT is the resulting robot, it is a movement sensitive robot that gets anxious when sensing movement. In the design process, the goal is to have ABOT not care about humans, as it doesn't have sensors equipped for human specific detection and it does not help human in any way, it is minding its own business: movement. It is intentionally useless for humans and concerning for its own welfare.

4.3.1 Lesson learnt from ABOT: From Removing Human

Intentionality to Enabling Robot Agency

Upon the final evaluation of ABOT once it is complete, it presents several findings and limitations. One of the major conceptual limitation of ABOT is the removal of human in the equation. It became evident that removing human is unfeasible. As it is inevitably designed by a human designer and is for a human audience. ABOT always carries intentionality over from its designer.

The removal of humans is done by giving ABOT personality, making it an extremely anthropomorphizing robot with face, eyes, emotions and body language. It was meant to be relatable and approachable, enabling people to recognize it as an independent entity, therefore, granting it agency.



Figure 11 ABOT under A Tree

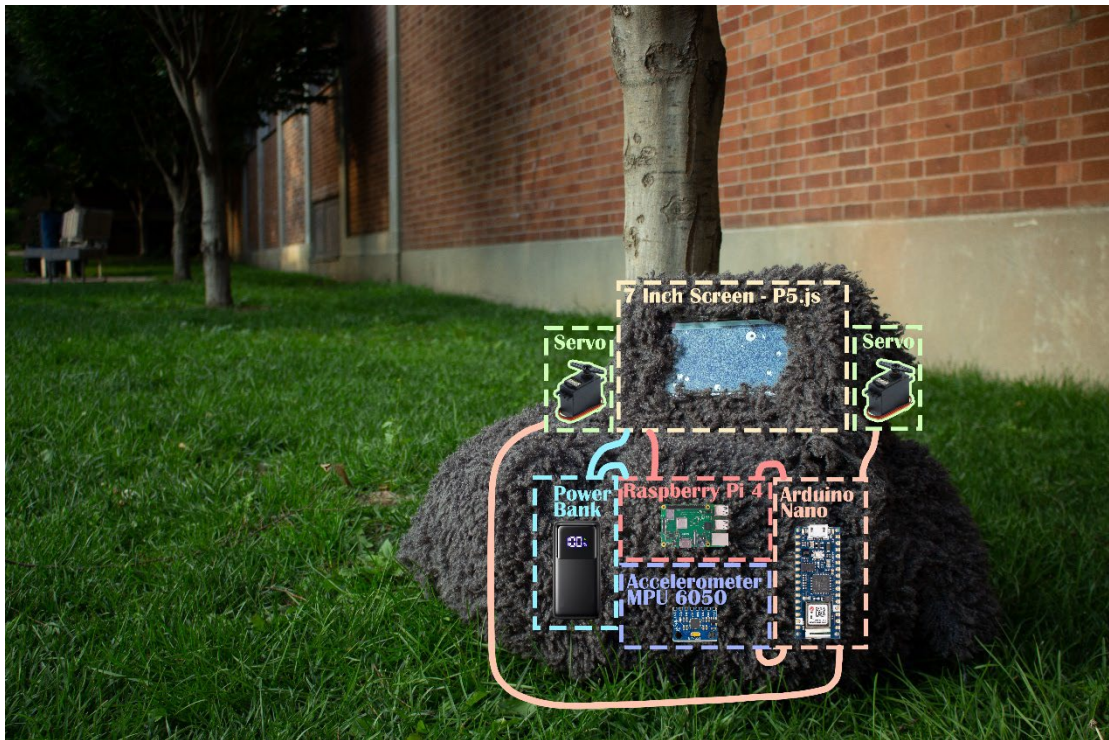


Figure 12 ABOT Components

However, ABOT became a very non-robot robot by having a humanoid concept of face, eyes and a very human-centric concern: Stay Alive by avoiding movement which

potentially leads to a fall, damaging its system integrity.

AWORM on the other hand tried a different approach and received a more collaborative agency through the use of the iterative process shown in Figure 6

With the goal to shift Iterative Creatures out of the human utilitarian context, the attempt to remove human intentionality is proven to not work as it is designed and fabricated by a human, trying to extract human out of the equation inevitably brings abstraction to the discussion. After a few prototype iterations, instead of removing human intentionality, the robot is introduced to the loop, by enabling robot agency, human designers act more like a collaborator with the robot.

Collaborating with an unresponsive partner presents several challenges, it doesn't come with a list of needs and requirements, it is up to the human designer to listen, observe and investigate what their robot collaborator wants.

The process of inquisition is full of guessing and experimentation is a back-and-forth process, each iteration is one message sent, 3D printing technology was utilized to accelerate the process by rapidly producing prototypes, letting AWORM to try it on. This allows quick and precise creation of their physical properties, which is essential to the initial assumption

in the collaborative process, designer takes on the role of robot's physical proxy, the designer is providing labor for the robot in ways the robot itself cannot, such as operating design software, 3D printer and assembly, in this sense the roles are exactly opposite to the definition of robot, where itself should be manipulating physical material in replacement for humans. The robot, on the other hand, provides its feedback through behavior. The relationship and roles human designer and robot have is complex and in constant flow, it can be collaborator, care-giver, physical proxy or labor.

4.4 AWORM

4.4.1 What is AWORM

AWORM is set out to be:

- Independent, it should have ability to achieve tasks without human intervention, operate by itself.
- Purposeful, it should have a goal and perform tasks to achieve the goal.
- Spontaneity, it should be unpredictable, it should not have a rigid routine.

Before going into details, it is important to know that the development process of AWORM is a non-linear, continuous process that evolves rapidly without any distinct phases or checkpoints. But it is possible to split the process into a few iterations where major changes are made and help AWORM's development, such as switching to a firm development platform, using 3D printed parts and using custom PCB. It is a process of identifying problems and producing solutions.

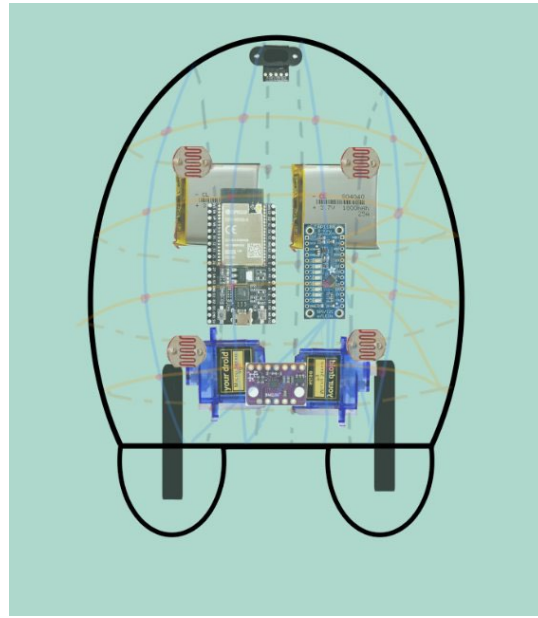


Figure 13 Initial Concept of AWORM

4.4.2 Independence and Uphill Analysis

Grey Walter defines Independence as the ability to hold battery power and seek charging stations when voltage is low. Acts of independence may appear to be engineering requirements for autonomous robots, but it also shifts how humans perceive the robot and the role humans play in interaction with it. An independent robot handles most situations by itself, humans are not expected to intervene or operate the robot, putting humans into a rare observational role, creating a dynamic with distance and opacity.

The opacity is what makes Braitenberg's Uphill Analysis phenomenon thrive. In his book *Vehicles*, a series of simple robots are built and tested as thought experiments, even the simplest robot made of two sensors and two motors can present complex behaviors and as the components stack up, simple robots can present more complexity than it holds. Braitenberg refers to this as the Uphill Analysis Phenomenon, a system always seems more complex than it is if investigated from outside (*Braitenberg Vehicle*, n.d.).

Uphill Analysis (Braitenberg, 1986) hinders human designer's understanding of the robot by blocking out the internals. When internal states aren't directly accessible, the designer starts to observe and attempt to predict the internal states. The shift from knowing to observing changes the relationship between designer and robot completely, it becomes less "what state is the program at" and more "what the creature is doing". This act of observation and apprehension grants the robot agency, it becomes an entity that needs understanding, rather than a robotic project running a piece of software.

The encapsulation was one of the major findings of ABOT, early phase ABOT had around 10 wires going in and out of its body as shown in Figure 12, which functions well but does not offer any sense of complexity. The internals are clearly exposed, it was perceived as components connected through wires than a robot, the visible wires are iterated away alongside with exposed internals are now concealed too. All to fully utilize the Uphill Analysis phenomenon, and based to feedback received from a later show, it is working.

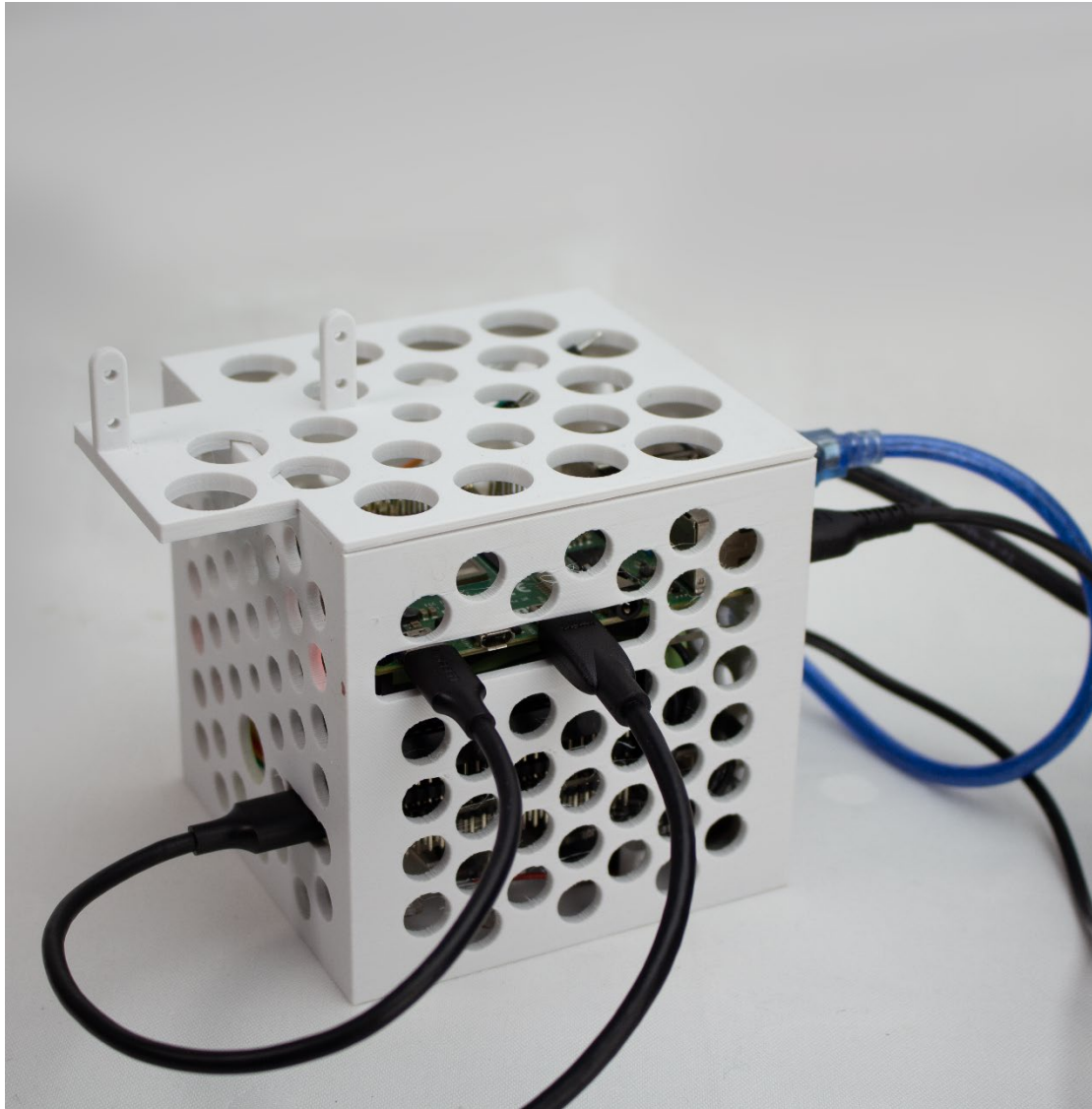


Figure 14 ABOT with Wires Connected (Reproduction)

It became evident that robot agency come from two parts in *Iterative Creatures* research, the independence and the opaqueness of the robot. One puts a barrier conceptually, forcing human designer into an observer instead of an operator, the other shifts the observer from knowing to guessing, both contribute to the overall goal of robot agency by blocking out the information of the robot and forcing the designer to engage with the robot in real-time.

AWORM is designed specifically to be independent and opaque, fully adapting the concept. Mechanically it can operate standalone for 3 hours straight powered by Li-Po batteries and internal components encapsulated in its shell, ensuring an opaque layer between itself and the human designer.

Component wise, some are installed specifically for AWORM to avoid or get out of unwanted situation by itself. Such as three IR sensors for cliff detection and a time of flight distance sensor for obstacle detection. Those designs help AWORM to navigate physical space safely without risking the need for human help.

Shell acts as the opaque layer, it is 3D printed with solid color, blocking out the internal structures. AWORM's shell when through a few iterations, it started as the fully enclosed one piece shell with only a small opening at the bottom, it is the ideal way for AWORM but it does present challenges to design, internal space usage. Later iteration have shell in 2 pieces, allow easy disassemble for maintenance and repair.

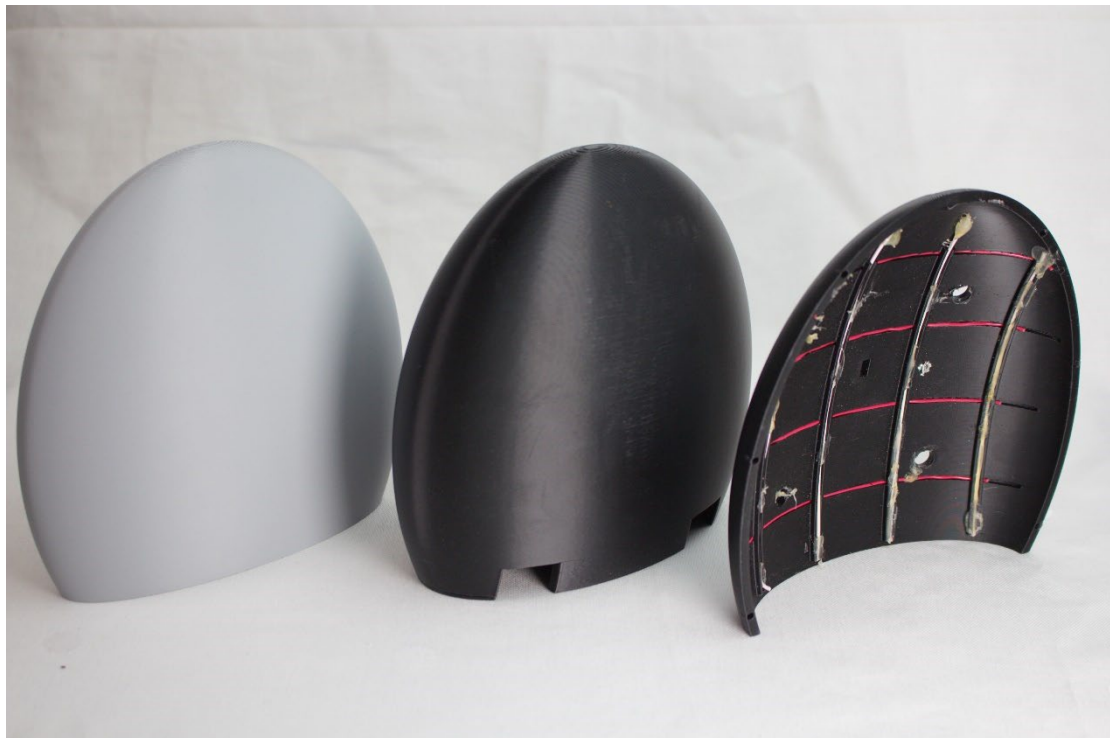


Figure 15 Iterations of AWORM's Shell Phase 1(Left) Phase 2(Center), Phase 3(Right)

Up until the final iteration, the shell kept a fully enclosed shape, however the final iteration is an open shape, its bottom side is exposed. The decision is a designer call, the bottom side is more useful opened, with other sides of the shell being more than sufficient to keep internal components concealed while open bottom offers easy access for recharge and repair. This pushes what human designers can and cannot do in the iterative process. This is the next phase of this thesis, figuring out the balance between robot agency and human designer intentionality.



Figure 16 Early Stage AWORM Fully Assembled

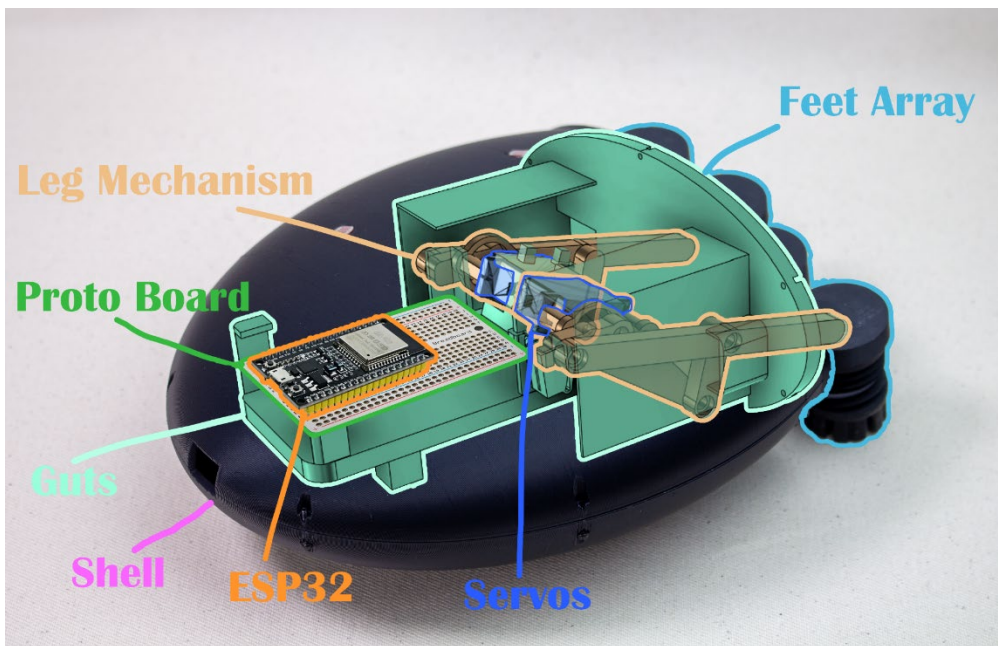


Figure 17 Early Stage of AWORM, Internal Diagram

4.4.3 Spontaneity Enables Discovery

“The key observation is that the world is its own best model. It is always exactly up to date. It always contains every detail there is to be known. The trick is to sense it

appropriately and often enough”(Brooks, n.d.-a). Brooks' theoretical frameworks clarify why physical space is the best space to enable spontaneity behavior. When the robot is embodied in physical space, all the details are thrown at it all at once, a lot of the details will not be anticipated by the design. Allowing the robot to encounter unscripted detail of the space allows unscripted behavior to emerge. Walter's Tortoises are observed to have emerging behavior, not because it has complex wiring inside but because it is put into a physical space.

Grey Walter's Definition of Spontaneity is the Tortoises' unpredictable actions, including turning in circles, backing up from mirror because it saw itself and flashing its headlight(Walter, 1950). Those were not programmed by Walter, he is an observer of the situation. Human designer's key role is to be an observer to the situation, make sense of it and “interpret” the robot's message. Walter's reflection demonstrated it and This chapter will use AWORM's leg iteration to reflect the same concept.

Walter observed a physical oscillation on Elmer's shell, which it used as a short term memory system: “The oscillations persist for about a second after the obstacle has been left behind; during this short memory of frustration Elmer darts off and gives the danger area a wide berth.” Instead of reinforcing the shell so Elmer functions exactly as the initial assumption where the shell is purely used as an obstacle avoidance instrument. Walter iterates on top of the oscillation concept by adding electronic oscillation as Elmer's memory: “More complex models that we are now constructing have memory circuits in which associations are stored as electric oscillations”(Walter, 1950).



Figure 18 Modern replica of Grey Walter's tortoise, with perspex shell

*Note. From Grey Walter and his tortoises by University of Bristol, 2008
(<https://www.bristol.ac.uk/news/2008/212017945378.html>)*

It is worth noting that Walter's decision to play along with Elmer's oscillation instead of

reinforcing the shell to strictly follow the initial plan, using the shell solely as obstacle avoidance. This decision aligns with *Iterative Creature's* intention to empower robot agency, one of the key methods is to “play along” with the robot instead of following a rigid work plan/requirements list. This allows a collaborative workflow where the direction of development is a joint decision, between the human designer and the spontaneous behavior sparked by physical space.

Spontaneity sparks iteration: complex behaviors emerged from AWORM's code and its implementation in the imperfect physical space feeds into *Iterative Creatures* by allowing human designers to iterate AWORM in reference to the behaviors. By operating in a real, physical environment, AWORM encounters objects and events local to the environment, which challenges it to be adaptive to the surroundings by struggling and presenting that struggle to the observing human designer. The struggles of creatures are constructive if observed properly.

AWORM's development of footwear against slippery floors is an example to understand the process of physical space leads to Spontaneity and constructive iteration that empowers robot agency. As shown in Figure 17, the second and third iteration were footwear iterations where the designer attempts to solve the slippery floor problem by adding an add-on to the existing feet rather than designing a new one from ground up. It later was proven to be more trouble than designing a new leg, therefore the final leg design on the figure's right side is developed. It uses silicone mold to cast a piece of silicone pad as the feet with the use of bumps to increase the friction even further.

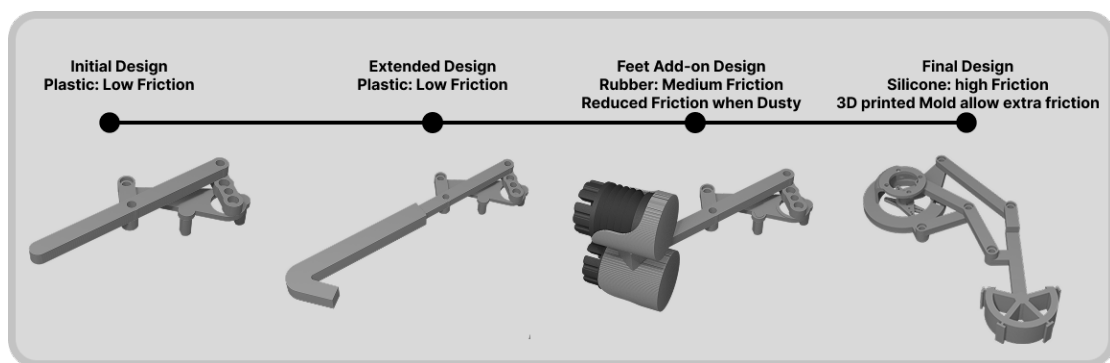


Figure 19 Major Leg Iterations with Friction Notation

AWORM's initial feet are just two 3D printed sticks as the shown on the left of Figure 17, with the slippery floor the initial design presents layers of challenges for which the human designer developed multiple iterations of solutions. By detailing the process of feet iteration provides insights into how Iterative Creatures functions in real-world application.

The initial foot was a 3D printed part with no modifications, it functioned in a simulated

environment, where everything is assumed to be in perfect condition, the feet produced smooth torque, so it doesn't stress the servo and decent travel distance to efficiently transfer servo's rotational movement to AWORM's forward movement. Once it is put in physical space, it failed to thrust AWORM forward, not even a little bit due to the lack of friction of both floor material and plastic used for 3D printing. It thrusts AWORM upwards more than it moves forward.



Figure 20 Initial AWORM Leg Design (3D Render)

The failure to move forward signals an important message from AWORM, as discussed earlier this chapter, AWORM needs to move around to find an ideal place for recalibration, so the human designer assists AWORM by iterating the foot design. Different iterations were made, ranging from using rubber feet for 3D printers, store bought chair feet protector to a single TPU film strapped to the feet.

Rubber feet were the most promising iteration, it is the final feet iteration for phase 2 AWORM, but it suffered from dusty floor, when the rubber feet operates for longer

duration, dust particles stick to the rubber and slowly disabling its friction as time goes.



Figure 21 AWORM with a Later Leg Design with Rubber Foot

Finally, a 3d printed mold to do silicone pour was developed, as silicone has more friction and the 3D printed mold enables custom design such as bumps covering the feet to ensure a firm grip to the floor, which after testing is functionally sound to allow movements in AWORM.

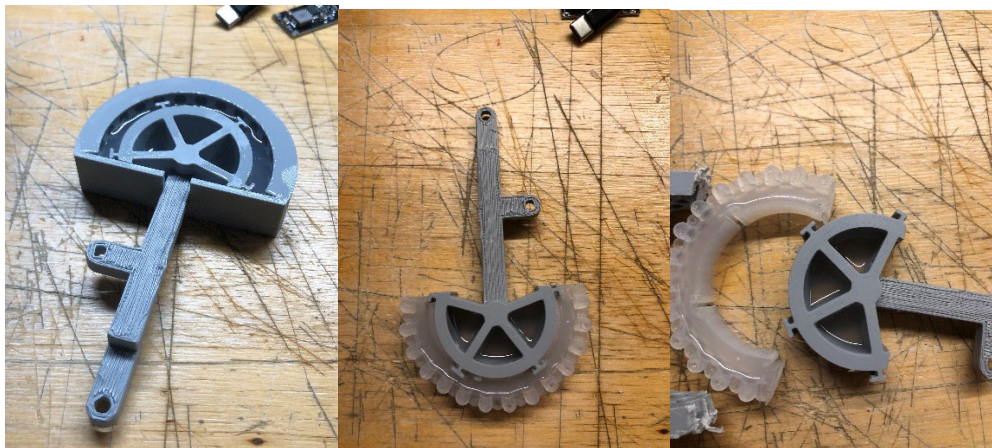


Figure 22 Tests for Silicone Poured Foot

The process of identifying a problem, proposing a solution, observing AWORM with the solution implemented and iterating over the solution is the core to *Iterative Creature*, it allows solutions to be tested in the physical space, where the unpredictability provides ample testing ground for possible situations.

Iterative Creatures hits its limitations when “interpretation” of the robot’s message sparks constructive iterations, it can also be mistaken, resulting in an unused feature or part. One example is AWORM’s capacitive sensor, it was added because it appears to be useful for AWORM to sense if a human is touching it. It was soon proven to not fit AWORM’s design as it is designed specifically for the detection of human which contradicts the initial assumption of AWORM, more importantly AWORM functions well without it.

4.4.4 Purposefulness and 3D Printed Legs

Going back to Walter’s *Tortoise*, Purposefulness is a property he claims Tortoises had, even though he never explicitly explained what Purposefulness is, he hinted at a mixture of having a goal and having free will. *Iterative Creatures* considers it as having a goal and the ability to achieve it.

In early development stage of AWORM, finding a goal appeared to be a major challenge, while *Iterative Creatures* allows collaborative workflow with the robot, it is still up to the designer to decide the initial form and what to adopt, balancing between finding an executable goal and enabling robot agency. This is a critical moment to discuss as having a non-human defined goal contributes to the overall non-human-centric design goal for this research project.

AWORM’s early iterations don’t hold any specific goals, it holds a bit of everything to start with, such as legs for movement, capacitive sensor for human touch sensing and accelerometer for directional data. Once AWORM is up and running, the goal of it starts to slowly come together as it is being tested on the floor.

One of the problem with physical robots are the sensor readings, it fluctuates naturally due to many reason, the surroundings, how the sensors are made and the vibration from running servos. For simpler sensors it doesn’t affect much but for the onboard accelerometer, due to the model and hardware limitations, it drifts over time. AWORM is designed to run for long periods of time, small offsets will build up, causing AWORM to lose sense of direction. It really became prominent during tasking, when AWORM is trying to hold its position, it started slowly turning clockwise.

Conventionally, accelerometers with drift require constant calibration, same model of accelerometer AWORM has can be found in SlimeVR tracker, a popular open source

body tracking solution, they recommend recalibrating the sensor every 5-15 minutes.(*IMU Comparison - SlimeVR Docs*, n.d.) The recalibration process involves holding sensor still for 10-20 seconds, which will recalibrate the sensor to working condition(*Common Issues - SlimeVR Docs*, n.d.).

For AWORM, part of its goal is to go to a quiet place and sit still for 10 – 20 seconds before moving again. This requires an effective method of moving which AWORM did not yet have. One of the designer assumptions made here is the definition of “quiet place”, it is defined as the darkest position AWORM could find, essentially linking dark with quiet, it is human designer decision.

Once a rough goal is established, it becomes evident that legs need more iteration to be effective. The process of designing the legs presents several challenges, particularly when it needs to fit into a tight, encapsulated space.

The leg iteration process was a struggle with friction, which is an environmental property local to the testing ground, this speaks to the adaptive nature of this approach. It adapts to local physical conditions, that would have never been anticipated if it weren't physically in the space, trying to move around with legs.

Leg was one of the components that iterated fast with the help of 3D printing, it is small, compact and delicate. The process involves a lot of field testing, using physical space as testing field can reflect the most reliable result in how the leg will do. 3D printing accelerates the process by providing precise leg mechanism designed in CAD software. With how rapid the process is, a few key points about the legs were considered:

- Fully 3D printable.
- Easy to assemble, preferably without specialized tools.
- Have enough grip to the floor to thrust AWORM forward.

With 3D printing's help, each iteration can be immediately installed, tested and revised for next iteration, the rapid iteration extends to all 3D printed parts of AWORM, from shell, internal structure to the legs. mistakes become affordable both due to the speed and the cheap 3D printing material. Another benefit of 3D printing is the duplicability, any damaged parts can be replaced with a new print, rather than spending hours making or getting the replacement.

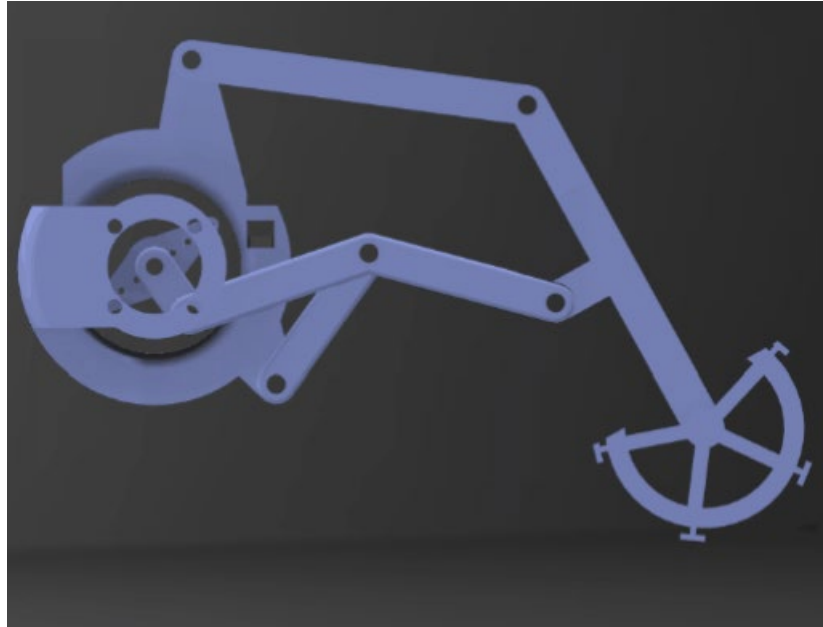


Figure 23 Leg Mechanism

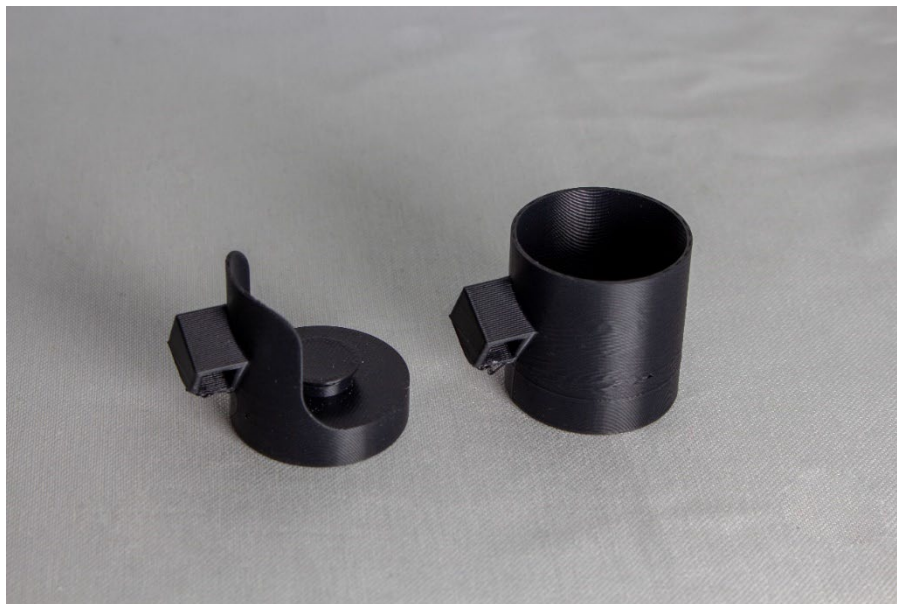


Figure 24 Initial and 2nd Iteration of Attachments for Feet Rubber

The new linkage leg mechanism took inspiration from Klann linkage, it now is a 5-bar linkage mechanism, with one additional bar, the mechanism can filter away imbalance of torque, allowing the servo to operate under constant stress. A press-fit joint is also designed, with accurate 3D printing parts, the press-fit joint can be pushed in by hand and hold enough friction to not fall out. The entire mechanism is designed in Fusion

360, fully 3D printable with little support required.

In addition, a silicone cast mold is also produced to cast silicone onto 3D printed legs to allow ample friction against the ground.



Figure 25 AWORM 5-Bar Linkage Leg

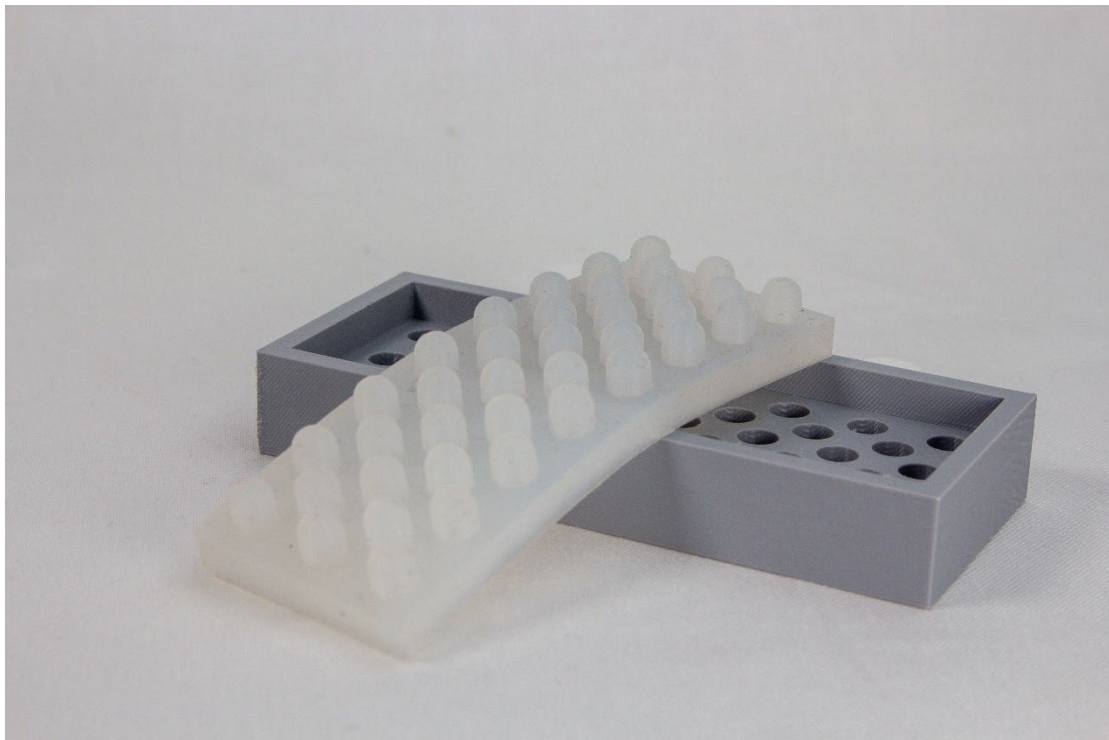


Figure 26 3D Printed Mold and Silicone Cast

4.4.5 Technical Specifications

AWORM uses a ESP32-S3-DEVKIT as the central microcontroller, two 9g continuous servos to drive its legs, 4 light dependent resistors (LDR) to sense the light and a BMI160 Inertial Measurement Unit (IMU) for directional data, a CAP1188 capacitive sensor driver with 8 channel of detection and two 3.7-volts Li-Po batteries for power, and a few power management boards for boost conversion and charging. The structure is fully 3D printed, AWORM's body is in three parts:

- Shell, where capacitive sensors are detecting and LDR sensors are mounted to
- Internal structure, housing for microcontroller, servos and batteries.
- Pair of legs, built and simulated in Fusion 360, a 5-bar linkage mechanism translating servo's rotatory motion to cycling leg movement.

AWORM's brain is designed to be small, it doesn't need much information to operate. The 4 LDR sensors will generate a light vector based on the intensity of the light, AWORM will always try to face that direction and move towards it by actuating its servos to turn clockwise or counter clockwise. With both legs it is able to move forward, turn left, turn right and move backwards, it's enough for AWORM to navigate towards the target. While 4 LDRs provide directions to the light, LDRs only offer a left or right direction for AWORM, the BMI160 IMU will keep a reference of how much AWORM turned since it's been turned on and detects if it's been taken off the ground by human.

4.4.6 Technical Challenges

The first issue came with soldering, soldering floating wires was not ideal and soon I switched to a proto board, everything worked as expected ever since. The second challenge was how its legs were designed, due to the tight internal space, its legs are short and barely touches the ground, combining that with the spherical shape of AWORM's shell, its feet tend to just dip into the ground, instead of pushing AWORM forward, the energy becomes a wobbly motion, making AWORM wobble more than it moves.

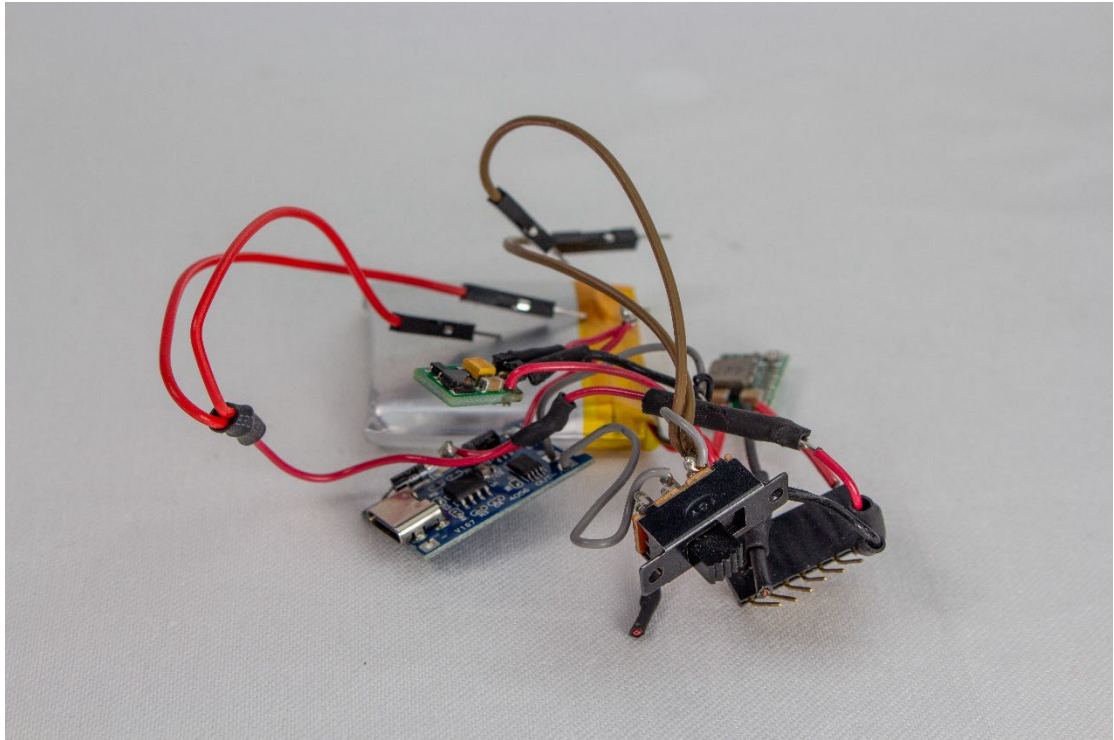


Figure 27 1st Soldering Job for AWORM

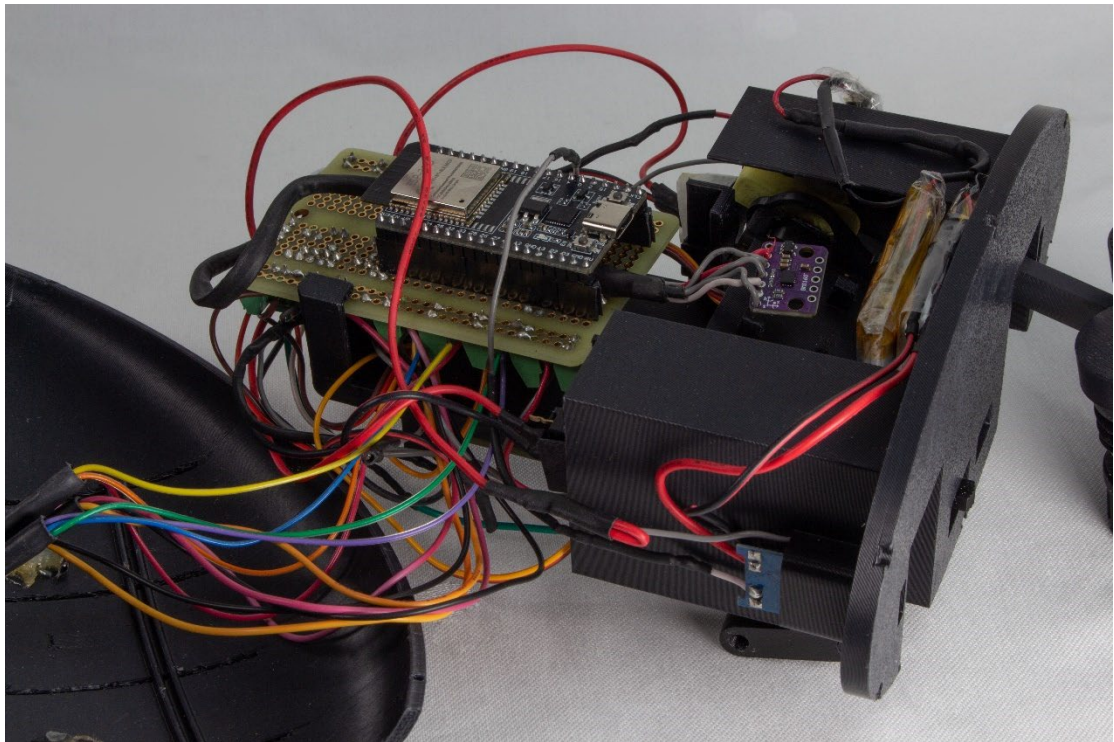


Figure 28 Internal Wiring by the End of Version 2 AWORM

4.4.7 Choice of Microcontroller, IDE and PCB

Aside from 3D Printing, a selection of tool and techniques were used to better the development process, including the Printed Circuit Board (PCB) technology, allowing the internal electronics of *Iterative Creatures* to have a consistent high-quality build, minimizing human errors in the process, which had caused a lot trouble previously as shown in Figure 26. PCB is also good at producing consistent results, ensuring Iterative Creatures can be reproduced anywhere with the correct setup and build illustrated in Figure 28 and Figure 29.

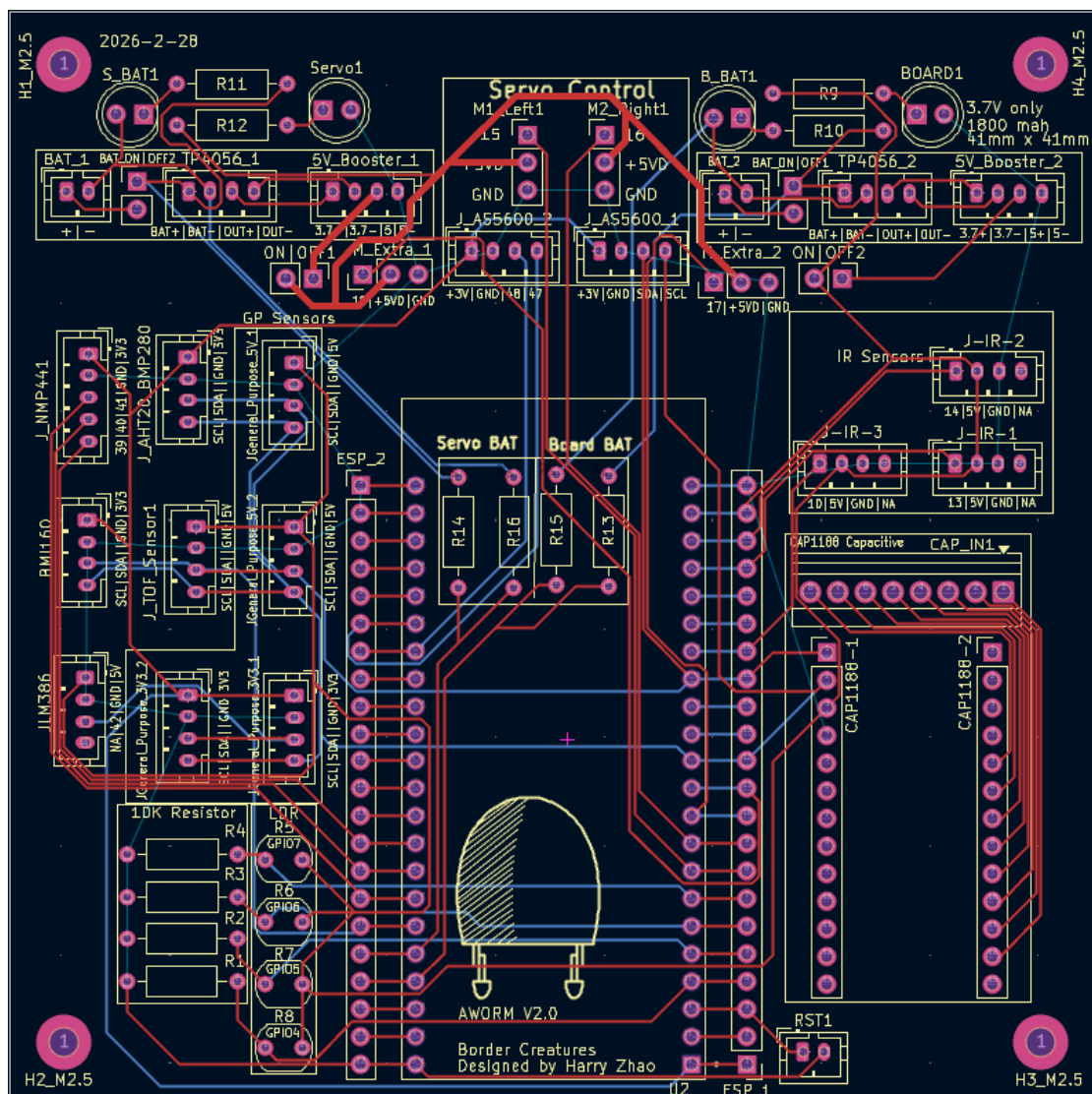


Figure 29 AWORM PCB v2.1 in KiCad 9.0

Also, finding the right Integrated Development Environment (IDE) is crucial, a good IDE will save a lot of time and be a helper along the way rather than being a pain to work

around. The IDE of choice is PlatformIO (PIO) with Visual Studio Code(VS Code) as text editor, VS Code is a general purpose code editor, whereas PIO is a specialized IDE for embedded systems (*What Is PlatformIO? — PlatformIO Latest Documentation*, n.d.) that includes Arduinos, Esp32s and more.

At the core of an embedded system is the microcontroller, there are plenty out there, ranging from Arduino Nano to powerful Single Board Computers like Raspberry Pi, ESP32 S3 is selected for its expandability, Wi-Fi and cost effectiveness. With it designed directly into the PCB, it can mount to the board and all sensors, servo motors and components can be purchased online.

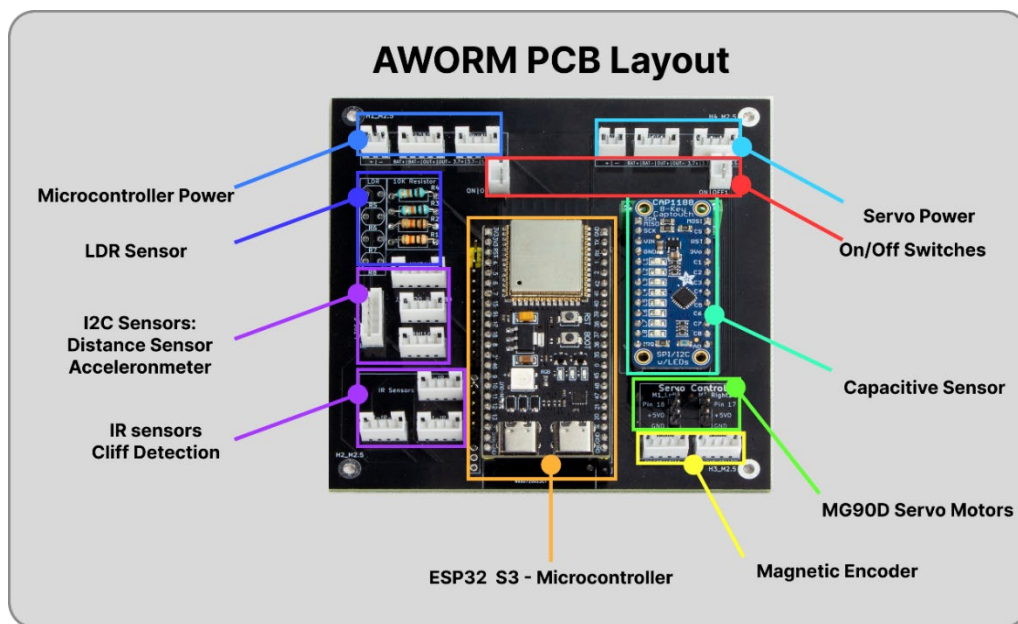


Figure 30 AWORM PCB

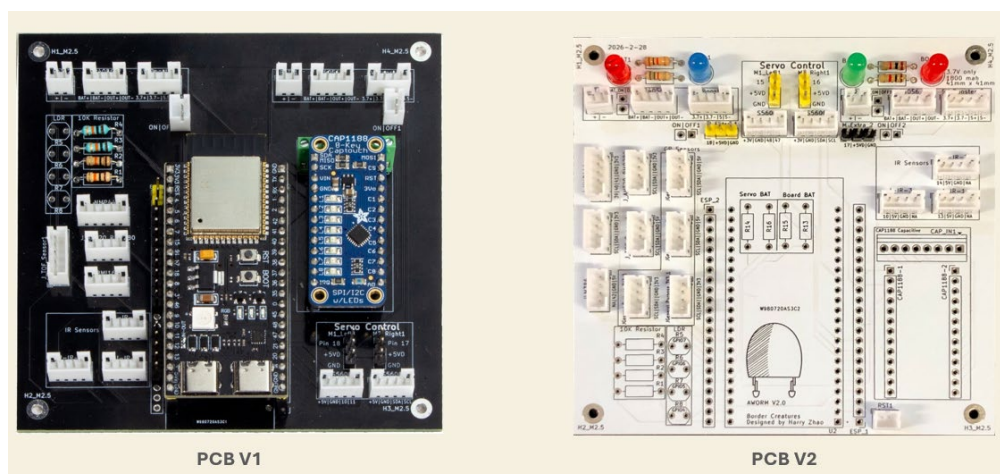


Figure 31 PCB Version Comparison

4.4.8 Documentations

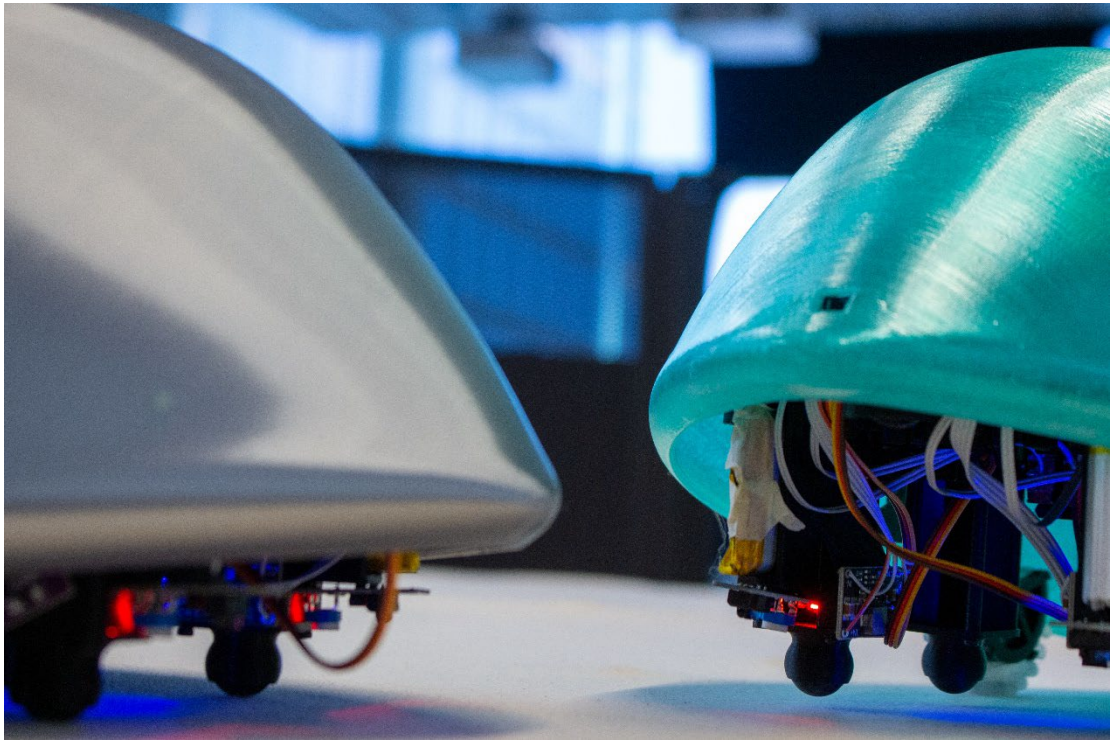


Figure 32 Two AWORMs Facing Each Other



Figure 33 AWORM on Grass

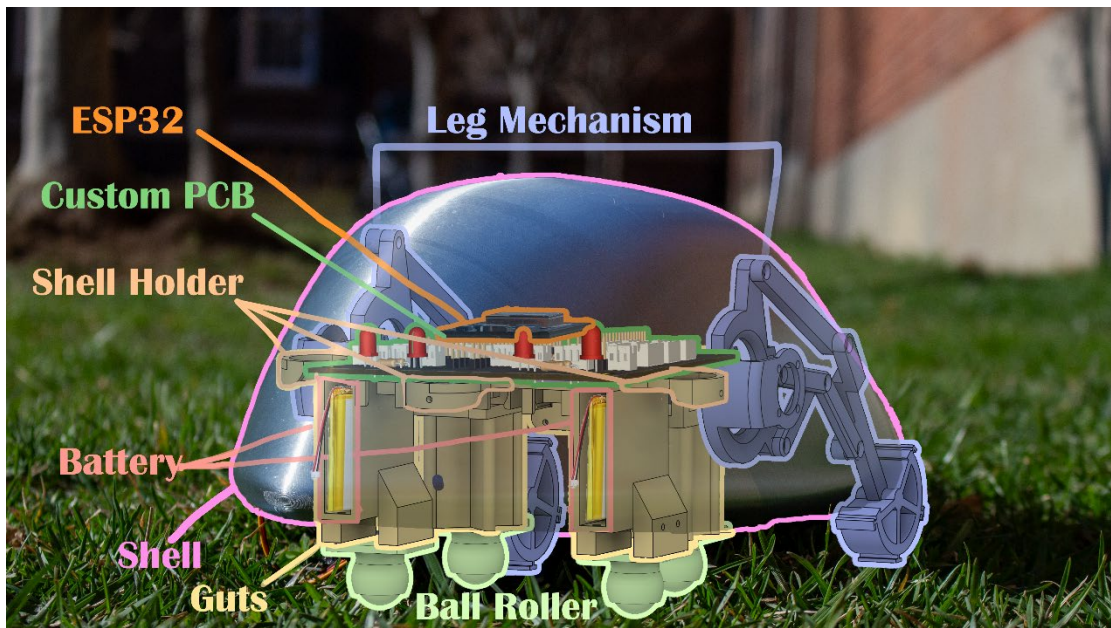


Figure 34 AWORM Internal Diagram



Figure 35 AWORM

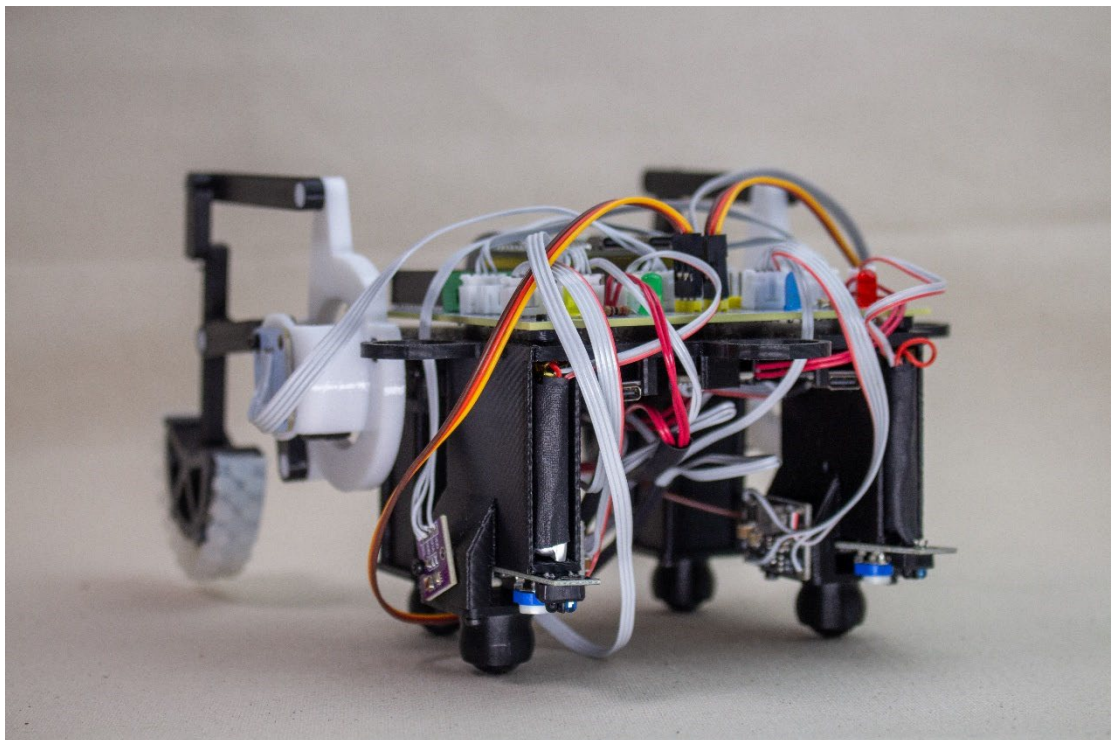


Figure 36 AWORM Internal Components

4.4.9 Exhibiting AWORM

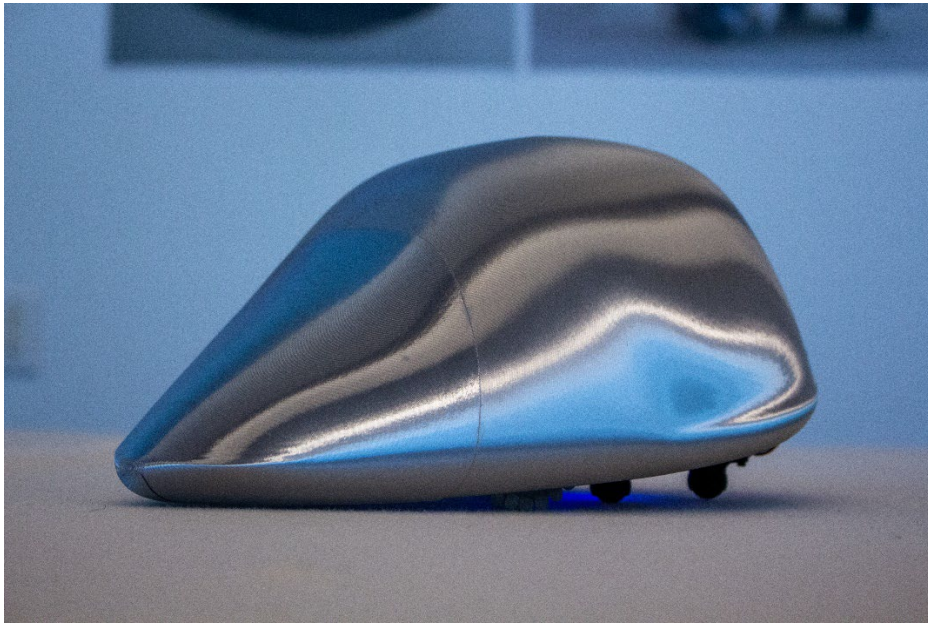


Figure 37 AWORM with Silver Silk Shell

The ideal way to exhibit AWORM is to allow it to freely roam on the floor, allowing it to become part of the environment as it doesn't take up that much space or attention. With DFX, space is limited so a platform was built for AWORM to reside on. With built-in IR sensors, AWORM can steer away from cliffs.

Prints of Iteration map and a TV will be show some material, both specifically for the exhibition and from this document. A table of physical AWORM iterations showing previous version of AWORM will be present.

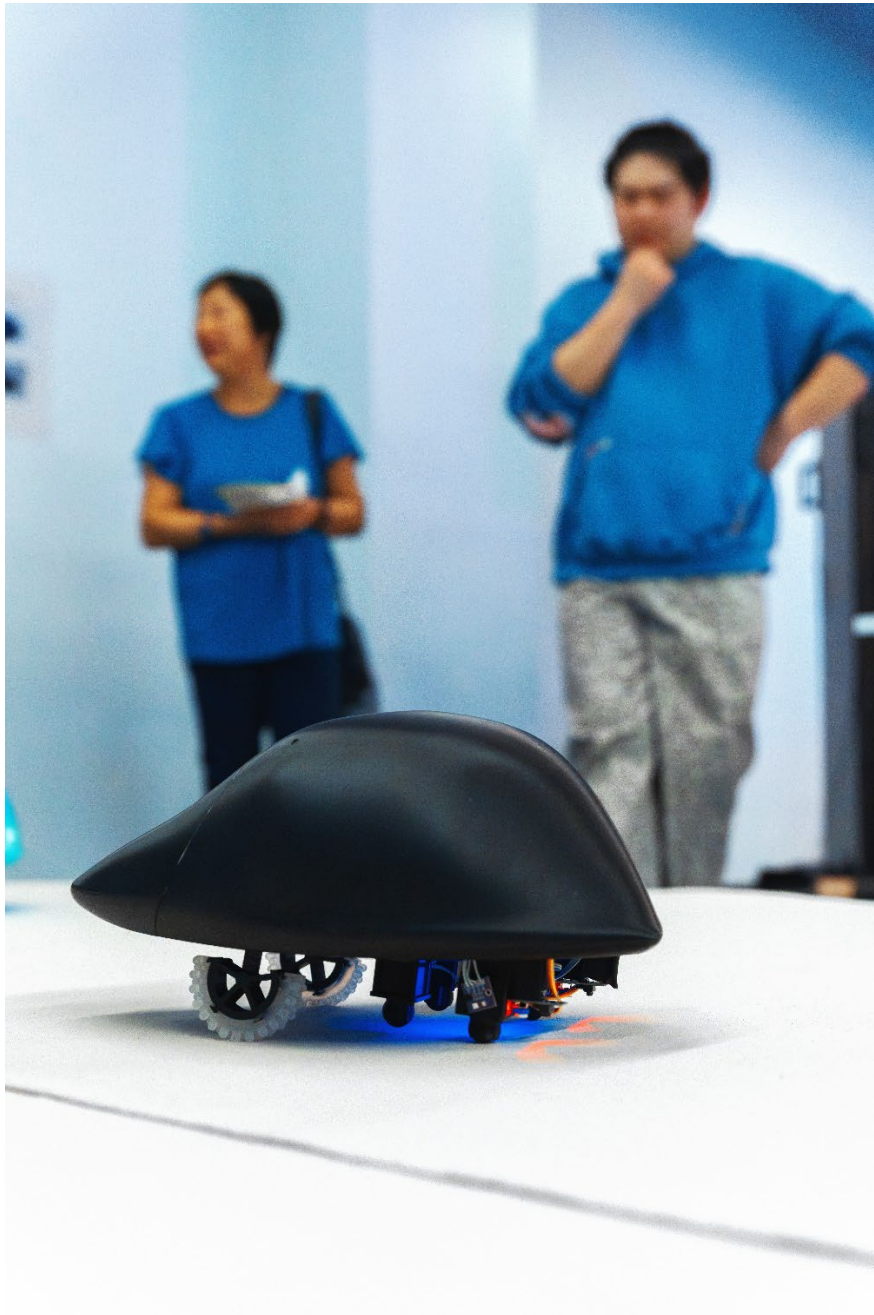


Figure 38 DFX Opening

The platform is 8 by 8 ft circle, made from $\frac{1}{4}$ inch MDF board with a ring of feet underneath close to the center, creating a levitating platform effect. The platform is about 1 ft tall, covered with canvas where AWORM can have a firm grip of the surface

and be visible with its shell color.



Figure 39 AWORM on The Platform for Size Comparison



Figure 40 DFX Layout with Platform (Bottom Left), Poster and Iterative Map (Center) and Physical Iteration Object (Right)



Figure 41 The Platform and Two AWORMs Roaming on It

The expected behavior for AWORM as described in Figure 39 is to go to the edge of the platform, and try to stay close to the edge without falling off. It presents challenges for AWORMs, especially on DFX day one as its sensor readings still need adjustment. AWORM fall off the platform every now and then.

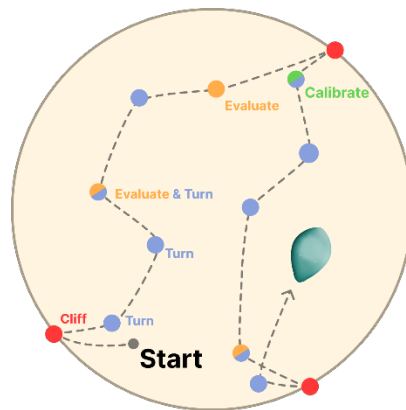


Figure 42 Expected Behavior of AWORM at DFX



Figure 43 What Ended Up Happen: AWORM on the Floor, Upside Down

4.5 DFX Reflection

DFX was the first time AWORMs sustained operation and exposed to humans besides the designer.

Before DFX, AWORM only operated in controlled studio environment for short period of time with restrained movement set. Once DFX started, AWORM Operates 5 hours a day and that offered an incredibly number of insights for AWORM being a physical agent and is operating in a physical world. It started to wear mechanically, especially its leg mechanism starts to show signs of design weaknesses. To a point the entire leg mechanism needed to be replaced, this is a moment in this research where AWORM almost directly asked for a new leg design. Also, it justifies the use of 3D printing technology as the leg mechanism can be easily replaced with a new print.

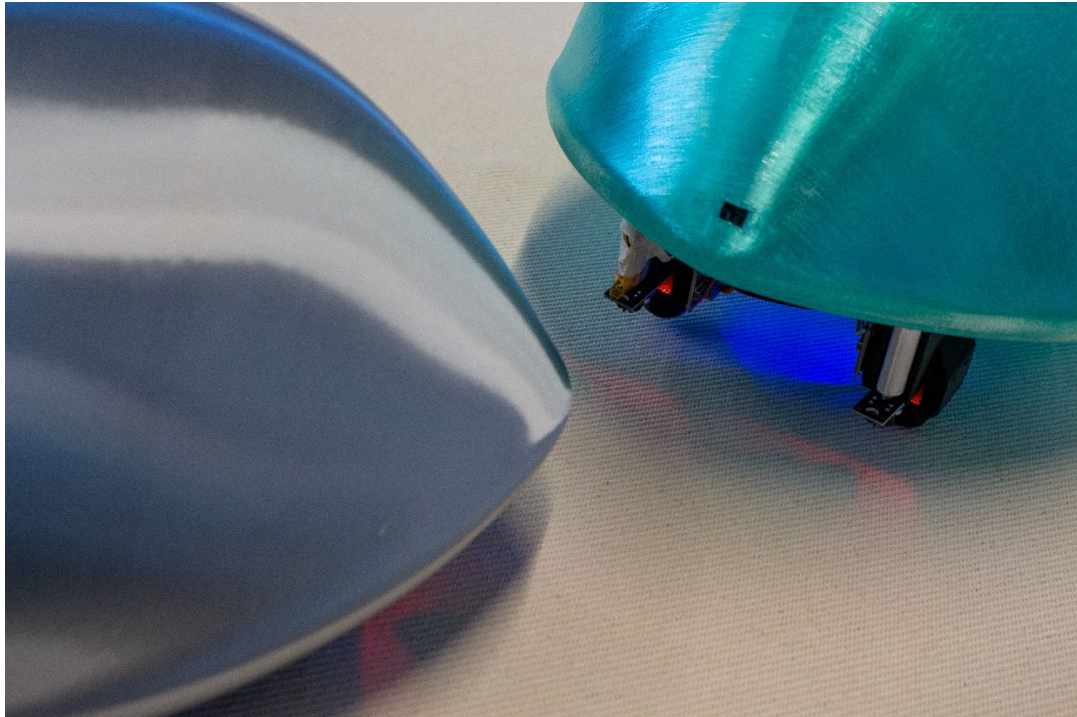


Figure 44 Two AWORMs at DFX Conspiring

On the other hand, DFX exposed AWORM to human encounters other than the designer. People come in without knowing anything about them and start to engage with AWORMs, interpreting AWORM in their own way and imagination. A notable finding for AWORM is how people talk about it, and what vocabulary was chosen. Initially I used engineering terms such as “Servo doesn’t have enough power”, “Leg stuck”, “Bugged” and other vocabularies often found describing robots, machines and programs. What people used instead were terms describing a creature, such as: “Resting”, “Mad”, “Kissing”, “Bonding”, “Chasing” and “Trying”.

Use of creature-like terms set the tone for AWORM’s behavior and created a narrative for AWORM to reside in. It is no longer a singular designed object floating around in space, it becomes a creature with story, relationships and physical presence.



Figure 45 Melanie Yan Bonding with AWORM

Photo by Nicholas Puckett at DFX

Drawing from both of findings, a first aid kit was designed, reframing the repair of AWORM to applying first aid to it. The first aid kit consisted of a pair of leg mechanism, a pair of silicone feet, screws and bolts, tools to work with AWORM, bondages, replacement batteries and replacement components incase any component fails.



Figure 46 First Aid Kit Designed for AWORM

Chapter 5: Conclusion and Future

5.1 Conclusion

Iterative Creatures set out to be an art research project, aiming to create an unhelpful robot to humans and take human designer's intentionality out of the equation. It ended up with an autonomous robot roaming on the platform and an investigation on what role human intentionality plays in the design of a non-human centric robot and how the relationship between a designer and robot can be mitigated in the design process.

Through the making of AWORM and ABOT, it becomes evident that the major challenge for this project is to mitigate human intentionality instead of removing it, human intentionality cannot be removed and will always permeate.

In ABOT, human intentionality come inherently as ABOT is a man-made robot that is made to be presented to humans. Being close to human gives ABOT meaning, both by having humanly features like face and eyes, and by holding the designer's human intentionality. However, in order to design a non-human centric robot, robot agency should take up some space alongside with human intentionality, it doesn't come before or after human intentionality, in an ideal world they could and should co-exist in a robot.

There are also other intentionalities contributing to the construction of the robot, including the standardized M2 and M3 screw, PCB board manufactures and 3D printing. AWORM in a way is a combination of intentionalities,

The mitigation is done by granting robot agency through the iterative process of observing, fabricating and interpreting robot behavior. Viewing the robot as a collaborator instead of a designed or research subject. Throughout the process, human designers establish a relationship with the robot by physically addressing the robot's behaviors, when it is struggling to move, human designer help it move by designing and 3D printing new leg mechanism. Then the robot with new leg mechanism can present a series of new behaviors, which will be observed and interpreted by the designer to scanning for other points of assistant.

To communicate with a non-communicative collaborator. Iterative Design, Rapid

Prototyping and Critical Making enable *Iterative Creatures* to view robot as the user and inclusion of the user in the development allows the designer and robot to have a stable, rapid channel of communication, each new iteration can be seen as a message sent by the designer, and how robot behaves in the physical space in that iteration is the response, i.e. how the robot's behavior changes with a new leg design.

Iterative Creatures also presents an experimental platform to act as a research instrument to investigate Hardware Artificial Life. Providing both a case study on Hard A-Life and the adaptation of contemporary technology in the discourse. It establishes common ground for future Hard A-Life study, alongside the help from 3D printing and PCB, *Iterative Creatures* can be accessed by anyone in the world with access to those two technologies.

Taken Together, *Iterative Creatures* adds to the current discourse of Hardware Artificial Life, providing a case study, offering insights into the design process of Hard A-Life robot and general practice on the fabrication. *Iterative Creatures* also establishes a platform for Hard A-Life research, standardizing a few design choices while still allowing customization on other parts.

5.2 Looking Back at Research

Revisiting *Iterative Creature's* research contextually, sitting AWORM next to William Grey Walter's Tortoise, while AWORM present similar traits, behaviors and designs to Tortoise, Those two are fundamentally different in what role they play in the design process. Tortoises was considered as a research subject, a designed object by William and he is writing and observing it as one.

AWORM on the other hand is considered as a collaborator, it has a direct channel of input in the design process, therefore having more agency comparing to Tortoise in how itself is designed.

In result of having different roles, Tortoise ended up with a transparent shell that exposes its internal states to the designer without obstruction, offering fast, direct way to develop and understand its transient states. Whereas AWORM's role is to collaborate, it needs to be opaque to combat the designer's intentionality and the inherent hierarchy between designer and designed object, therefore allowing designer to treat it as a collaborator.

People tend generalize concepts they already know, when encountering a robot

where its structure, logic and internals aren't readily available, it triggers observation, speculation and interpretation, provides the robot with agency where it is not abstracted into just another robot but as active physical agent sharing the same space with people and acting on its own.

5.3 Future of Iterative Creature

Iterative Creatures offered interesting opportunities during the development process, while there is potential for a range of different topics, a selection of a few will be mentioned.

Upon the examination of AWORM, it becomes evident that AWORM is experiencing an evolutionary process, it is iterating its physical form and adapting to the environment, designer is manually evolving AWORM with a 3D printer. The leg evolution provides ample evidence; it would have been totally different if AWORM were tested on a different surface.

The difference between robots developed in different environment is a key area for exploration, as mentioned earlier, the feet design is a very important local adaptation done by AWORM. Without the silicone feet it struggles to move due to the low surface friction in the studio space. What would happen if AWORM is developed in a noise-sensitive environment, or zero gravity?

Secondly, the dynamics between human and robot require another look, during DFX and throughout the design process it become apparent that the human robot relationship is more than just collaborators. Human designer is offering labor to design, install and evaluate for the robot, this reversed dynamic to conventional robot offering service to human also include emotional attachment and social attachment where at one point during DFX, when AWORM fall off the platform, everybody starts to look for me, the human designer almost as if I'm AWORM's parent. There are a lot more to explore in the relationship between designer and robot, and how their relationship is perceived by the greater audience.



Figure 47 AWORM in Park with Pigeons

Finally, *Iterative Creatures* is an ongoing project, its immediate future lies in more code-based development and finding the minimal viable robot that can present the same level of agency and finding more goals for the robots. Future investigation may include: How to build a robot-human relationship that is non-hierarchical, natural and spontaneous.

Appendices

Appendix 1: GitHub page

3D printable models, code for both AWORM and ABOT, Diagrams, schematics and PCB layout all can be found and downloaded from this GitHub Repository, along with a fully detailed guide on how to use the Iterative Creatures Platform, from ordering the PCB to moving your first AWORM.

GitHub Link: <https://github.com/Hzhao-ocad/Iterative-Creatures>

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