DeciZebro

The design of a modular bio-inspired swarming robot

Mattijs Otten
Master Thesis - Integrated Product Design
Faculty of Industrial Design Engineering
Chair: Erik Tempelman - Coach: Rob Scharff

TU Delft

Acknowledgments

This project is the culmination of a 5 years of studying at the TU Delft. During this period many teachers and professors contributed indirectly to this project through their enthusiasm, knowledge and passion for education. I would like to extend special thanks to the chair of this project, Erik Tempelman. Through his hands-on experience of what it means to actually make a product reality, he has helped this project to reach concrete results and go even beyond that. His questions triggered me as a designer to become aware of responsibilities and role as designer in multi-disciplinary teams.

Rob Scharff, the coach for this project, helped me to remain focused at the important matters. Any large design project is in serious jeopardy of losing focus, and through weekly meetings Rob helped to direct my attention at the most important issues at hand. His help with arranging prototyping equipment was critical to producing the necessary prototypes.

Zebro Team supervisor Edwin Hakkennes greatly helped with integrating the design approach in a team consisting mostly of electrical engineers. I owe him great thanks for helping to create an efficient work-flow and cooperation between many different engineering disciplines. Chris Verhoeven, leading professor of the project, helped inspire me to think beyond limiting questions, and dare to dream and envision. His enthusiasm is truly inspiring.

Special thanks also to Lisanne Kesselaar who invested much of her free time in developing the necessary electronics to help Zebro function as soon as possible. Thanks also to the entire Zebro team; to Floris, Laurens, Martijn, Remco, Jeffrey and Maneesh; working at Zebro has been a truly enjoyable and inspiring learning experience.

Executive Summary

Within this report is described the process of designing a new Zebro robot for the TU Delft Robotics Institute. Zebro is a six-legged robot specifically intended to become one of the first truly autonomous swarming robots on earth. The specific aim of this project was to design Zebro to become ready for series production, and to become a robotic platform that allows future students and companies to build upon.

This report covers an analytical phase (Chapter 2), aimed at examining the roots of Zebro and giving theoretical background regarding swarm robotics. Furthermore, a detailed oversight is given of the approach used to redesign the robot (Chapter 3). Several prominent design methods have been used within this project, including the modular approach, concurrent design approach and design for assembly. The motivation for choosing these methods, and the implications of using these methods is described within the analysis phase.

Two chapters are dedicated to the process of designing DeciZebro. These chapters show the reasoning behind design choices (Chapter 4) and ends by presenting the final result (Chapter 5). The result is a modular robotic platform called DeciZebro which can be mass produced. A series of 10 robots was produced within the context of this project as proof of concept for its manufacturability.

The final chapter (Chapter 6) of this report takes the design out into the world and asks the question; how will this robot be implemented in society? Because no autonomous swarms exist yet, this question can only be answered once the Zebro platform is working. However, within this chapter suggestions are given.

In the appendices a technical data package can be found, detailing the different parts featured in Zebro. Furthermore, a selection of important design decisions is shown within the Design Tree appendix.

Table of Contents

1. Introduction

This project is part of the Integrated Product Design (IPD) master at the faculty of Industrial Design Engineering (IDE) at the University of Technology in Delft. This project functions as the final design project that finalizes the master program. As such, the goal of this project for the student is to prove mastery over the skills associated with IPD. Furthermore, it is key that the student demonstrates a capability to adjust to different design contexts and operate efficiently together with experts from different fields of engineering and design in general. An attitude aimed at learning and performing is important.

This project is performed within the TU Delft Institute of Robotics. This institute is responsible for key projects within the domain of robotics in Delft. Examples of projects by the TU in the field of robotics include the DelFly (Figure 1a), the Delfi N3xt and C3 Satellite (Figure 1b) and numerous other projects. The Zebro (ZEs Benige RObot, Dutch for Six Legged Robot) project is one of these (figure 1d). Originally inspired by the RHex robot designed by the Penn State university and Boston Dynamics(figure 1c), Zebro is a unique, bio-inspired, crawling robot.

The goal of the TU Delft in continuing the Zebro legacy is to design it to become a platform for swarm robotics testing. Swarm robotics involves the copying of group behavior of animals by robots, the goal being to create autonomous swarms of robots. Being relatively slow in nature, and capable of scaling natural terrain, the Robotics Institute believes Zebro is a suitable platform to test swarm robotics with. For information regarding swarm robotics the reader is referred to section 2.4 of this report.

This project takes place within the Zebro team and is meant to facilitate the transition from prototypes to series production and possible mass production in order to facilitate swarm robotics testing. As such, a target for series production is set, and a concurrent design method is used. As stated by Tang, Zheng, Li, Li, & Zhang, (2000), Concurrent Design (CE) is "a philosophy that suggests the need to consider design issues simultaneously where they were considered sequentially in the past". In relation to this project, it means design considerations across disciplines (electromechanical, mechanical engineering, software and industrial engineering) are taken into account simultaneously, with the goal of realizing series production. As such, questions like 'how can this part be produced, assembled and at what cost?' or asked from the very start of the project.

Figure 1a: The Delfly (Lentink et al, 2009)

Figure 1b: Delfi N3xt Satellite (DelfiSpace, 2013)

Within this report, the design of a Zebro for series production is described. What might stand out to the reader and be slightly puzzling is the apparent lack of a clear use case and target group for Zebro. Instead of solving a problem and adhering to criteria derived from this, the design process within this project focuses at the creation of a testing platform. Rather then solving a problem, the Zebro designed within this project is aimed at facilitating experimentation with swarm robotics. As long as no such platform exists, the possible societal uses for swarms are based on speculation. The potential for autonomous robotics is believed to be very high, and the design of a platform to start verifying this belief on is what this project is about.

First, the context within which this project takes place is examined in chapter two. The reader will find this chapter useful to gain a general understanding of the principles of swarm robotics, and the specific way in which the Zebro functions. Furthermore, the reader will be informed about the relevant history of the Zebro team, which has a strong influence on the way this project is executed.

In chapter three the approach towards this 6-month design project is described. This approach arises from the context and goals, and within this chapter the reader is informed regarding the methods to be used and the general planning of the entire project.

Within chapters four to six, three design phases are presented. Each phase aims to take the design of Zebro to a next level, both in quality and quantity. The first design chapter (chapter 4) describes the design of a single prototype. The second design cycle describes the transition towards a series of 10, and the third outlines the future steps within the development of Zebro.

During this project numerous design decisions were made, too many to cover within the report itself. For this reason, the reader is referred to the Design Tree (Appendix C) for further information. During this project many parts were designed, which are fully detailed within Appendix B, the technical data package. Within appendix A a roadmap to future implementation is provided, extending the scope of chapter 6.

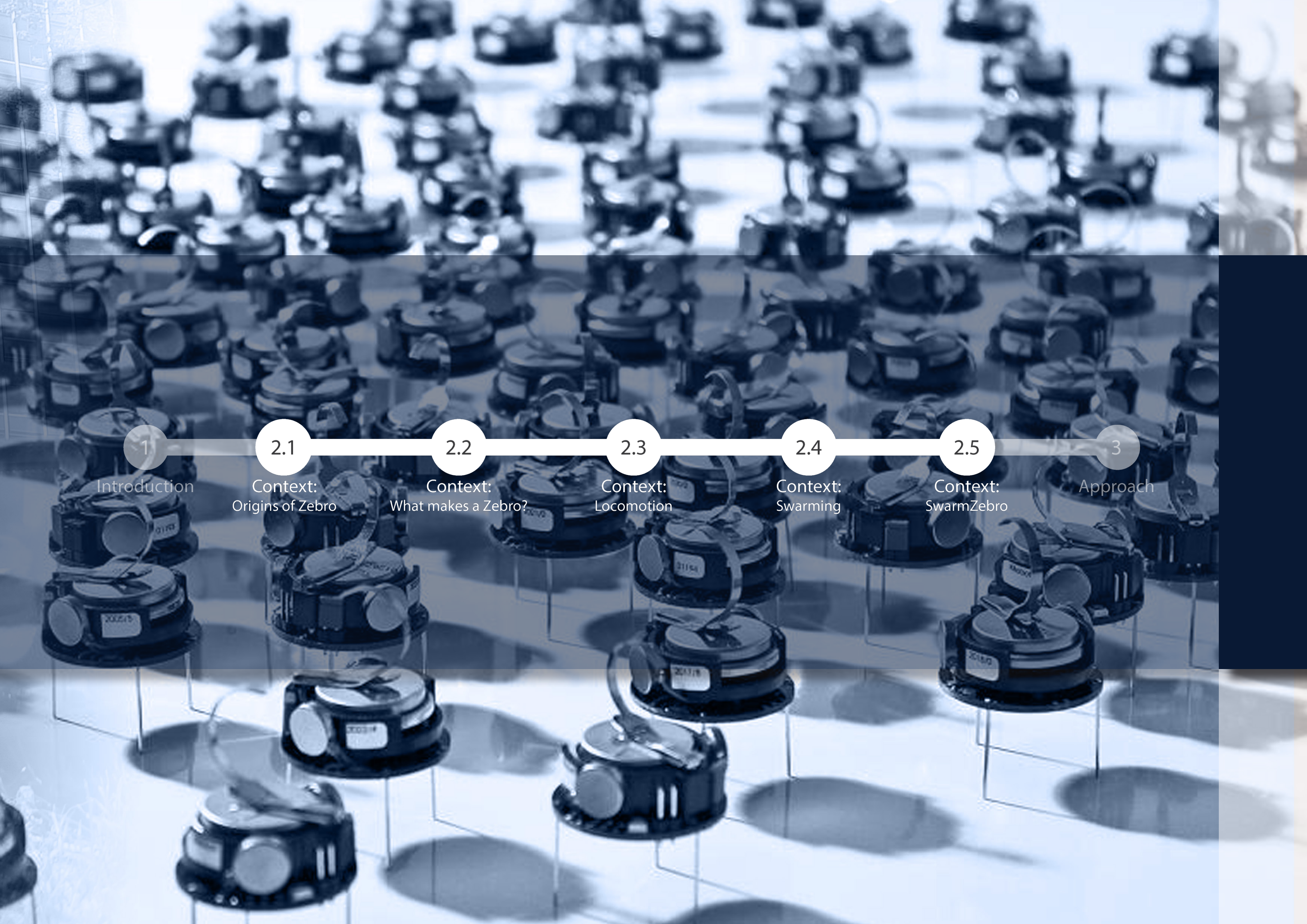
Figure 1a: RHex (Boston Dynamics, 2012)

Figure 1d: One of the Zebro's

2. Context

This graduation project takes place within the context of the Zebro Robotics team at the TU Delft. As such, the team's goals and history are of great importance to the project. Taking a critical look at the team's past achievements and analyzing the goals of the team contributes to a better understanding of the necessary design approach to take.

Within this chapter the origins of the six legged robot (Zebro) are explored. A definition is given of what makes a robot a 'Zebro'. Furthermore, the different Zebro's that have been designed within the Zebro team are discussed. A special interest is taken into Swarm Zebro, the first attempt at series production of Zebro for swarming purposes. Based on this robot, the two elements that define Zebro are examined: Locomotion and Swarming. These topics are explored in detail and allow the reader to understand the concept of Zebro in a deeper way.



2.1 Origins of Zebro

During the early 2000s Boston Dynamics developed a robot named RHex (Boston Dynamics: Rhex, 2012) for DARPA (Defense Advanced Research Projects Agency) in the US. It's main use was to be a rough terrain scout robot. Sparing no expenses, this robot was designed to perform. This resulted in an expensive robot which was mostly useful within the army context. Its main goal was exploration, and therefore it was designed for rugged terrain, with a focus at being robust and unstoppable.

The project was discontinued, and was picked up by universities across the US. Notably, the University of Pennsylvania redeveloped RHex to be both modular, simpler to produce and more cost-effective ("Kod*lab : RHex", 2012). Still, series production was never intended, featuring mostly expensive single prototypes.

In 2010 Gabriel Lopes, who worked on the design of six-legged robots in the US (University of Pennsylvania and Michigan) became assistant professor at the TU Delft and brought with him the idea of using animal like walking patterns to incorporate into robots. A first six legged Zebro was designed (Figure 2a). In 2012 it was decided by the TU Delft that research needed to be done into swarm robotics, and Zebro was chosen as the favored platform to test swarming on. This choice was made based on the similarities between Zebro and many insects. Having no wheels, it walks just like many insects do. Insects are one of the main sources of inspiration for the field of swarm robotics, and hence the two were combined.

After the first Zebro was constructed in Delft (Figure 2a) a new and improved design was made by a team of students, supervised by Gabriel Lopes. This Zebro, named 'Zebro Light' (Figure 2b) cut weight by over 50% (down to 3.2kg) and successfully demonstrated a cockroach-like walking gait. With the design of this robot, the Zebro team was founded. The goal, as stated, is:

To design, plan and build self-deploying, fault-tolerant, inexpensive and extremely miniaturized robust autonomous roving robots to cooperate in swarms, capable of functioning on a wide spectrum of topology and environment that can quickly provide continuous desired information with the help of distributed sensor systems and carry and support payloads suitable for a wide range of missions.

From the second half of 2016 onward, the Zebro team focused on three different Zebro designs: KiloZebro, a large Zebro with interchangeable leg modules capable of handling rough conditions on planetary exploration missions. Next, there is PicoZebro (Figure 2d); a matchbox size robot aimed at simulating swarm robotics in a contained environment. It is currently operational and frequently exhibited, drawing a lot of attention. Swarm Zebro (Figure 2c) is aimed at taking a step into the direction of Zebro becoming a swarming platform, and was aimed at taking a first step towards Zebro's that can be produced in series.

Figure 2a: Gabriel Lopes' Hexapod (TU Robotics Institute, 2012)

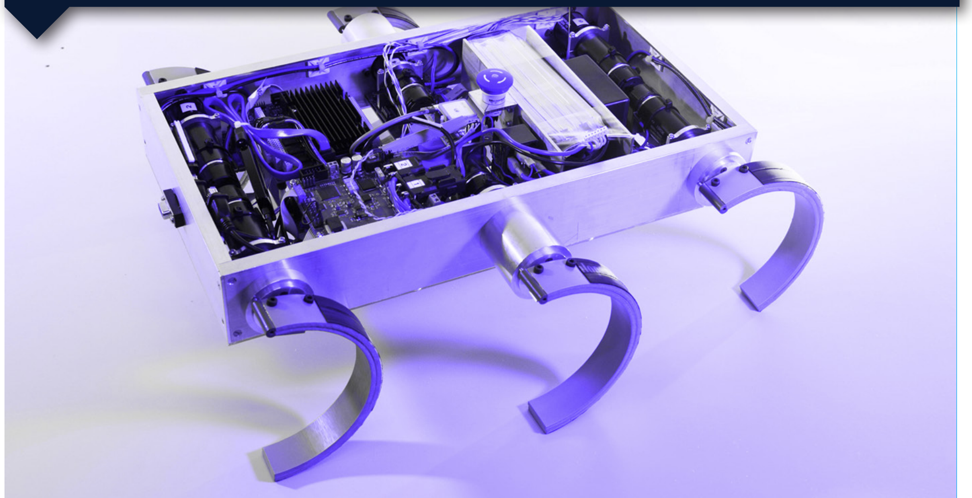
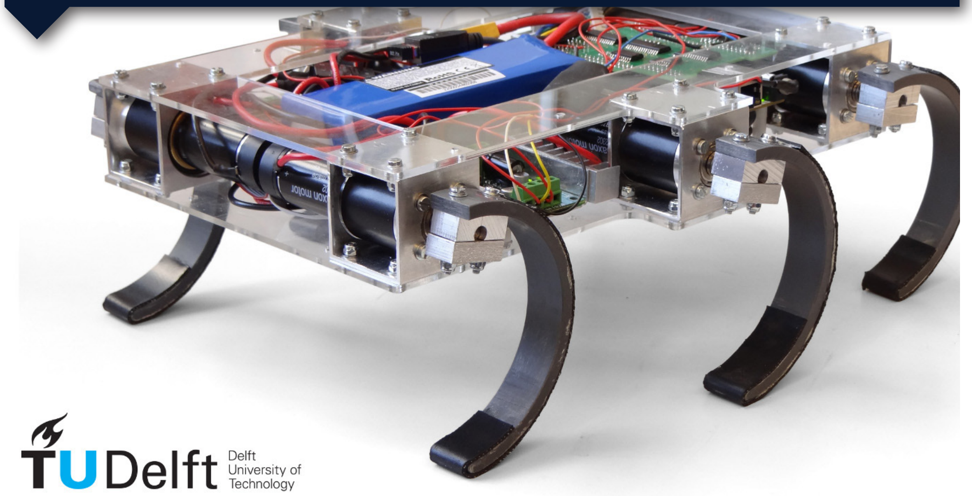


Figure 2b: Zebro Light (Robotsquare, 2013)



2.2 What makes a Zebro?

Locomotion

Zebro is unique amongst robots due to its method of locomotion. If speed is needed, most robots (or cars, or most other forms of transport), use wheels. Wheels efficiently transfer torque to a preferably flat surface, and are capable of reaching high speeds. However, on rough terrain, wheels fall short. Zebro does not use wheels, but C shaped legs. Much like a beetle, it moves itself by rotating pairs of legs in an alternating way (Figure 2e). In this way it can scale large objects and is virtually unstoppable. When encountering objects too large to climb, it will keep rotating its legs until it finds some way around it. It outperforms wheels and continuous tracks on rough terrain, and provides a stable and natural way of locomotion. Looking at Zebro, one is likely to make the comparison with an animal. This quality is both endearing and amusing, and adds to what 'makes a Zebro'. The subject of locomotion is further explored in paragraph 2.3.

Swarming

"the study of how large numbers of relatively simple physically embodied agents can be designed such a way that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment." (Sahin, 2005)

Setting the TU apart from other institutes working on six-legged robots is its aim to develop Zebro as a platform to test swarm robotics. If this would succeed Zebro would be one of the first (if not the first) platform worldwide on which this testing can actually take place. The implications of this approach are widespread, redefining the entire way in which the Zebro's must be designed. The topic of swarm robotics is further covered in paragraph 2.4.

Figure 2e: Zebro uses an alternating tripod walking gait

Figure 2c: Swarm Zebro (R. Buitenhuis, 2016)

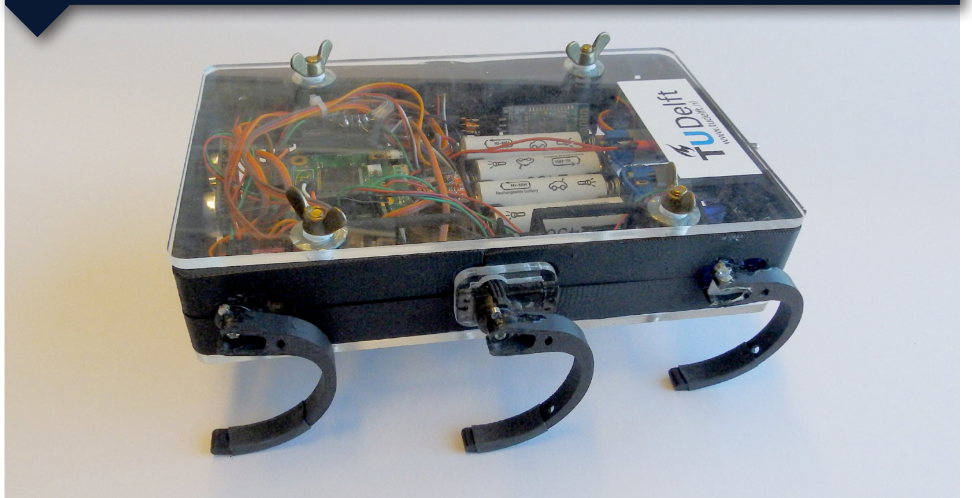
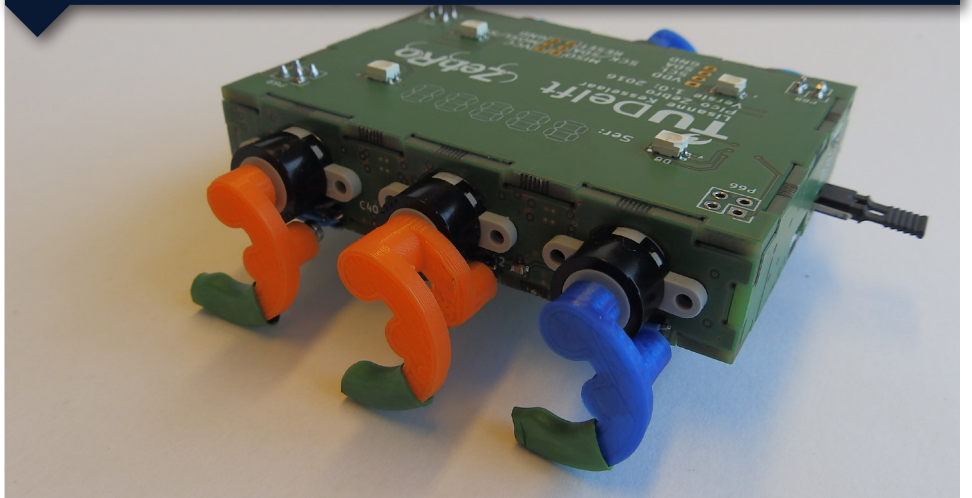


Figure 2d: PicoZebro (L. Kesselaar, 2017)



2.3 Locomotion

One of the most important things for a Zebro to do, is to walk. Within this section the way Zebro walks is analyzed. Simple formulae are presented that help to quickly understand the principles of walking like insects using C-shaped legs. Climbing and walking are discussed, as well as the necessary lift weight. By understanding these underlying principles the design of a new Zebro will be much easier. The examples are given based on the design of SwarmZebro (Figure 2c).

Climbing

For climbing, several things are important. First of all, the radius of the legs determine the maximum height Zebro can climb (Figure 2g). This height is measured from the shaft of the motor (the rotation point) to the outer tip of the leg, and is called the leg radius (L_r). The maximum radius available for a leg is determined by the size of the body (Figure 2f). As each side of Zebro has 3 legs and these legs cannot pass in front of each others motor shaft, the minimum length of any Zebro will be its L_r*2 plus at least an extra 2cm in total as clearance for the motor shafts, L_{c1} and L_{c2} (the shaft cannot be positioned at the very edge of Zebro). As such, the total length of each Zebro is largely determined by these three distances.

1. Approx. Zebro Length $(Z_l) = 2 * (L_r+L_{c1}+L_{c2})$

Where all units are given in millimeter (mm)

The body of the Swarm Zebro measures 200x125mm. Its legs measure 50mm in radius. As such, it can climb close to 2x its leg radius, as illustrated in Figure 2g. This number is slightly less, as its effective point of contact lies slightly in front of Zebro. It is safe to assume Zebro can climb a height of:

2. Approx. Climb Height $(C_h)= 2 * (L_r) * 0.8$

Where all units are given in millimeter (mm)

Given these numbers, the Swarm Zebro could potentially climb obstacles of about 8 centimeters high, if enough motor power can be provided. The problem, however, is the choice of motor. The Swarm Zebro has been designed with micro servo motors capable of delivering a torque of about 2kg/cm. That means that, if the leg were 1cm in diameter, the motor could lift 2 kilograms. The leg is 5 centimeters, so the maximum effective weight the motor can lift is 400 grams.

3. Effective Lift Weight $(W_{max}) = T_{max}/L_r$

Where W_{max} is given in grams , T_{max} in N/cm and L_r in mm

Given this formula and the weight of Swarm Zebro (approx 700 grams), one leg can not lift Zebro. Two legs could, but only just. This is an important consideration to take into account when designing a new Zebro; the choice of motor is vital.

Figure 2f: Zebro length

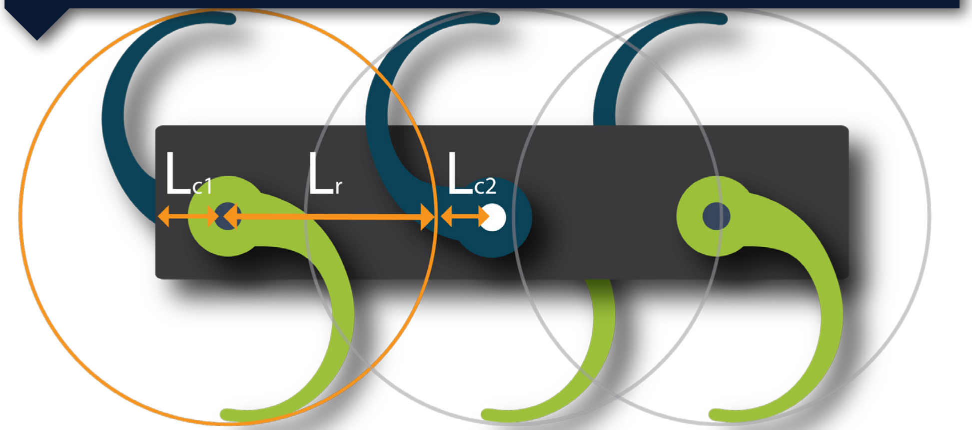


Figure 2g: Zebro climbing height

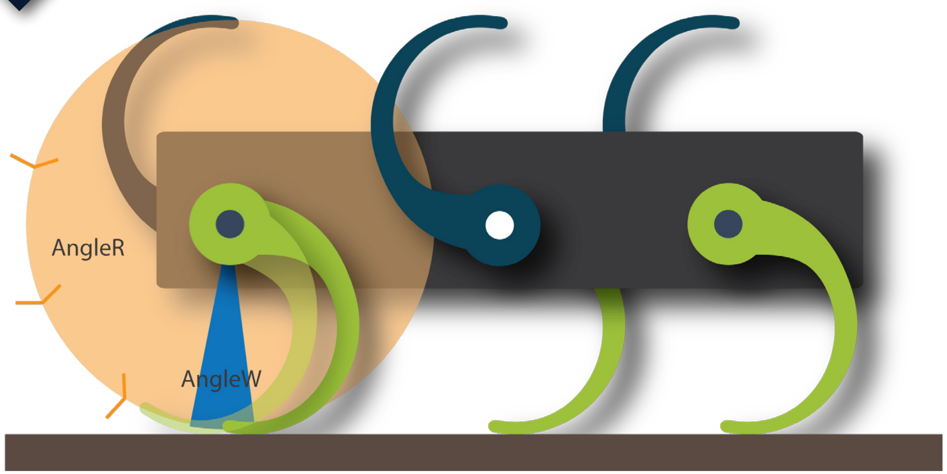
Walking

As opposed to climbing, which is mostly about motor torque, walking with Zebro demands a careful balance between torque and velocity (defined as revolutions per minute (RPM). Depending on the leg's size the leg is able to move Zebro a certain distance per revolution. During a revolution, a certain arc ($Angle_R$) constitutes rotation without contact with the ground, and a certain arc ($Angle_W$) constitutes the part where the leg touches the ground and Zebro walks (Figure 2h)

To increase Zebro's walking speed the $Angle_R$ should be traversed in a time period equal to that of $Angle_W$. As leg pair 1 (Green) walks, leg pair blue in that same time rotates. In the case of SwarmZebro the torque of the motor is quite low, meaning the time to traverse angle W takes longer then it takes to traverse Angle R. For this reason, SwarmZebro moves at about 0.18 km/h or 3 meter per minute

To work properly Zebro needs to know the position of its legs. Based on this feedback it can then optimize the walking gait. Swarm Zebro uses Hall Effect Sensors to detect changes in the magnetic field. A magnet is embedded in the leg, and as it rotates, the magnet passes in front of the Hall sensor which is then triggered. This means Zebro can detect the leg's position once per rotation and infer other positions from signal strength varations. Currently, this way of detection is not functioning correctly, and thus SwarmZebro can barely walk.

Figure 2h: Zebro climbing height



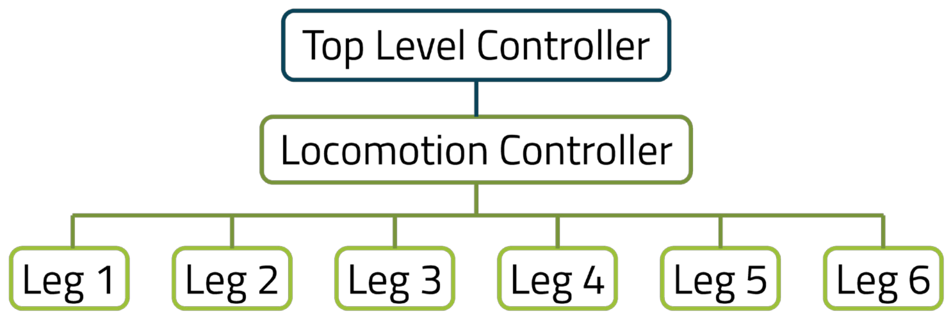
Locomotion Control

In order to be able to walk in a controlled fashion, Zebro´s legs must be controlled by a locomotion controller. This controller should be able to depend on the leg modules knowing the location of its legs. Based on this the locomotion controller should instruct each leg how and when to move, according to the defined walking gait. Six-legged walking is not limited to the alternating tripod gait as described before. The robot should still be able to work if one or two legs fail. Furthermore, Zebro should be able to switch its walking direction around. Whilst walking as described in figure 2h is most optimal for forward motion, walking in a reverse direction allows Zebro to scale high objects by hooking its legs onto them and pulling itself up.

Locomotion is a vital part of Zebro walking. It is also, however, the most difficult element to implement. Receiving correct leg position data requires accurate encoding (that is, measuring the position) of the leg. With previous robot designs, this has proven to be a great challenge.

In order to be able to show intelligent motion, the locomotion controller in its turn needs to be able to operate based on data it receives from its surroundings. Therefore, the locomotion controller must be in constant communication with a top level controller that, based on sensory input, instructs the locomotion controller (Figure 2i)

Figure 2i: Locomotion architecture (Lines show data flow)



2.4 Swarming

2.4.1 Basics of swarming

According to Sahin (2005) swarm robotics can be defined as "the study of how large numbers of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment."

Several important key concepts of swarming can be drawn from this statement. These will be discussed first. Afterwards, examples of swarms found in nature will be discussed within the contact of localization and communication within swarms.

Swarm size

Swarms typically consist of a large numbers of individuals. Deriving its archetype from nature, natural swarms often consist of hundreds, thousands or millions of individuals. In order for a group of individuals to become a synchronous ´organism´, swarming is therefore often constricted to numbers of 100 or more individuals. This means that any swarming platform must be produceable in large quantities.

Simplicity and homogeneity

Next, the agents within a swarm must be relatively simple. It is not extensive individual capabilities that make swarms effective, it is the simplicity and uniformity amongst individuals. By being uniform and simple, working together is possible and communication can be kept to simple and short messages understandable to all individuals. By working together on a grand scale, swarms are capable of achievements impossible for single specialized individuals to achieve. An ant colony will be able to survive in many different environments, being highly adaptive. Homogeneity also allows swarms to keep operating even if individuals are incapacitated. Only if a large portion of the population is no longer functioning, the swarm isaffected. In regard to robotic swarms, homogeneity also results in simple maintenance and effective repair processes. Finally, homogeneity allows economies of scale effects to reduce cost per individual. This is important, because swarming requires large numbers of robots to compete with single specialized robots.

Emergent behavior

Emergent behavior emerges as local agents in a swarm interact with each other. Group characteristics that result from decentralized interactions are termed 'emergent properties' (Clark et al. 1997).

Consider a situation where the swarm has three main instruction sets:

- Do not come within 'x' meters of any member of the swarm
- Do not be further away then 'y' meters of any member of the swarm
- While distance is between x and y (x<d<y), freely explore

In this scenario any group of robots placed together will start to evenly spread out to ensure the aforementioned parameters are met. After this has happened, the robots will start exploring. A cascade of reactions to each other will be necessary to ensure all robots meet all parameters, and the whole will start behaving as a collective; emergent behavior. In such a system, the system itself can never predict its future state but continually evolves. In order for emergent behavior to be possible however, local communication and localization between individuals must exist.

Local interactions & communication
Members in a swarm must be able to communicate with each other. The unique element about swarms is that they do not communicate via a central system, but through local interactions (Figure 2j). This is different from, for example, swarms of drones. Intel recently demonstrated swarms of 500 drones (Intel, 2016), but these drones were all controlled by a central controller. This means the drones are not autonomous and merely follow orders from a controller, and can in that sense be considered a single entity. In swarming, each individual only communicates with other individuals and receives no orders from a central controller.

In the same way that communication should not use central computing, localization should not either. For example, using GPS to know the location of all other members of the swarm does not qualify as swarming behavior, as it limits the swarm's independency. If GPS would not be available, the swarm would cease to function. Localization, therefore, means for each Zebro to sense its neighbors. If all Zebro's in a swarm see at least one other Zebro, swarm behavior can emerge.

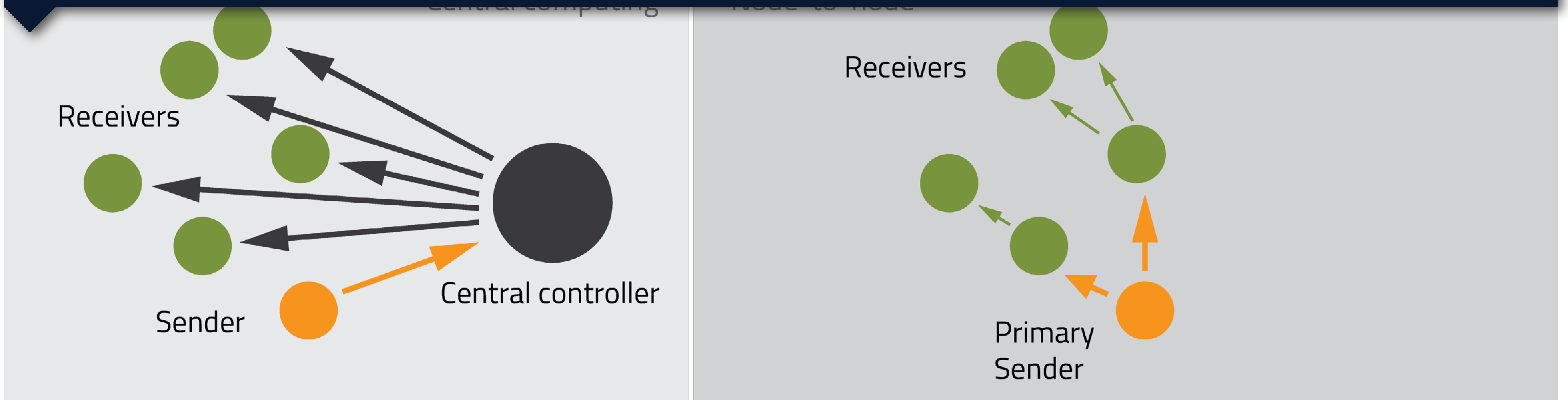
"However, most of the existing work on localization requires landmarks with known positions on the environment, addresses localization of a single robot, requires complex computations, or relies on expensive sensors. Many environments of interest prevent the use of landmarks, and in swarm platforms, computation is limited and large or costly sensors are not available" (Cornejo & Nagpal, 2015)

In order to further explore the topic of communication and localization in swarms, swarms occurring in nature are examined. For this, the reader is referred to chapter 3, section 1.

2.4.2 Applications for robotic swarms
Swarming behavior is vital to the survival of many animal species. However, the benefits of swarming can also be used to serve human purposes. Using large groups of robots, many applications can be defined based on even the most simple principles of swarming. However, none of these applications have yet been tested, due to the absence of a suitable platform to test on.

Regional exploration / sensing
By equipping a swarm of robots with sensors, they can easily and autonomously scout a large area and measure useful data. For example, search and rescue missions could benefit greatly. Furthermore, ecological research and monitoring or security patrol are area's of application. In case a potentially interesting 'source' is found, an instruction set signaling the swarm to focus n this source could also mean the source could be explored in great detail by utilizing the entire swarm to concentrate on a small area.

Figure 2j: Local Interactions in a Swarm; Central computing (Left) vs. Local communication (Right)



Hazardous Tasks

Swarm robots are, by nature, simple and relatively cheap compared to specialized robots. As such, losses are affordable. Clearing out a minefield could be done by swarms, without risking to lose costly equipment; they can afford to be lost in action. Exploring hazardous terrains autonomously can also reduce risks for humans.

Scalability and redundancy tasks

Swarms are easy to scale up or down; adding or removing any number of individuals (as long as a certain minimum threshold is respected) does not cause the swarm to function differently or lose functionality. Therefore, swarms are inherently scalable and adaptable to changing conditions. Furthermore, because the individuals are homogeneous, there is a large redundancy within a swarm. This means data is constantly verified by multiple individuals within the swarm, and anomalies can easily be detected and discarded. Compared to a single sensor or sensor network, which are static, the dynamic and flexible nature of the swarm results in more dependable information gathering.

Examples of Robotic Swarms

Swarm robotics is gaining attention as a research field, but only a limited amount of actual swarms exists. Swarming, in the full sense of the word, has not been implemented in any commercial context yet. Notable examples of ‘swarming’ include the swarmbot project (Swarm-bots, 2005) and the KiloBot project (Figure 2l) by Harvard (Rubenstein, Cornejo, & Nagpal, 2014). However, these are not examples of true swarming. The Swarm-bots come very close, but are limited in number and are highly specailized. The KiloBot swarm is focused at mass production and, in a sense, each robot determines its own path. However, its position is determined by a central controller. As such, there are currently no known autonomous swarms in operation worldwide.

Figure 2l: The Harvard KiloBot project (2014)

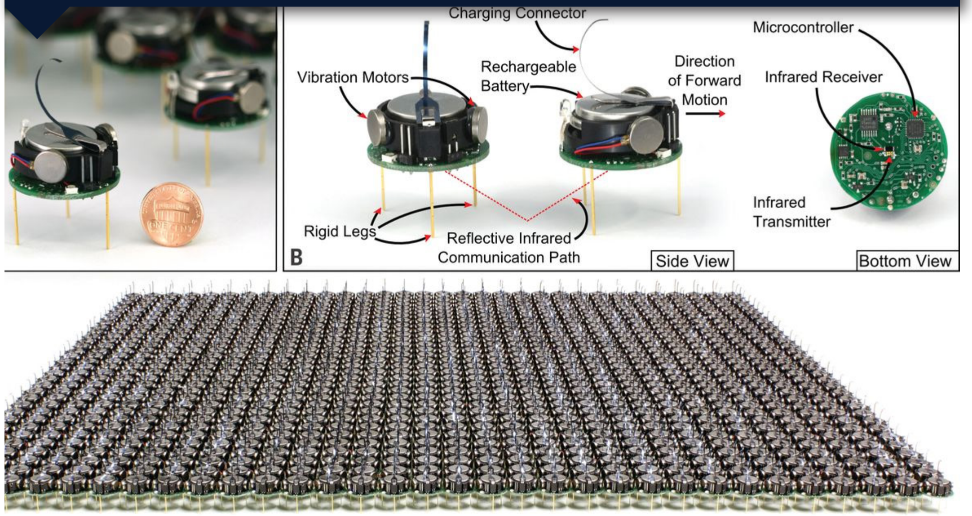


Figure 2k: The Swarmbot project (Swarm-bots, 2005)

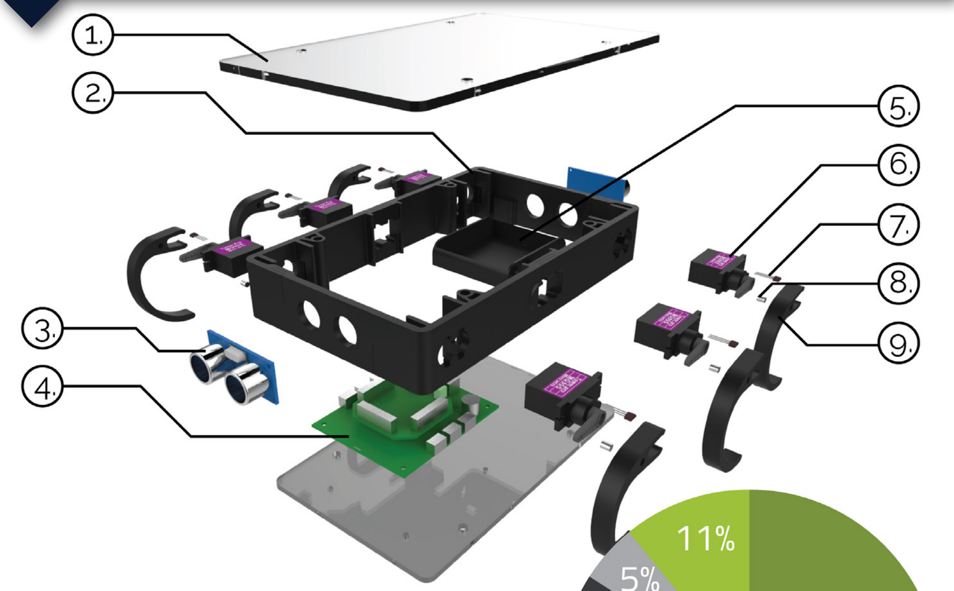
2.5 SwarmZebro

SwarmZebro (Figure 2h) is a Zebro designed by R. Buitenhuis (2016). The robot was designed specifically with mass production in mind. As such, the body of the robot was designed in such a way it could be injection molded and laser-cut. The assignment did not yet include the design of Zebro as a swarming platform, however. As such, it was not designed with this in mind. It does serve as a valuable case study and offers insights to be implemented within this project.

Locomotion

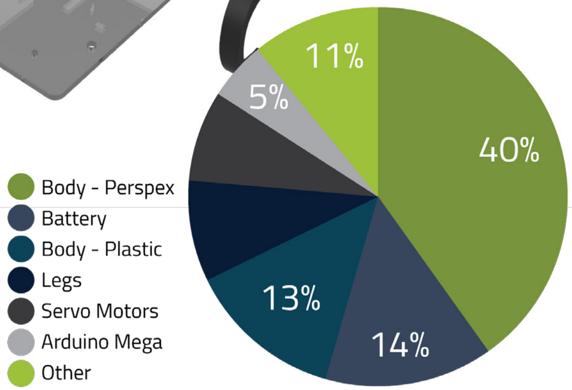
SwarmZebro uses 6 micro servo motors to propel itself. These motors have integrated motor controllers and are connected to an Arduino. The leg position is detected using Hall Effect sensors, which measure magnetic field strength. A small magnet embedded in the leg helps the sensor to detect when the leg passes in front of the sensor. At the start of this project, this system was not yet functioning properly. The servomotors are struggling to deliver the power needed to propel the Zebro. As such, the robot is operating at the edge of its ability.

Figure 2m: SwarmZebro exploded view



Zebro Parts List

1. Top/Bottom Perspex Plates
2. Main Body (8 3D printed parts)
3. Ultrasonic Sensor (Object detection)
4. Main PCB
5. Battery
6. (Servo) Motors (6 total)
7. Hall Sensor (Leg position detection, 6 total)
8. Magnet (For Hall sensor detection)
9. 3D printed legs (6 total)



Despite the fact that the body has been designed with mass production in mind, the locomotion system was not. Currently, dozens of soldering connections are required. All in all, assembling this robot takes several hours and is prone to failure due to human error. This robot could be classified as a do-it-yourself kit, rather then an industrial product. In order to design this robot to be mass manufacturable, it must be redesigned from the ground up. For every part to be designed several questions should be asked:

- With a safety margin of at least 2, does this part qualify to survive the worst-case scenario? (I.e. are the motors at least strong enough (with a safety of 2) to be able to lift the robot on one leg?
- Can this part be mass produced? What production process should be used?
- Can the parts be assembled in a quick, reliable and replicable way with a minimum error margin?

An insight into how these questions have been implemented in this project can be found in appendix C (Decision tree)

Swarming

The SwarmZebro is equipped with an ultrasonic sensor and a color sensor, giving it some ability to sense its environment. It is not equipped to detect other Zebro's, and is as such not suitable for swarming. Because of its integrated design there is no possibility for adding any modules. Neither could the motors carry this extra weight. Although the exact specifications of localization and communication modules are unknown, this design also does not facilitate later implementation of these modules.

3. Approach

Within this chapter the challenges and goals within this project are presented, along with an approach to successfully realizing these goals. First, goals of the Zebro team along with the role industrial design engineering could play in this context are presented (Section 1). These are then combined into an assignment proposal (Section 2), outlining the goals to be realized within this graduation project. Methods are presented (Section 3) that match the project goals and benefit the realization of them. Taking into consideration the context, goals and methods, an approach for this graduation project is suggested (Section 4). Within this approach key design phases are identified, along with the goals of each phase and the suggested time planning for each phase.

2 Context

3.1 Approach: Goals & IDE

3.2 Approach: Assignment Proposal

3.3 Approach: Methodology

3.4 Approach: Approach & Planning

4 Design Phase 1

3.1 Goals & IDE

To design, plan and build self-deploying, fault-tolerant, inexpensive and extremely miniaturized robust autonomous roving robots to cooperate in swarms, capable of functioning on a wide spectrum of topology and environment that can quickly provide continuous desired information with the help of distributed sensor systems and carry and support payloads suitable for a wide range of missions.
Zebro mission statement

Dealing with robotics, the Zebro team has often relied heavily on electrical engineers. This has largely shifted focus on hardware, such as printed circuit board (PCB) design. It has been mostly electrical engineers who worked to develop the individual hardware components without coordinated integration; most projects were isolated from each other. This was largely due to the fact that most team members worked within the context of a bachelor graduation assignment or a master thesis. As such, the goals of these team members were mostly limited toward achieving the goals within their own faculties´ project context, and individual goals were therefore not always aligned with team goals. Furthermore, a lack of continuity resulted from this; most bachelor and master projects take place during the time-frame of 6 months. As such, there were few long term goals and lack of integration.

The result of this lack of coordination has been that, up to 2016, the Zebro project did not show steps towards the realization of a swarming robotics platform. Many individual prototypes were created, which often failed to demonstrate flawless 6-legged locomotion, let alone function as a swarming platform. In 2016 a start was made through the design of KiloZebro, using a limited modular approach.

At the start of 2016 a full-time team manager and systems engineer, Edwin Hakkennes, was installed. The goal of his arrival was mainly to provide continuity and alignment of individual goals with team goals, thereby hoping to integrate individual projects toward realizing the Zebro goals. This led to the decision to start focusing on three main designs of Zebro: KiloZebro, DeciZebro (a replacement for SwarmZebro) and PicoZebro.

Industrial Design Engineering focuses at the design of products for mass production. This means single prototypes are always only a means to an end; namely, to create an optimized product that satisfies the needs of the users of the product. The master Integrated Product Design focuses specifically at the integration of all area's of design into physical products or product-service systems. Having basic knowledge of many area's of expertise, IPD students are able to form a bridge between these different expertises and utilize the strengths of each. Furthermore, as the IPD student is focused at the end-product and the user's needs, they are capable of working in a structured and goal-oriented way.

The knowledge of an IPD student is threefold, owing to the threefold nature of Industrial Design Engineering. Firstly, IPD is about design. It is about the bridge between technology and actual people. It is also a bridge between technical knowledge and practical implementation. Next, IPD is about industrial application. It has a natural tendency to aim towards series production, and avoid single off projects without seeing societal implementation. If a product is to be experienced by people, it needs to be produced in series. Thirdly, IPD is about engineering. About applying knowledge from many fields of engineering, and integrating this knowledge into making working products. This threefold nature brings valuable new knowledge to a team that is ready to create the world´s first swarming platform.

This graduation project, taking an integral approach, can help bring together other projects that are currently running. By aligning interests and providing long-term and short term goals the different expertises within the team can be brought together to work on the three main designs (Kilo, Deci and Pico) in concurrent fashion. Furthermore, it can be guided to do so following the principles of Design, Industrial manufacturability and engineering solutions.

3.2 Assignment Proposal

Based on the discussed context an assignment is formulated. This assignment is based on the key interest of the Zebro team:
Design a series production robotic platform capable of facilitating experimentation of autonomous swarming behavior.

General guidelines include:

- 'Swarms' are often defined as having at least 100 members. As such, the robot to be designed must be produced in series in a reliable and cost-effective way
- In order to be inexpensive, fault tolerant and easy to service, the new Zebro must be as simple as possible. Components should be easy to replace, without requiring specialized tools
- In order to facilitate series production, the design must allow easy assembly and require as little permanent connections as possible
- In order to be inexpensive yet versatile, the design boundaries must clearly be outlined: a difference must be made between the basic framework of the Zebro, and any other modules that can be implemented at a later stage. The essence of Zebro is its locomotion. If this can be realized in a way that allows for series production, and it can facilitate later implementation of swarming behavior and additional modules, it is a success. Zebro must be as a-specific as possible, as opposed to many specialized robots

The a-specific nature of the design means the designer has little tangible requirements to work on. Rather, each design decision should lead to the greatest freedom in the final product. This challenging situation is quite unique to the field of industrial design engineering, where products are often designed with a specific application, problem or situation in mind. The goal of this Zebro is to be relevant in as many different situations and applications possible.

In order to guide the design process, certain renowned design methods and are used within this project. These are presented within this section. Each chosen method will be discussed, addressing the following issues:

- Relevancy in regard to project goal and principles
- Proposed way of implementation
- Contribution/Results gained by using this method

3.3 Methodology

3.3.1 Modular Design Approach

Relevancy
Zebro must become highly flexible and adaptable to many situations to facilitate a wide variety of research. However, it must also be produced in series (requiring high investment costs and decreasing flexibility; once a design is produced, it is final). When using terms as flexibility and adaptability whilst needing series production, the modular design approach immediately springs to mind.

As stated by Ulrich & Tung (1991), modularity arises from the way a product is physically divided into components. To do so in a modular fashion means to create similarity between the physical and functional architecture of a design, and to minimize interaction amongst physical components. As formulated by Sanchez and Mahoney (1996), this reads:
*Modularity is a special form of design which intentionally creates a high degree of independence or 'loose coupling' between component designs by standardizing component interface specifications. (*Sanchez, R. & Mahoney, J.,1996).

By applying these definitions of modular design to the design of a new Zebro as specified on the previous page, the following benefits (and therefore reasons for relevancy of this design method) can be identified:

- Much of the work done within Zebro has been done in a fragmented fashion. In this sense, a high degree of independence or loose coupling already existed. However, because of a lack of communication and a common goal, all these designs were not able to work together. By consciously adding a modular framework to the fragmented team of Zebro, different groups with different goals can still work together on a single robot.
- By standardizing component interfaces it will be ensured that whatever projects the Zebro team is working on, as long as these projects follow the same standardized interface and communication protocol, they can be integrated into a single design.
- By modularizing the design, interdependency between different designs/

modules will decrease, meaning teams can work more efficiently on their own projects without constantly having to check with other individuals or teams.
- By adding modularity, new 'modules' can be developed to fit specific contexts or clients wishes. As such, an all purpose base robot can be designed which can be adapted to context through the use of modules. In this way, Zebro remains widely applicable but offers the possibility of adaptation to specific contexts.

Project implementation

By viewing the Zebro as a modular design from the start of the design phases, modules can be identified. For each module the requirements as well as the necessary interactions of this module with other modules can be determined. Team structure and communication between teams and individuals can be shaped to reflect these interdependencies. Also, the importance of each module to the overall functioning of Zebro can be determined. By first designing and testing modules critical to Zebro functioning, prototypes can be evaluated earlier on in the process.

Results

By implementing a modular design approach, the following should be achieved:

- Highly functional critical-level(Critical = necessary for basic mechanical operation of Zebro) modules that offer wide implementation options for secondary modules (that is; highly critical modules are designed to facilitate the most possible types secondary modules, for example in terms of software compatibility or size restrictions) are designed.
- Standardized interfaces between modules that allow future design teams to easily design modules that fit within the critical-level framework
- Efficient communication structure between different projects
- Scalability: although the designs are made principally for DeciZebro, they should be able to scale up or down when size is concerned
- Flexibility: The design can be adapted to specific contexts without requiring high investment costs

3.3.2 Concurrent Design Approach

Relevancy

The concurrent design (CE) approach, as stated by Tang, Zheng, Li, Li, & Zhang (2000), can be described as "a philosophy that suggests the need to consider design issues simultaneously where they were considered sequentially in the past". Rather then viewing the design process as a single sequential process applied to a complete product, rather individual design issues become design processes that are developed alongside each other. Furthermore, because the process does not take place sequentially, the standard design cycle elements may be considered at the same time. Instead of first optimizing a product, then testing it and then evaluation whether it is viable, the designer may start from the assumption the product will be produced in series. From this assumption onward, the designer sets a goal regarding the point in time this series production should take place. Then, the designer starts to align the design process with this goal. As such, the designer does not take into account manufacturability and design for assembly only at later stages, but must take these into consideration from the start.

The Zebro team is currently not operating on a commercial level. To demonstrate a swarm is the first goal, with the underlying assumption that if such a swarm is realized, commercialization will follow naturally. Because there has never been a functional and truly autonomous robot swarm on this planet, the team is willing to commit resources toward realizing this swarm. As such, the CE design method allows the designer to exploit this certainty by adjusting the design process to the goal of series production.

Project Implementation

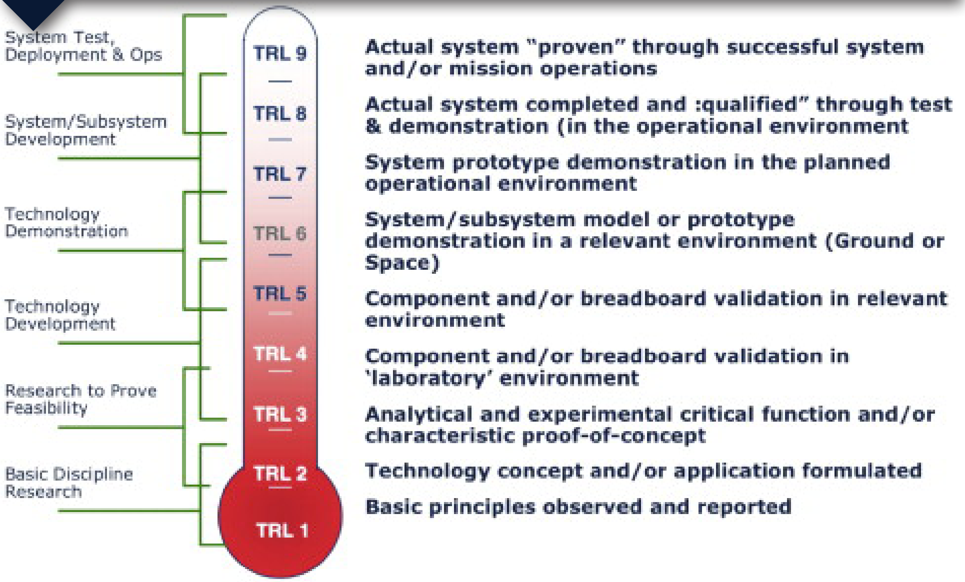
In order to implement concurrent engineering, the first thing to do will be to set goals regarding the production of Zebro. How many Zebro's are needed? When should these be realized? Next, the designer determines the different design issues and segments these into 'design tracks'. These design tracks are derived from the modular set-up of Zebro and represent different modules that have their own unique design issues. For each design track, relations and interdependencies with other design tracks are evaluated and a timeline for each design track is made. In order to achieve concurrency, it is critical to determine these interdependencies, to avoid having to stall one design track for having to wait on the results of another.

Results

By segmenting the design process whilst maintaining concurrency, the Zebro should reach the minimum required level of design progress required for series production within the set time. This should take place more efficiently by considering design issues concurrently instead of sequentially. Furthermore, by clearly segmenting different design issues in different design tracks, workload can be spread over the available manpower.

As defined within the paragraph 3.2, the aim of this project is to design a robotic platform suitable for series production for the specific purpose of implementing swarm robots. To achieve this suitability for series production a certain level of technology readiness must be achieved. Other then with prototypes, technologies that are used must be tested and proven, as series productions requires high investments and leaves little room for error. Furthermore, keeping in mind the previous Zebro designs, little is gained by creating another Zebro platform which is suitable only for one application.

Figure 3a: NASA's TRL system (Mankins, 2009)



3.3.3 Technology Readiness Levels

In order to estimate the level of technology readiness, the TRL (Technology Readiness Level) used by NASA (Mankins, 2009) can be used. This method utilizes a set of 9 readiness levels (Figure 3a). Key subsystems of a product are assessed and assigned a readiness level. Before series production can commence, all subsystems should reach TRL 6, after which they are tested together to reach TRL 7 and 8. At this level the design qualifies for specific investments required to reach series production.

When assessing the current Swarm Zebro (figure 2e) in regard to the goal of reaching series production aimed at implementing swarm robotics, only very low TRL values can be assigned. Regarding communication, localization and swarming TRL 0 is assigned. Since there is no clear overview of possibilities and no informed decision has been made as to the best method of communication and localization in regard to swarming and series production, this value assessment is justified.

In regard to series production, basic principles have been observed. However, the SwarmZebro is still designed for a specific kind of motor and overall set-up. Still, the principle of using plastic wall pieces with acrylic top/and bottom is validated as being a strong and mass produceable option. However, because it has not been designed with modularity in mind, TRL 2 is given. The housing will have to be designed with modularity in mind.

In regard to locomotion, TRL 3 is given. Zebro can walk, so the critical function of moving through the use of rotating legs, has reached proof of concept. Still, many improvements need to be made. Design considerations must be applied at a fundamental level, revisiting decisions on motor type and leg detection methods etc.

3.3.4 Design For Assembly

Design for assembly (DfA) is described by Boothroyd & Alting (1992) simply as 'the design of the product for ease of assembly'. This is especially relevant for this project due to the fact that the current Swarm Zebro (figure 2c) takes hours to assemble and test, due to, amongst others, the many soldering connections that need to be made. It is crucial, if large series of the new robot are to be produced, that design for assembly is taken into account from the start. The designer needs to ask, for every new part, how it is assembled and whether simpler or less labor intensive options are available. Permanent connections should be avoided, as well as the requiring of specific tools or equipment.

3.3.5 Design and Meaning

Product designers need to be aware of the meaning people attach to their products. The Sony Walkman revolutionized music, as it now allowed people to carry around their own music. The meaning attributed to it was that of portable music. Owning a Sony Walkman meant being able to transport your music around and listen to it any moment. The Senseo coffee machine means one can brew coffee without the hassle of swapping filters, meaning the coffee brewing process is clean and fast.

Likewise, robots have meanings in people's lives. For many, robots mean very little. We are vaguely aware they operate in the background, either in production facilities or as digital 'robots' managing big data. The mental picture that we, however, have of robots is the picture shown to us by Hollywood; human-like machines, often with evil intent.

In order for any robot to become part of a culture, people must attribute favorable meanings toward it. Zebro, being part of a swarm robotics movement, shows many similarities with animals. As such, Zebro should be viewed as a new kind of animal. If the design of DeciZebro can help people see it as an animal and treat it likewise, integration into society is much more likely. As such, the designer needs to ask; what does it mean to be an animal (more specifically, an insect?). Answers to these questions can translate into tangible design decisions.

For example; insects are found to be scary if they are unpredictable. As long as it sits still, a beetle is not found to be very scary. If it suddenly opens it wings and flies unpredictably and in close vicinity to us, we tend to become aggressive. As such, the design of DeciZebro should allow people to understand it, thereby giving them insight into its behavior and allowing them to decide how to react. The behavior and looks of DeciZebro should facilitate this.

Because this project is centered around the design of Zebro as a platform, no clear target group will be chosen. For this reason, there are no specific requirements for meaning attribution. Therefore, the principle of design and meaning is applied generally throughout this project and is not leading. Deci is designed to be inviting and look happy. Further then this the design cannot go until the target group is specified. Within section 6.3 the topic of meaning and interaction is explored further.

3.4 Approach and Planning

Within the previous chapter a number of methods have been described. These methods provide the framework for the approach towards this design project. One of the main guidelines provided by the methodology is the need for segmentation/modularization of the Zebro design. In order to be able to deliver an integrated product solution, all aspects of the Zebro design are taken into account and grouped into 6 distinct 'design tracks'.

Design Track: a design cycle, specifically aimed at developing a subsystem of Zebro, that has as the least possible interactions with other design tracks thereby ensuring modularity and loose-coupling. Each design track reflects a critical subsystem needed to come to a working swarm robot.

6 design tracks are identified. Each design track is shortly described below:

- **Top Level**

Top Level control is responsible for Zebro's swarming behavior. It provides a backbone for internal communication in Zebro using a I²C communication protocol, called ZebroBus. This standardizes communication between all modules under one protocol. Top Level control also recognizes any additional plugged in modules and uses input from these modules if needed. It is the ´central brain´ of DeciZebro

- **Communication**

The communication module is responsible for communicating to other Zebro's. Reasons for communicating may be passing through an important event or , for example, signaling the swarm its battery is about to run out. Using a node-to-node type of communication, each Zebro should also be able to relay messages from other Zebro's.

- **Localization**

Localization is about Zebro sensing it´s environment. Three levels of localization can be implemented. The first is detecting static environment. This is about basic collision avoidance. If any Zebro is capable of this, it can autonomously maneuver in any environment. Detecting other moving objects or people is a different story. Interpreting movement and seeing and interacting with humans would require improved sensing. Seeing other Zebro´s requires identifying them as being Zebro´s. This means some kind of identifier must be visible on a Zebro, and must other Zebro´s must be able to see this identifier and recognize it.

- **Locomotion**

The locomotion design track consists of 6 leg modules that are controlled by a central controller, called the locomotion controller. This controller controls the leg modules and tells them what to do. Each leg module consists of a motor and a leg, and should be a closed system.

- **Power Supply**

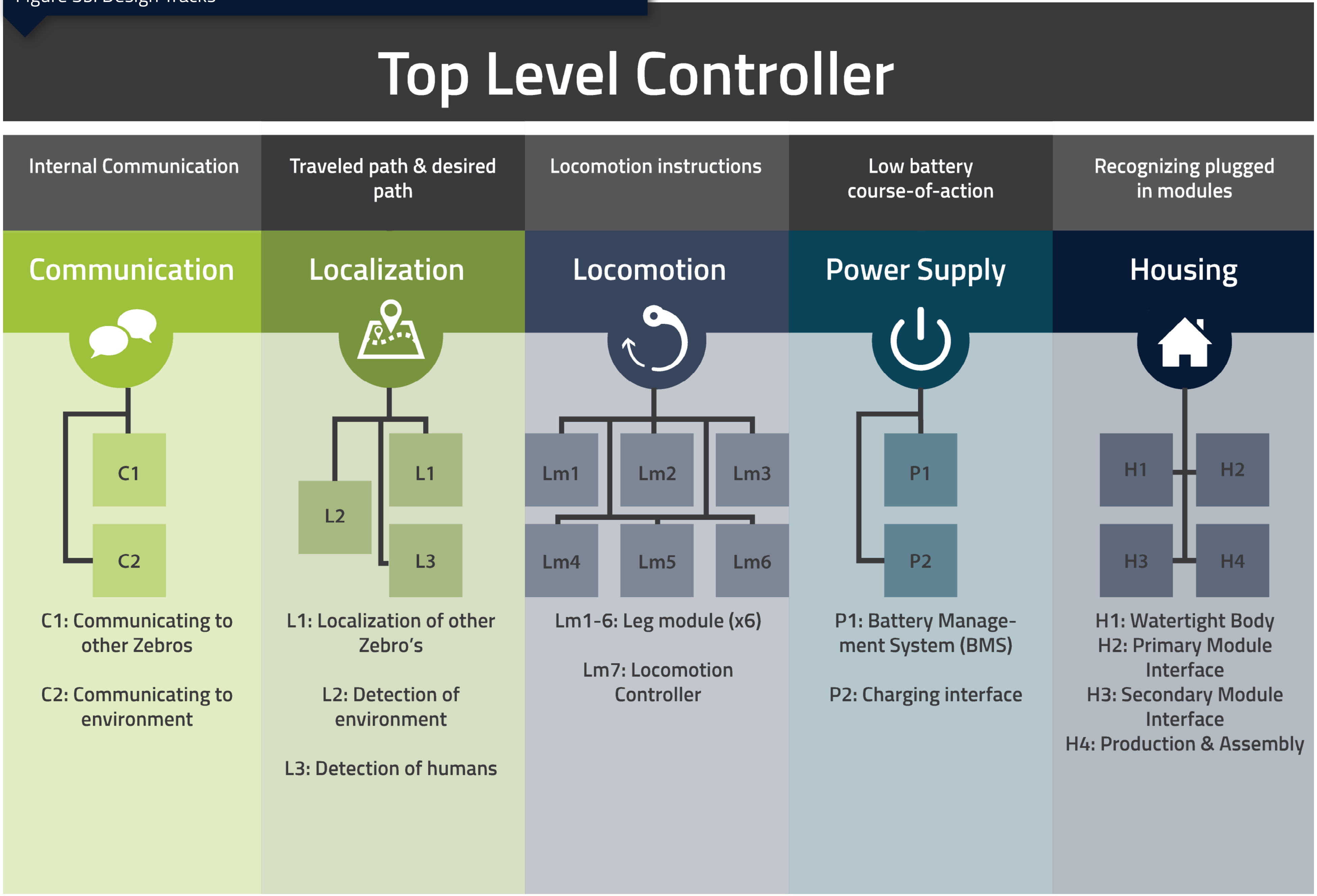
Power supply is responsible for delivering the correct voltages and currents to each module. Broadly speaking, motors require higher voltages as sensors etc. Furthermore, power supply is responsible for measuring battery charge and signaling top level in case charging is needed.

- **Housing**

The housing brings together all modules under one roof. It should therefore offer easy insertion and replacement of these modules. Flexibility is the key term. The mechanical interfaces between the module and the housing should facilitate this.

On the next pages, a visual representation of the design tracks (Figure 3b) and system architecture (Figure 3c) is given.

Figure 3b: Design Tracks



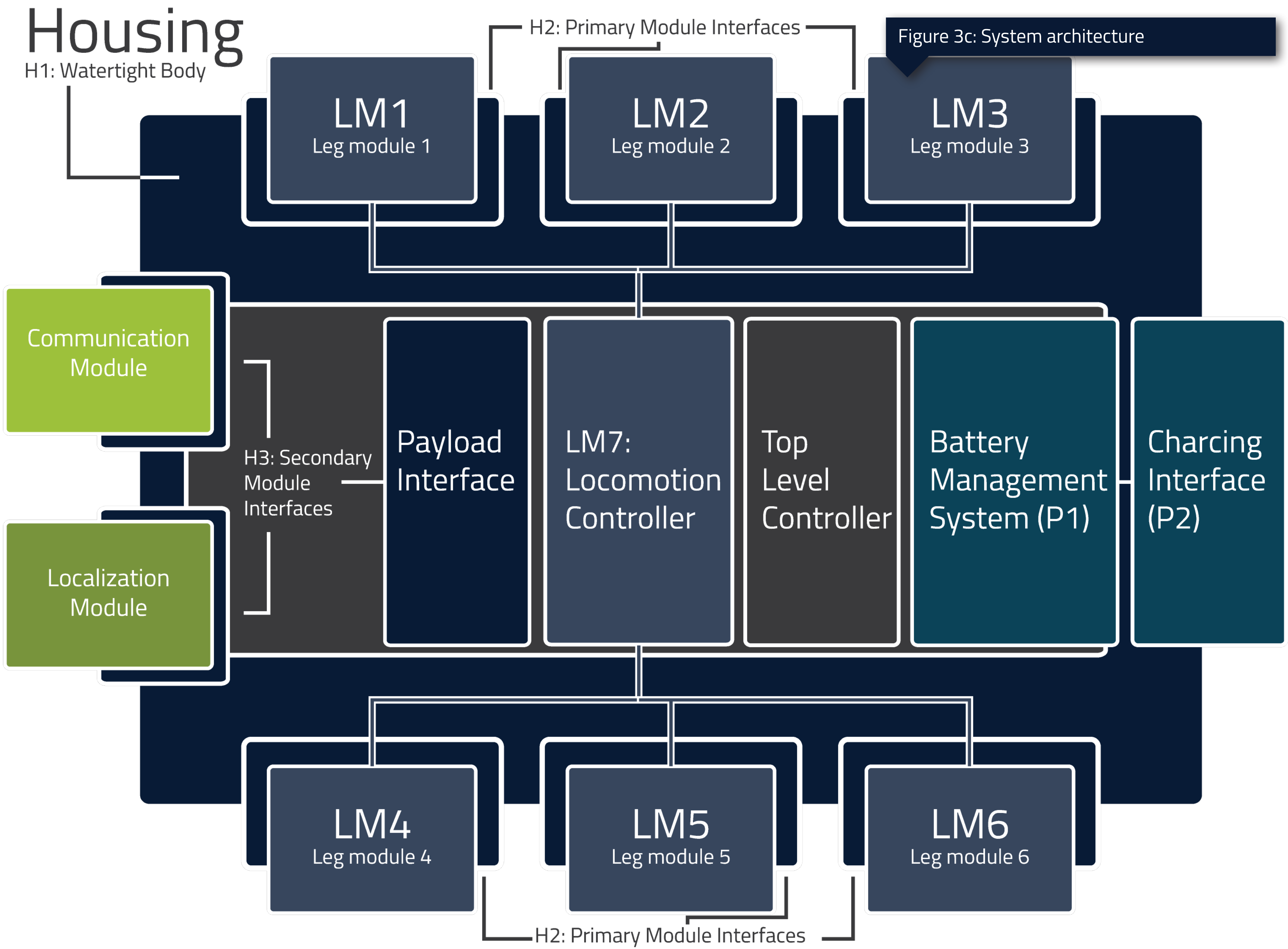


Figure 3c: System architecture

Planning

As stated, the goal of this project is to design a modular Zebro that is suitable for series production. Currently, Zebro's have only been produced as prototypes. Within this project, the step from single prototypes to a series of 100 robots will be made. To facilitate this, four design cycles will be implemented.

Design Cycle 1
During this design cycle a first prototype is designed that is modular. The main goal of this prototype is to prove the effectiveness of modular design and aims to demonstrate a mechanically working prototype. During this design cycle, the focus is at the design tracks 'housing' and 'locomotion'. This focus should allow the first prototype to be fully functional from a mechanical perspective; it will be able to walk. Furthermore, this prototype should provide the necessary hardware and connections to allow communication and localization modules to be connected.

This design cycle should characterize itself by continuous iterations and rapid prototyping. Direct problems standing in the way of an operational Zebro will be addressed, and therefore the focus will not be on literary review and research. Rather, as problems are addressed, research will be conducted if necessary for solving the problem. For each design track within this cycle, TRL 3 should at least be reached; proof-of-concept for the chosen technologies should be given.

Design Cycle 2
During design cycle 2 the focus shifts from making the Zebro function from a mechanical perspective to making it function as a system. Therefore, integration of all different design tracks is crucial during this phase. Furthermore, production methods and assembly become more important during this phase. The shift is made from one prototype to a series of 10. Most likely, this series of 10 will still be produced using rapid prototyping methods. Nonetheless, the design at the end of this cycle will be optimized for the chosen series production processes. The design at the end of phase two will be optimized for this production process.

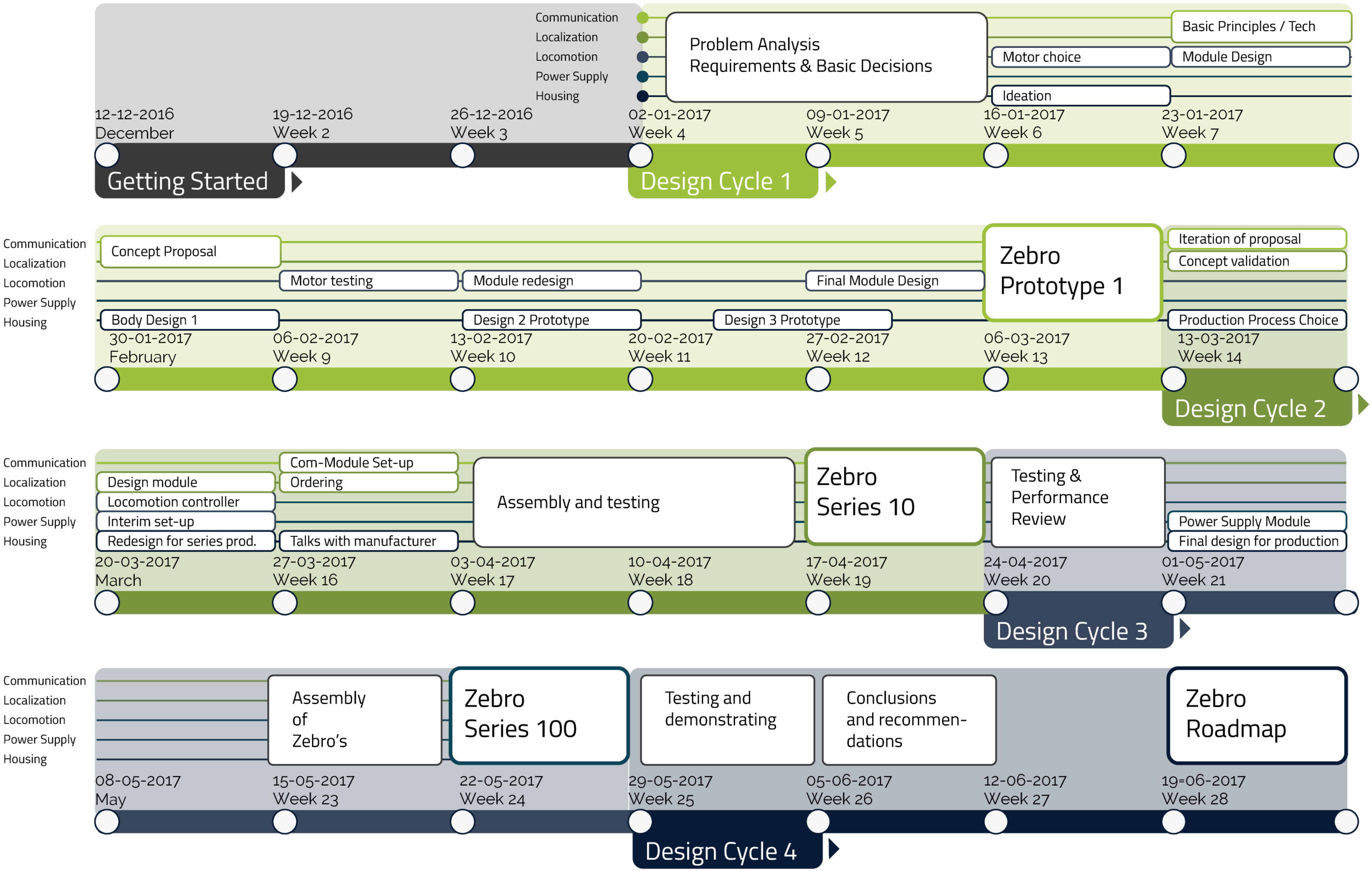
Design Cycle 3
During this design cycle the resulting 10 Zebro's from phase 2 are evaluated by the entire team. Critical reviews of the Zebro's performance will be done, in order to prepare the Zebro for the next design phase. In order to be ready for series production, and in order for large investments to be warranted, Zebro should perform at least a satisfactory level on each design track. TRL 7 should be reach, meaning that the entire Zebro has been tested in a relevant environment. Based on the reviews and testing, a redesign is proposed specifically suited for series production. Potential manufacturers are involved and their expertise applied to the design.

At this stage, target market and cost will start to play a role. A decision will be made on the desired market price. At the end of this stage, Zebro is ready for series production. If the funds are available, and the usefulness of producing a 100-strong swarm is clear, a series of 100 Zebro's will be produced.

Design Cycle 4
During cycle the design is finalized and a roadmap is created describing the future development of Zebro. Furthermore, several Zebro applications scenario's are presented, showing the potential of Zebro.

Planning
Based on the aforementioned four design cycles, the following planning is proposed. This planning takes into account all 5 design tracks and gives a general insight into week-by-week activities. For further details regarding planning, the reader is referred to the planning presented at the start of each design cycle chapter.

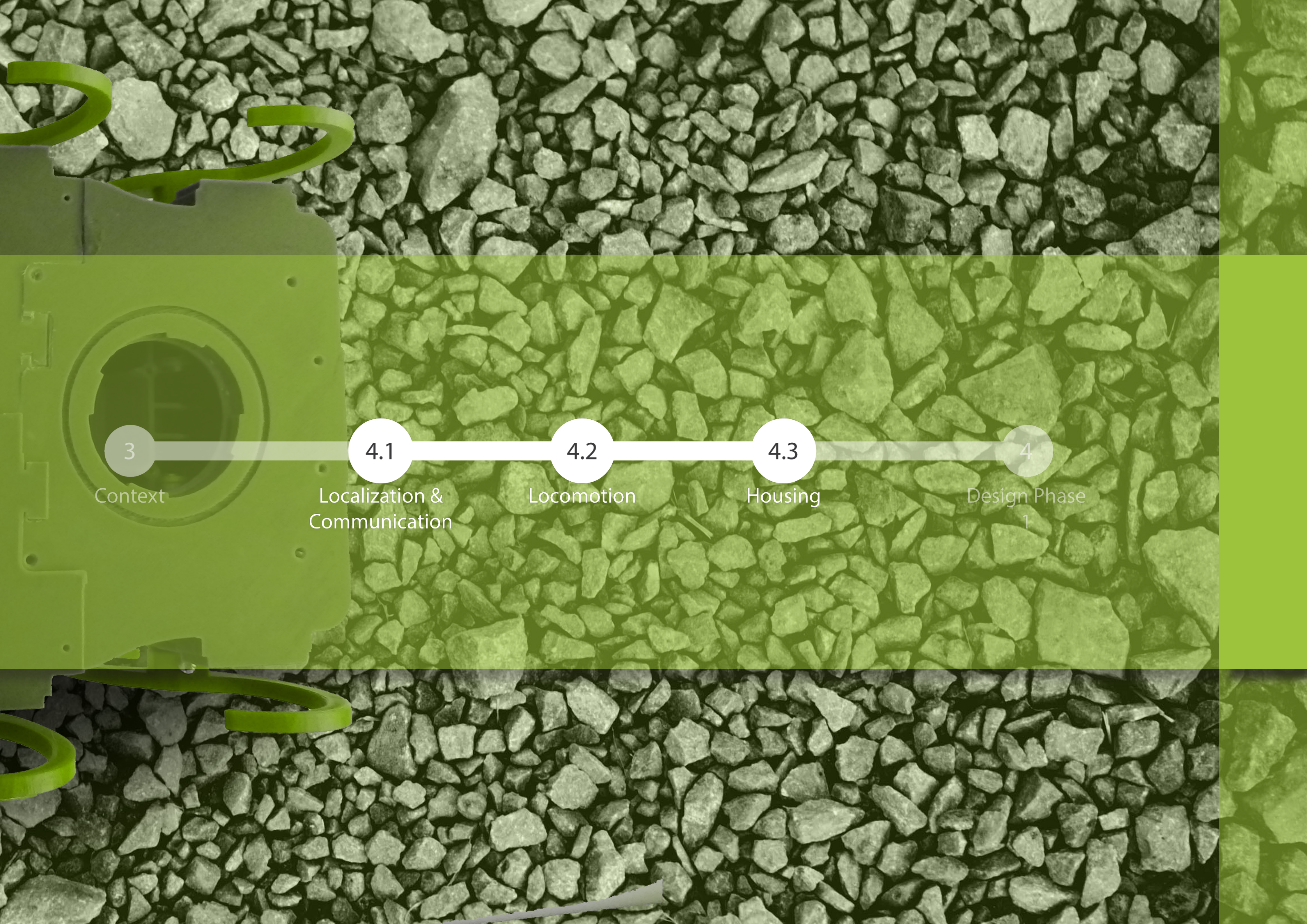
Note: Design Cycle 3 was eventually not part of this project. For further details regarding this, the reader is referred to the afterword


Communication
Localization
Locomotion
Power Supply
Housing
Problem Analysis
Requirements & Basic Decisions
Basic Principles / Tech
Motor choice
Module Design
Ideation
12-12-2016
December
19-12-2016
Week 2
26-12-2016
Week 3
02-01-2017
Week 4
09-01-2017
Week 5
16-01-2017
Week 6
23-01-2017
Week 7
Getting Started
Design Cycle 1
Communication
Localization
Locomotion
Power Supply
Housing
Concept Proposal
Motor testing
Module redesign
Final Module Design
Body Design 1
Design 2 Prototype
Design 3 Prototype
Zebro
Prototype 1
Iteration of proposal
Concept validation
Production Process Choice
30-01-2017
February
06-02-2017
Week 9
13-02-2017
Week 10
20-02-2017
Week 11
27-02-2017
Week 12
06-03-2017
Week 13
13-03-2017
Week 14
Design Cycle 2
Communication
Localization
Locomotion
Power Supply
Housing
Design module
Locomotion controller
Interim set-up
Redesign for series prod.
Com-Module Set-up
Ordering
Talks with manufacturer
Assembly and testing
Zebro
Series 10
Testing &
Performance
Review
Power Supply Module
Final design for production
20-03-2017
March
27-03-2017
Week 16
03-04-2017
Week 17
10-04-2017
Week 18
17-04-2017
Week 19
24-04-2017
Week 20
01-05-2017
Week 21
Design Cycle 3
Communication
Localization
Locomotion
Power Supply
Housing
Assembly
of
Zebro's
Zebro
Series 100
Testing and
demonstrating
Conclusions
and recommen-
dations
Zebro
Roadmap
08-05-2017
May
15-05-2017
Week 23
22-05-2017
Week 24
29-05-2017
Week 25
05-06-2017
Week 26
12-06-2017
Week 27
19-06-2017
Week 28
Design Cycle 4

4. Design Cycle 1

Design cycle 1 focuses at the design of a first DeciZebro prototype. This prototype must demonstrate the feasibility of upscaling the design of Swarm Zebro to series production. During this phase, concept solutions for each design track are presented and tested, in order to reach at least a technology readiness level of 3 on all tracks, and 5 or higher on locomotion and body design.

Within this chapter the progress on each design track is presented. Below, a chronological planning is presented. The track-by-track paragraphs present a chronological design path within the track, but the tracks themselves were often worked on in parallel, as can be seen below.


3
Context
4.1
Localization &
Communication
4.2
Locomotion
4.3
Housing
4
Design Phase
1

4.1 Localization & Communication

As described within paragraph 2.4, swarming is heavily dependent on successful localization of others within the swarm, and communication with them. In order to be able to facilitate this functionality within the housing design, a first analysis of possible localization and communication methods is done, along with a concise summary of notable swarms found in the animal kingdom. Within the context of this graduation project only the basics are explored, and design recommendations are given. Furthermore, based on the recommendations, the necessary steps are taken in the body design to facilitate as wide a range of possible localization and communication methods as possible.

4.1.1 Swarming in Nature & Robots

Swarming exists in many different forms in nature. Often, the word 'swarming' is specifically used to describe large congregations of insects that work together. However, the English language boasts over 50 different words to describe these gatherings of animals; flocks, schools, herds, packs etc. Moreover, over 50% of all animals exhibit group formation behavior (Wilson, 1978). Although these animals are radically different from each other, their respective swarming behavior shows many similarities. Within the next few paragraphs case studies are presented that help gain insight into swarming.

Schools of fish

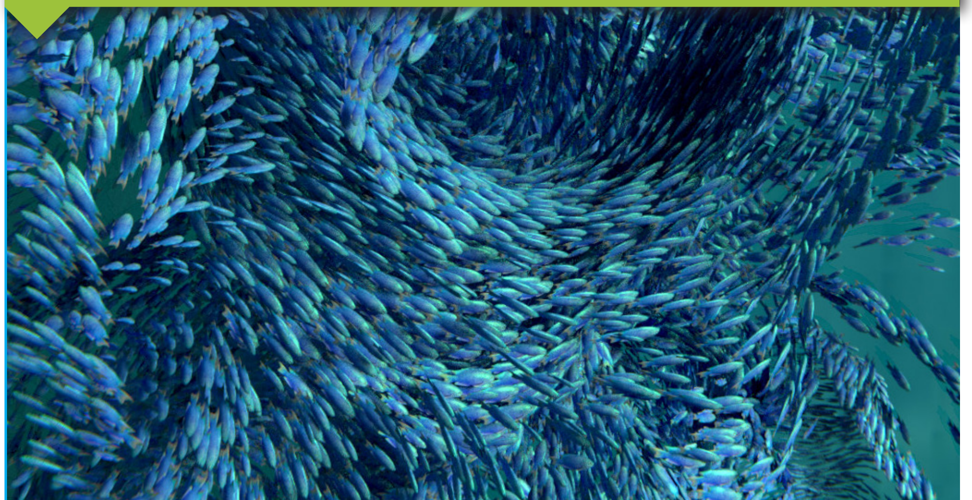
Schools of fish swim together in perfect unison (Figure 4b), often with many thousands of fish. In order to be able to do this, fish must be perfectly aware of their own position relative to neighbors. Tests have shown that fish rely mostly on vision to do this. Having eyes on the sides of their heads, they are capable of tracking their neighbors constantly. Often, fish have distinct markers on their sides that help others to track them (Bone, & Moore, 2009). Fish space themselves out evenly, maintaining constant distances between all individuals. Furthermore, each individual responds in exactly the same fashion to changes in water current or the presence of predators. Being instinctively programmed to react in the same fashion, working together is much easier. This supports the idea of having robots run on the same basic set of instructions, ensuring their responses are not completely random. Furthermore, uniformity is important. Clear visual markers are also needed for quick identification and relative positioning.

Swarms of bees

Unlike schools of fish, bees form swarms (Figure 4a) that need to be guided in specific directions. It is estimated about 5% of bee swarms are comprised of scouts (Seeley et al.,1979). Still, these scouts are able to guide entire swarms (of up to 10,000 individuals) who are not aware of the location, to a new hive location or to locations with rich flower fields. Two ways in which bees do this have been identified. The first (Janson, Middendorf, & Beekman, 2005)

Figure 4a Complex Structures: Beehive ("Beehive", 2017)

Figure 4b: Complex swarming in schools of fish ("Fish Photography", 2017)



is to show abnormal behavior in the direction of the target. As such, scout bees start flying very fast into the direction of the target, thus showing the direction to other bees. Because the behavior is abnormal and the bees are identified as scouts, the rest follows. Another method is one of using a specific dance indicating the direction of the source, the length of the dance signaling the distance. Bee swarms are physically mostly uniform. However, their roles differ. The fact that scouts are recognized as scouts means they can influence the entire swarm. If all bees would be scouts, this would result in chaos.

Bees (and most other insects) do not use eyes similar to those of humans, but have so called 'compound eyes' (Figure 4c). In short, insects have many small 'eyes' (lenses) that each individually can detect an amount of incoming light. Together, these eyes allow insects to spot movement very easily. Any moving object is first picked up by lenses on one side of the eye, and then on the other. As such, tracking movement and direction is easy and requires little processing. This principle is very well suited for robotic swarming applications, where computing power is limited. Interpreting camera data requires a lot of computing power. Processing the input of simple 'on/off' light transistors however is much simpler.

Current Project Examples

If these aforementioned principles of swarming in the animal kingdom are considered, many similarities can be found with current swarm robots.

Figure 4c: Insect with compound eyes (Insect Compound eyes, 2014)

One of the first projects that stands out is the KiloBot (Rubenstein, Cornejo, & Nagpal, 2014) projects by Harvard University. Here, a swarm of 1000 robots was produced (Figure 2l). These robots communicate and localize each other via an IR transmitter and receiver. The project shows that, on a very basic level, simple IR transmitters and receivers working at a small range (<10cm) can provide communication and localization functionality to a large group of robots.

KiloBot is a very basic and small robot. Another example of communication and localization can be found in Jasmine (Figure 4d). This robot, measuring about 3x3 cm and being propelled by wheels, uses a more complex variant of IR communication and localization. Here, the robot can look in several directions and thereby also communicate in multiple directions. This way of splitting the robots view into 8 distinct ´eyes´ is quite similar to the compound eyes found in insects. Jasmine can successfully locate other sources of IR and communicate using IR modulation. Moreover, it can do this on a simple micro-controller.

As becomes clear from research, most research oriented robots use IR for communication and localization. However, for example in consumer electronics, other options are used to. Cozmo, an intelligent 'personal' robot is equipped with a camera using open source pattern recognition software. As such, it can map its environment and recognize specific patterns, such as human faces. However, Cozmo cannot interact and track many robots at the same time.

Figure 4d: Jasmine (Swarmrobot, 2013)

4.1.2 Localization & Communication in DeciZebro

Based on examples found in the animal kingdom and current robotic swarms, several guidelines can be drawn up regarding localization and communication:

- Only local communication is necessary to facilitate swarming
- Localization of immediate neighbors is key. Swarm members should be clearly recognizable, being equipped with clear markers or colors
- A minimum amount of processing power should be required for localization
- Seeing movement and direction is important
- All members must have basic localization and communication. However, using specific roles, some robots may have extra capabilities to guide the swarm
- For swarming, only two distances to neighbors have to be measured (max distance and minimum distance) (Figure 4e)

A wide variety of technologies is available for localization and communication. One of these is using infrared light. Another is acoustic (audible or ultrasonic) sound. Then there are the radio based forms of communication and localization, such as Bluetooth and Wifi. Each has its own advantages and disadvantages. IR is used most often, due to its low implementation cost and proven working principle.

IR light is used by remote controllers to, for example, control a TV. To do this, modulated light is used so that meaningful data can be transmitted. The modulation allows the signal to stand out from other IR sources, which are constant. IR can be used both for transmitting information and localizing, making it a viable option for swarm robotics. IR light is susceptible to interference from sunlight. It is questionable whether the technique will function in broad daylight or sunlight.

Sound can also be used to transmit signals. The amount of information that can be transmitted through audible sound is very low, however. Furthermore, if a swarm of Zebro´s would all be using sound as a means to localize and communicate, all signals would interfere with each other causing chaos.

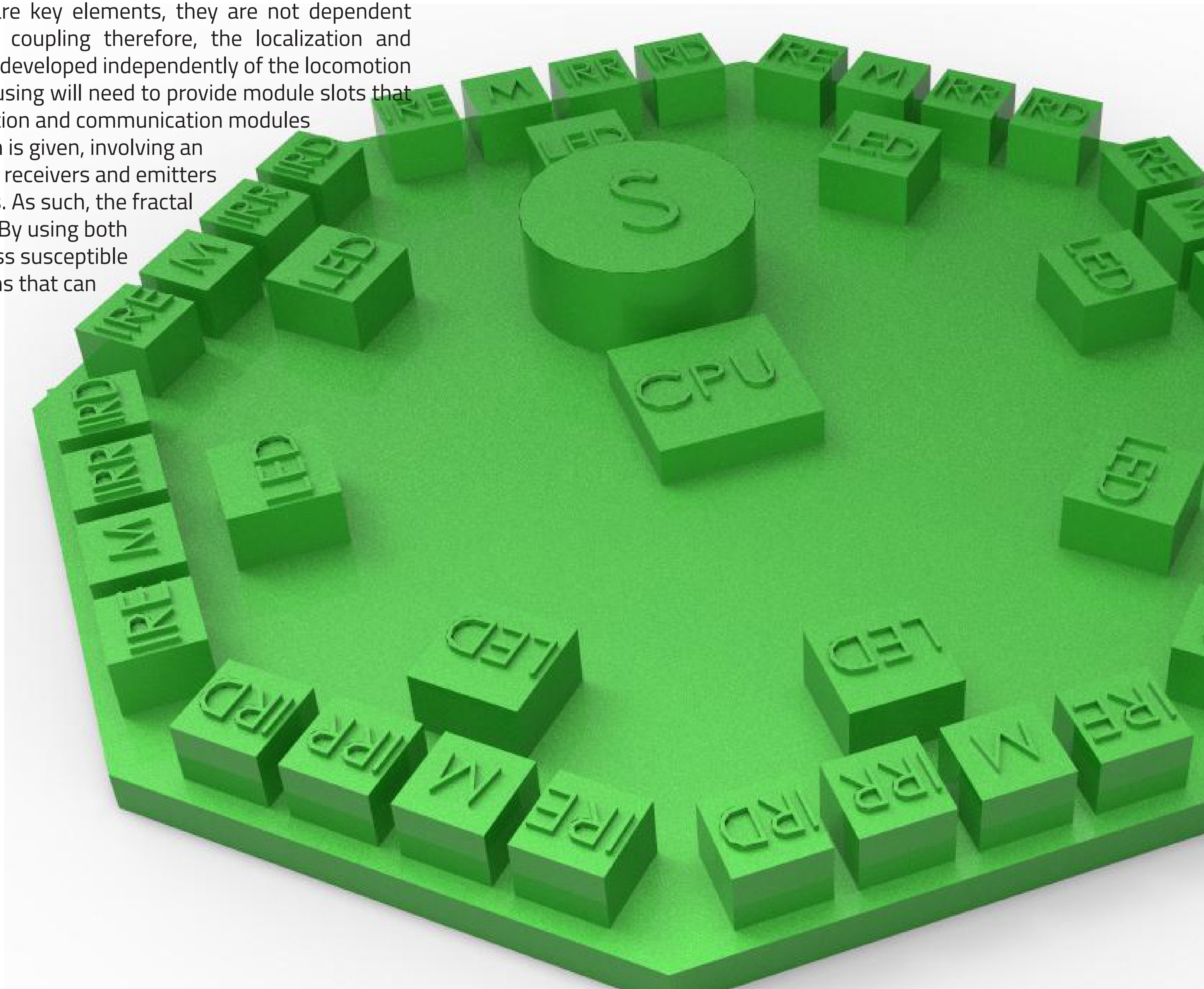
Other localization and communication methods include Bluetooth, Wifi and GPS. The first is more costly and requires intricate communication protocols. Wifi is only available at indoors locations and requires the use of Wifi beacons. GPS can only be used outside and is not precise enough (3m).

Figure 4e: Distance measurements in swarming

4.1.3 Design recommendation

In order to maintain modularity within the Zebro design, the decision is made to view localization and communication as modules. The primary function of the Zebro is locomotion, and this forms the core of DeciZebro. Although communication and localization are key elements, they are not dependent on locomotion. To ensure loose coupling therefore, the localization and communication modules are to be developed independently of the locomotion design. As such, the DeciZebro housing will need to provide module slots that facilitate easy adoption of localization and communication modules into the robot. A design suggestion is given, involving an 8-sided PCB (figure 4f)featuring IR receivers and emitters and microphones in all 8 directions. As such, the fractal nature of insect eyes is mimicked. By using both audio and IR, the system will be less susceptible to interference, having two systems that can back each other up

Figure 4f: Loc/Com module mock-up



4.2 Locomotion

Locomotion is the first and foremost functionality of Zebro. Unlike other locomotion systems, hexapod walking is not commonly found amongst machines. Moreover, hexapod walking is not found in any mass-produced products. Either wheels or continuous tracks are used. Because of this, the way Zebro walks is a challenge in itself. However, if it walks, the door is opened for widespread experimentation with localization and communication modules , which is almost guaranteed to produce the desired swarming behavior in the long run. For this reason, locomotion is seen as the starting point for the design of the housing, and the bodies form will follow the function of hexapod walking.

During the first design iterations it became clear the modular nature of Zebro required a modular approach to leg design. Being inspired by the design of KiloZebro, leg modules were created. It was decided all modules should be identical and interchangeable. As such, the design of the locomotion system could be simplified to the design of 1 effective motor module. The housing design in its turn has to facilitate the mechanical framework for these modules and provide the structural integrity to lock these modules into place.

The basis for the leg modules are the motors. The motor choice is therefore described first. Next, motor modules must be self-contained and therefore contain their own leg position encoder and processing power. These are facilitated by the design of a motor module PCB (printed circuit board).

- 4.2.1: Motor choice
- 4.2.2: Encoding

4.2.1 Motor Choice

In order for locomotion to take place, a motor is needed. A team meeting was held in order to properly consider the requirements a motor for Swarm Zebro should meet. These requirements are based on past experiences with other motors and Zebro´s, as well as new performance standards for the Swarm Zebro. The requirements are:

- In order to be able to run (as opposed to walking, where there are always legs in contact with the ground), **the output rotations per minute (RPM) of the motor needs to be at least 150RPM** and preferably higher. At 150 RPM or higher it is expected the impact of the legs on the ground will be able let Zebro jump when walking. This would allow for a more efficient way of locomotion, using the legs to store elastic energy to conserve momentum.
- In order to be able to lift Zebro, the motors must provide enough torque. It is estimated Zebro will weigh anywhere between 700 and 1200 grams. Furthermore, it is estimated the legs will be between 4 and 8 cm in diameter. Zebro should be able to lift itself on two legs at least, preferably on 1. Combining this data with the formula presented in chapter 2, this yields **a needed torque of at least 9.6kg.cm per leg,** if Zebro is to lift itself on 1 leg.
- The size of Zebro should be between the size of an A5 and an A4 paper (210x148 - 297x210). This size is needed to be able to perform mechanical tasks and to be able to traverse sizable distances (kilometers, as opposed to meters). As such, the motors may not be to large. Specifically, length should not exceed 7 cm.
- The weight of the motors should ideally be under 100 grammes per motor, to keep the weight of the motors to be less then half of the total weight.

Taking into account these requirements the viable alternatives were investigated and a choice was made. Alternatives included servomotors and brushed/brushless DC motors. Stepper motors and AC motors were ruled out, respectively due to their high weight to torque ratio and size.

Servo motors are embedded systems, equipped with a DC motor, gearbox and the electronics needed to fully control the motor and measure position. This allows servos to offer good all-round functionality. Although being mostly limited to small angular movements, full rotation servos are sold and do provide enough torque. However, their RPM rate is too low (always <100 RPM). Furthermore the embedded nature of servos means their shape is fixed, and so are their specifications. This places restrictions on the body design and limits modularity. For this reasons, servos were not chosen.

As such, brushed DC motors were chosen. Although brushless DC motors require less maintenance and generate less heat, they are significantly more expensive. Due to the modular nature of the motor modules, replacing any defective motors will be easy. Brushed DC motors are available in wide ranges of torque's, RPM's and sizes. Careful research led to the choice of one specific motor.

Running at 170RPM no-load and providing a maximum torque of 22kg.cm this motor is strong and fast enough (See appendix B). Furthermore, its total length (excluding shaft) is only 53mm. The manufacturer of this motor was contacted and provided a significant bulk-buy price reduction, bringing the price per motor down below 10 dollars each. The motor was tested to verify its performance. With the help of mechanical engineering colleague motor curves were drawn up and the motors were verified to provide enough torque.

4.2.3 Motor Encoder

The locomotion controller must always know the position of the legs in order to coordinate the six legs into following a specific gait pattern. These measurements need to be precise (2 degrees angle or less), preferably 8-bit (256) measurements or more per rotation. Two options are commonly used; using an off-the-shelf motor encoder which is placed at the input shaft on the backside of the motor, or using a form of output shaft encoding. Output shaft encoding is more desirable as it more precisely predicts the actual leg position

Swarm Zebro uses magnetically effect sensors, called Hall-Effect Sensors, at the edge of the housing, together with embedded magnets in the legs itself to measure leg position. This system has its flaws, as its susceptible to magnetic interference. Furthermore, the distance between leg magnet and Hall sensor must be close (<1cm) if accurate data is to be gathered.

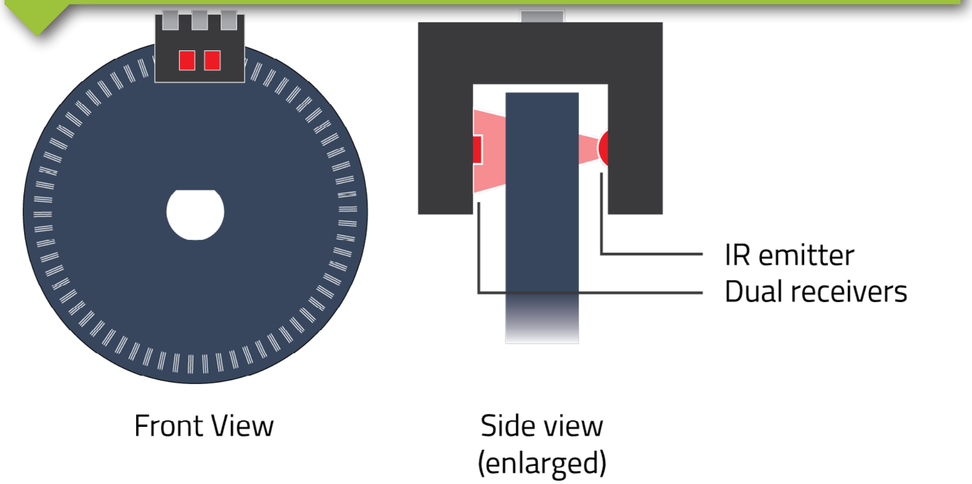
Encoders on the input shaft are expensive and would almost double motor cost, as well as delivering only semi-reliable data that is not directly linked to the actual leg position.

Market research and brainstorming led to the idea of implementing an optical encoder on the output shaft. In this case, a simple encoder wheel featuring a ring of slits is slided onto the motor shaft. A so called photo-interrupter is placed over the side of the wheel (Figure 4g). This optical encoder wheel uses a beam of IR light that is interrupted by anything passing in front of it. The encoder wheel's slits let through the light, while the non-slitted area's block it. Thus, the speed and orientation of the output shaft can be measured.

A test series of rapid prototyping encoder wheels was made using 3D printing. A double slit photo interrupter was selected, to be able to detect direction. A double phase signal is received, from a hole first passing in front of slit 1, and then in front of slit 2. In signal processing, a 00 signal is first received, followed by 01, 11 and 10. As such, the amount of slits multiplied by four amounts to the total amount of measurements possible per rotation, reaching 8-bit encoding.

After extensive testing with 3D printing wheels and getting the hole sizes right (hole sizes are around 0.5x1mm), 3D printed materials proved to be completely permeable to IR light. This made the wheels unusable. Furthermore, 3D printing did not yield the right tolerances on the slits in order to reach 8 bot encoding. The switch was made to laser cutting, and a test batch was ordered and tested. The results provided a proof of concept and gave enough credibility to the method to implement this in the final prototype.

Figure 4g: Motor Encoder Wheel



4.1.3 Motor module housing

Having solved the two major problems concerning locomotion, a housing for the motor module could be designed. Several requirements were drawn up for these modules in the process of designing them:

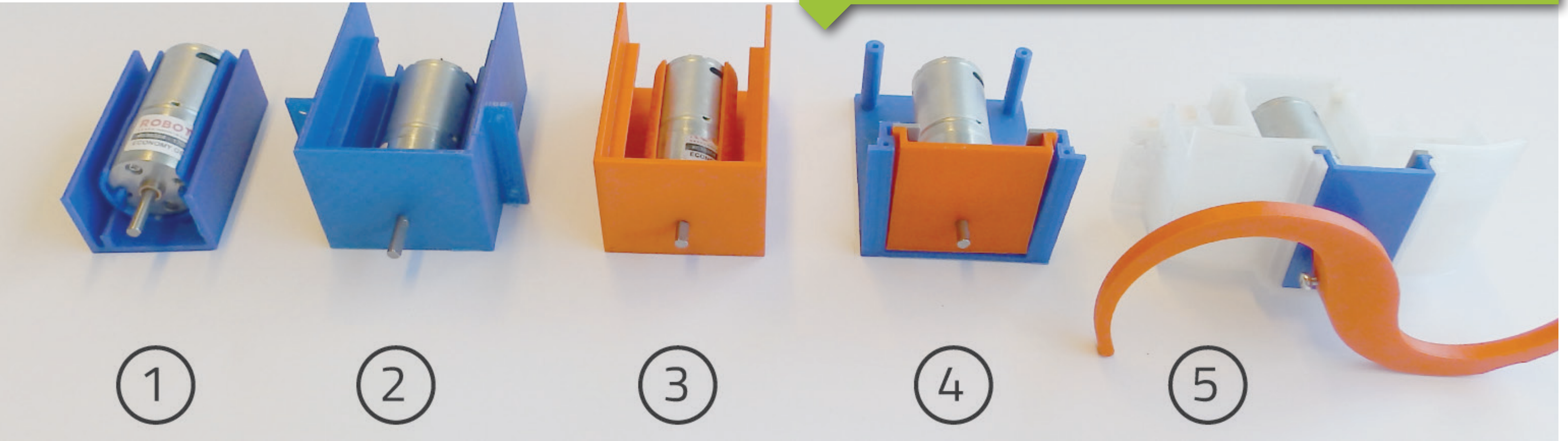
- Modules should attach without mechanical connections (screws, bolts etc.). Form closures/snap fits should be used
- Modules themselves should be easy to assemble by any person, not requiring any specific skills, except for soldering.
- Soldering connections should be kept to an absolute minimum
- The modules should be at least splash proof
- The modules should work on the ZebroBus I²C interface and be self-contained, presenting clear output data to the top-level controller
- The modules should be the same on both sides of Zebro; mirroring should not pose a problem. Therefore, the modules must be symmetric over the vertical mid-plane.
- The module should facilitate convection as a cooling method for the motor and not insulate the motor. Plastic parts should not be in direct contact with the motor
- The housing should be mass-producible; draft angles and no cavities etc.

A total of 5 iterations (Figure 4h) of the motor module were made and prototyped (in chronological order from left to right). The first prototype involved a small enclosed casing for the motor. This enclosure would make it hard for the motor to cool. Also, the Motor PCB was placed on the side of the motor in this case. If this were the case, using this module on the other side of Zebro would mean the PCB would be located on a different side. This led to the requirements of symmetry and cooling. Furthermore, a new solution was needed to secure the motor with a material that would not melt at 50+ degrees.

In design 2 the entire motor was surrounded by walls. This meant the module was more 'enclosed' and could be slided in from the side. However, assembly now became a problem. Due to the closed in nature, and the fact that the motor shaft needed to be slided through the module wall from the rear, assembly was very difficult. In this way, the motor could not be secured in place using the two screw holes at its front. Also, the walls are not strictly needed for the module, as the front needs to be waterproof only. Being part of the module, they also added no structural integrity to the entire robot housing.

In design 4 and 5 the step was made to integrating the walls in the main body, and sliding the module into the body from the top. An aluminum plate is screwed onto the motor, the encoder wheel is placed and a front plate is installed, and the whole package is then slided into the body. This makes the design splash-waterproof and easy to assemble. The PCB is placed on top of the motor, with the photo interrupter facing down.

Figure 4h: Motor module iterations



4.1.4 Final Motor Module Design

The final design consists of 6 parts (figure 4i). This design will be discussed in this chapter. First, the leg (1). Part two is the motor module front (2), which, together with the main body, forms the outside wall of Zebro. Next is the optical encoder wheel(3), which is slided onto the motor shaft. The motor module PCB (4) rests on top of the motor connection plate (5) and the motor (6).

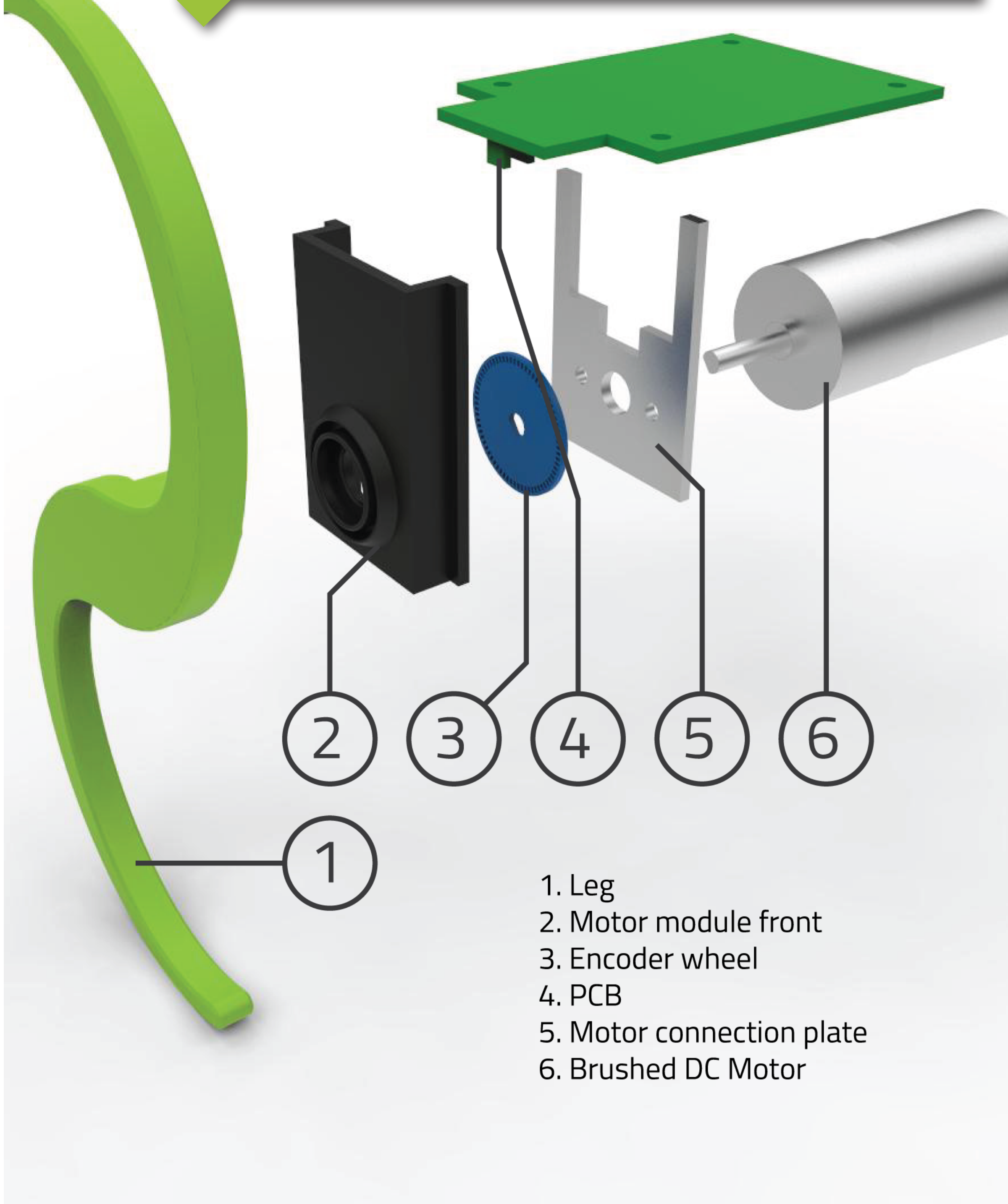
1. Leg
The original Zebro legs have a C shape. Early on in the process, based on the leg rotation diagram (Figure 2k) presented in chapter one, it was determined a double C leg (S-leg) would more then double walking speed. The S-shape does not impede climbing in any way and maintains the same climbing height as a C-leg.

The design was tested on strength using finite element simulations and proved to be strong enough to withstand forces of up to 10-15 kilograms; well enough to support Zebro.

Three iterations of the leg were made in order to create a strong connection between the D-shaft of the motor and the leg itself. First, a flat-end screw was used to screw onto the flat D-surface of the shaft. The screws however would wear out the plastic within a few uses. A final iteration, using a slide-in hexagonal nut through which a bolt would be screwed onto the D-axis. The nut fixes the bolt, and the nut itself is locked into place due to a form closure.

The leg can be 3D printed within an hour. As such, 3D printing could be feasible as a series production method for this part. Material-wise, total part costs amount to less then 20 cents. Furthermore, the low printing time and the fact that multiple can be printed at the same time means it is feasible to print

Figure 4i: Exploded view motor module



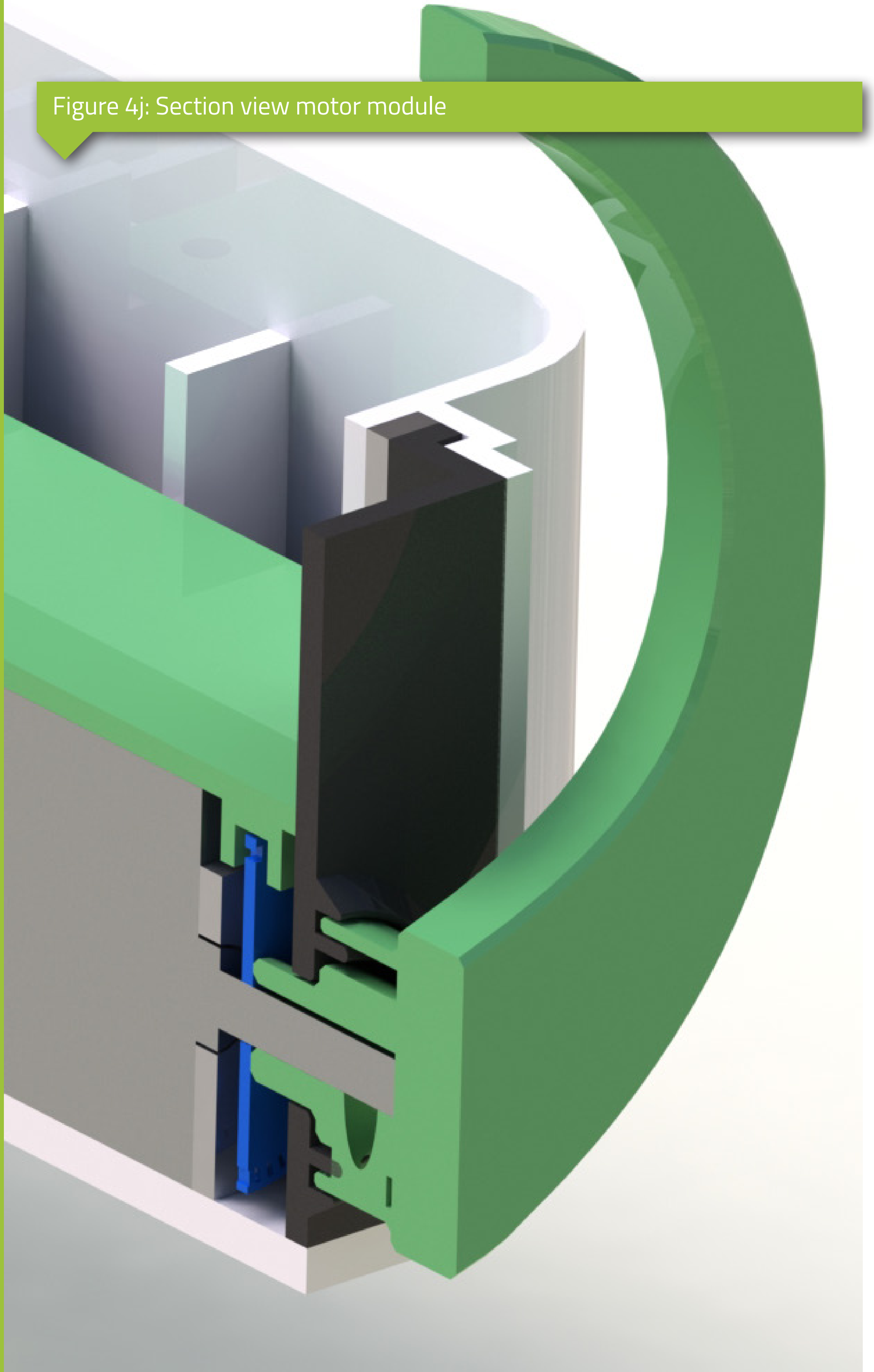


Figure 4j: Section view motor module

up to several hundred legs without problems. The part could also be injection molded, although a mold slider would be required to form the hole for the nut.

2. Motor Module Front

The motor module front is part of the outer wall of Zebro. It uses a form closure to connect with the body. The U-shape of the closure ensures an extra degree of splash proofing. The front of the module features a hole for the motor shaft. The leg protrudes into this hole, and through another u-seal creates a watertight connection with the motor module front. The part is fully injection moldable, but given its small size the same principle applies as for the leg; 3D printing is feasible for series production of up to several hundreds of units.

3. Encoder Wheel

The encoder wheel is locked into place on the motor shaft by the leg. It rotates with the motor shaft, it's slits passing through the photo-interrupter on the bottom side of the PCB. The wheel is made from 1mm thick acrylic in which the holes are cut using a laser. The cost per wheel lies at around 50 cents. Its 64 holes, combined with the double slit encoder create an 8 bit, 256 measure points per revolution data output.

4. The Motor PCB

The motor PCB (Figure 4k) was designed in collaboration with Lisanne Kesselaar, one of the team members, and ensures the module operates as a self-contained unit. The PCB fulfills several functions:

- Provide full control over the DC Motor through the motor controller. A motor controller capable of controlling a wide range of motors was selected to keep the system as flexible as possible.
- Provide connection with the I^2C ZebroBus (This 'Bus' is derived from a former NXP communication protocol standard) , so that each motor module can be plugged in with a simple snap fit connection and communicate with the locomotion controller, which controls all legs. This controller, in turn, communicates with the top-level controller.
- Provide temperature measurements of the motor in order to initiate an

emergency shutdown in the case of overheating risk.

- Provide internal feedback regarding the leg position. To achieve this, a photo-interrupter is placed at the bottom of the PCB, using the previously described optical encoding system. As back-up a Hall Effect sensor is also integrated
- Integration of components, thereby limiting assembly times. By placing all components directly on the PCB, the need for extensive soldering (for example, 4 wires for each photo-interrupter, 3 for each Hall Sensor, 3 for the temperature sensor) is avoided. This drastically decreases production times and is a prerequisite to series production.
- Modularity of the motor module. By integrating all necessary components, including a microprocessor, on the PCB, the motor module is a self-contained system that can be switched out with any other module at any time. The module can be assembled stand-alone and slided into the body, after which the I2C bus connector is plugged in and the power wires are screwed on. This means any motor module can be switched out for another in a matter of a single minute.
- The motor PCB's (Figure 4o) take about 3 hours to solder by hand. For this reason, series of more then 10 Zebro's (with 6 PCB's per Zebro) will need to be manufactured using pick-and-place robotics assembly. This will add to the cost price, but also decreases expensive labor times.

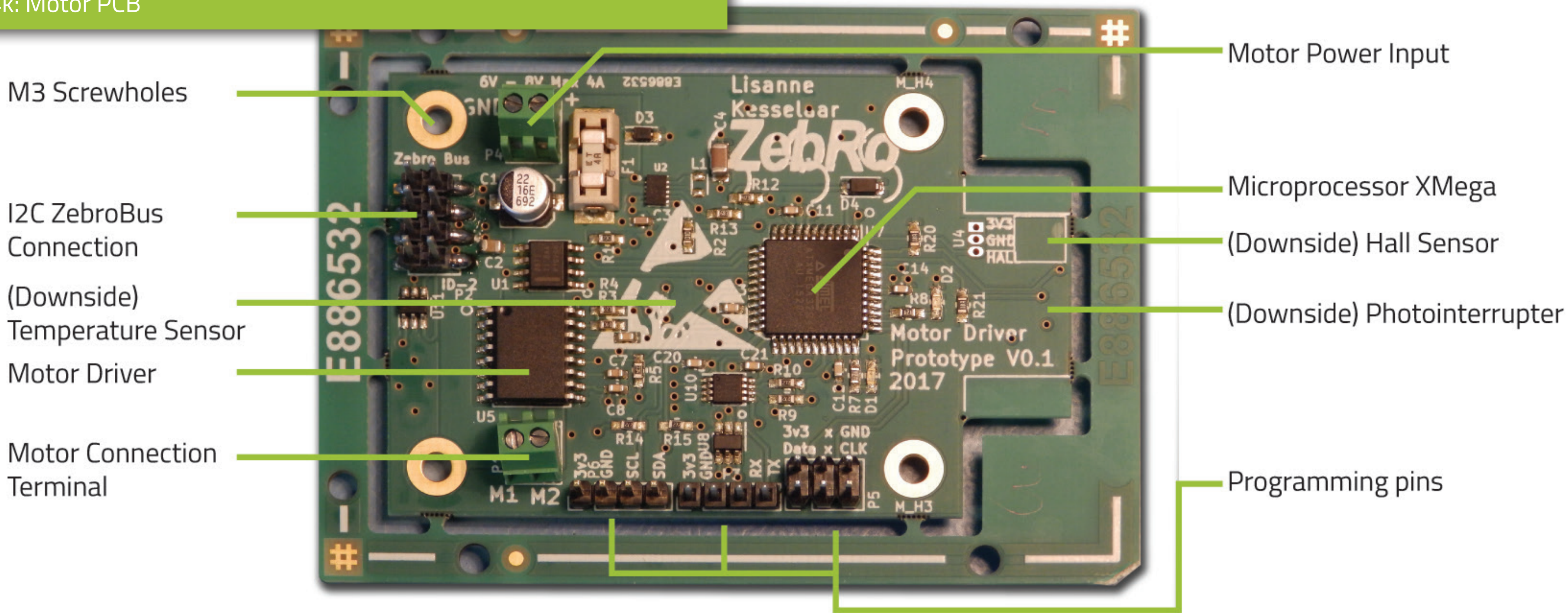
5. Motor connection plate

The motor connection plate is connected to the engine through 2 M4 screws. This plate is meant to absorb torsion forces from the motor and dissipate it through the body. This plate is laser-cut from aluminum and, together with the motor module front, locked into place in the body of Zebro.

6. Motor

The choice for this motor has been discussed before. It is important to note that, because of the open design of this module, the motor will cool better. Furthermore, because of the open design, installing a different motor is no problem. As long as the output shaft of the motor is at the same place, any motor can be used that fits inside of the body.

Figure 4k: Motor PCB



4.3 Housing

The Zebro housing was developed in conjunction with the motor module. As the motor module largely determined the shape of the housing, the motor modules were taken as a starting point and the body design adjusted. A total of four designs, each including many iterations, were made, of three where fully prototyped.

Design 1

The first housing design was made based on the second and third motor module iterations. In this design, the motor modules are 'boxes', that were are slided into the body from the side. The difficulty here, however, is making sure the modules are locked into place. As quickly became clear, it would be very problematic to lock these modules and unlock them without having to disassemble Zebro. Furthermore it become clear assembly of the modules themselves would be very difficult using the box concept.

Design 2

Designed 2 (Figure 4l, left) was designed using the following criteria:

- Motor modules must slide in/out easily
- The design be smaller then an A4 paper (297x210mm)
- The design should be able to withstand the forces involved during walking/running
- The design must be mass-producible using a common mass production method

Due to print bed size limitations in the available printers the design was split into four parts and assembled later on. After the first prototype was assembled, several conclusions were drawn regarding the criteria:

- The way the part was split up, with the four parts joining together on a single point, meant the entire design was to weak and tended to flex along the parting lines
- Tolerances were to low, requiring extensive sanding to fit
- Mechanical connections were not strong enough
- In general, the motor module connection was not rigid enough and tended to bend outwards. The openings were the modules slide in reduce the rigidity of the walls. Ribs should be added to properly dissipate forces and add rigidity
- The design can be made more compact, reducing flexing and bending stresses and production times in the process
- The design features a flat bottom with 90 degree angled walls. This is not ideal for injection molding, were products tend to curve along the injection direction. A choice needs to be made if injection molding is the way to go, or whether other production processes should be considered. For example, plastic or metal extrusion could be used to form the walls

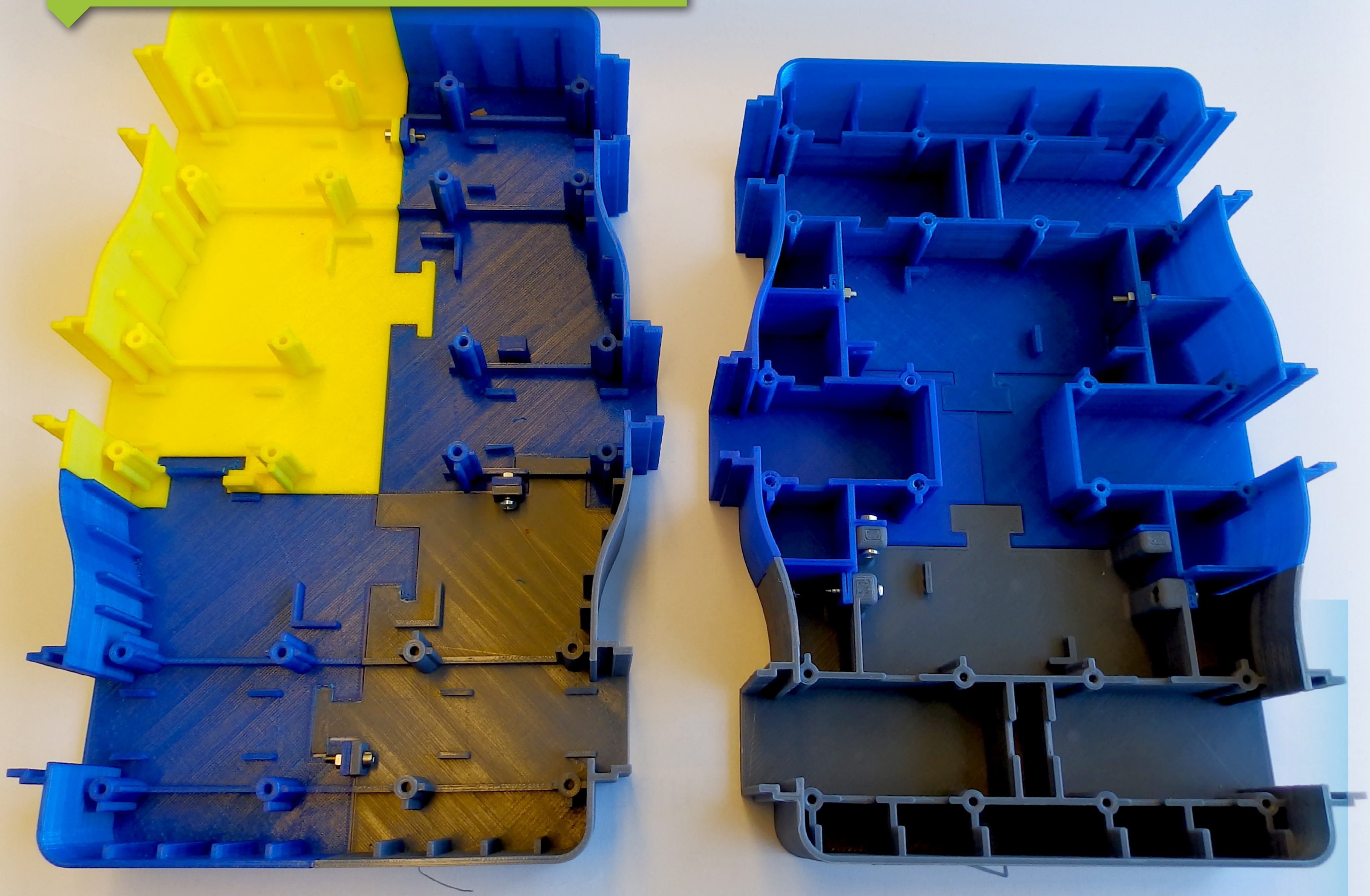
Design 3

Based on the conclusions from testing with design 2, an improved version was prototyped (Figure 4l, right). This design is much more rigid, featuring ribs to absorb forces along the north-south axis. Furthermore, this design features more robust fixation points for the PCB's. The ribs do decrease the amount of airflow in Zebro, thereby decreasing the cooling rate for the motors.

There are two production processes suitable for producing the kind of complex structures such as the one featured in design 3. These are injection molding and plastic or metal extrusion. Injection molding is suitable for creating complex curved shapes, but is much more expensive and requires intensive redesign. Typical investment costs lie around €25,000 and up, typical series sizes are €50,000 and up.

Extrusion molding is used to create uniform 2D profile extrusions, often from metal. Extrusion molds typically cost around €1000-5000, and series sizes of 1000 to millions of units.

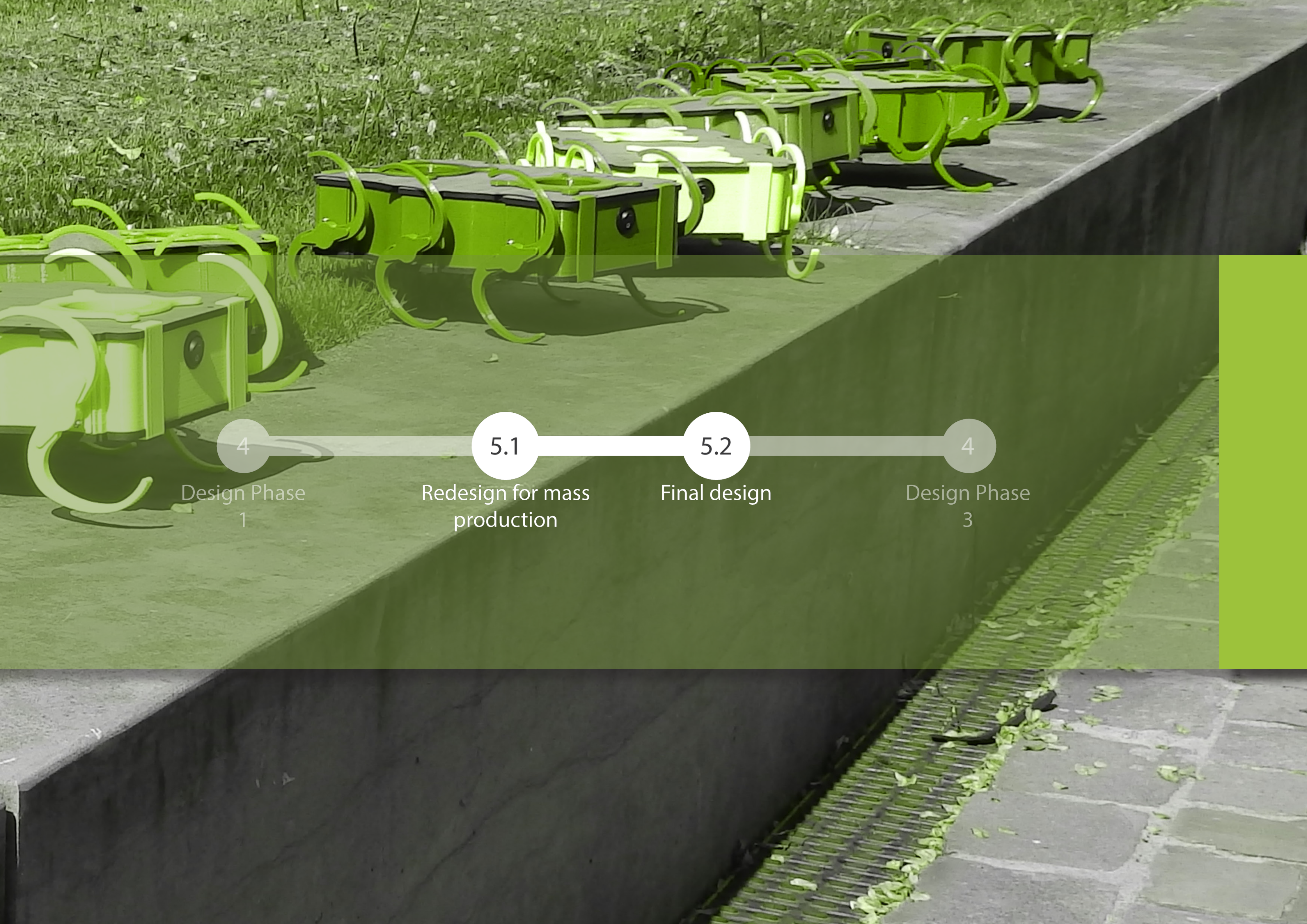
Figure 4l: Housing iterations



5. Design Phase 2

Within the last chapter the design of the individual components of DeciZebro were described. Combined, these result in the first full prototype. This prototype is then redesigned for mass production, after which the final DeciZebro design is presented. Many models and prototypes are built to come to this design, which are not discussed within this chapter. For this, the reader is referred to the ´Prototype Evolution´ Appendix.

The final design is discussed in regard to parts, cost and assembly, leading to the production of a series of 10. Based on experiences from this series 10 production, a plan is proposed that facilitates the future production of large series of DeciZebro's.



4 Design Phase 1

5.1 Redesign for mass production

5.2 Final design

4 Design Phase 3

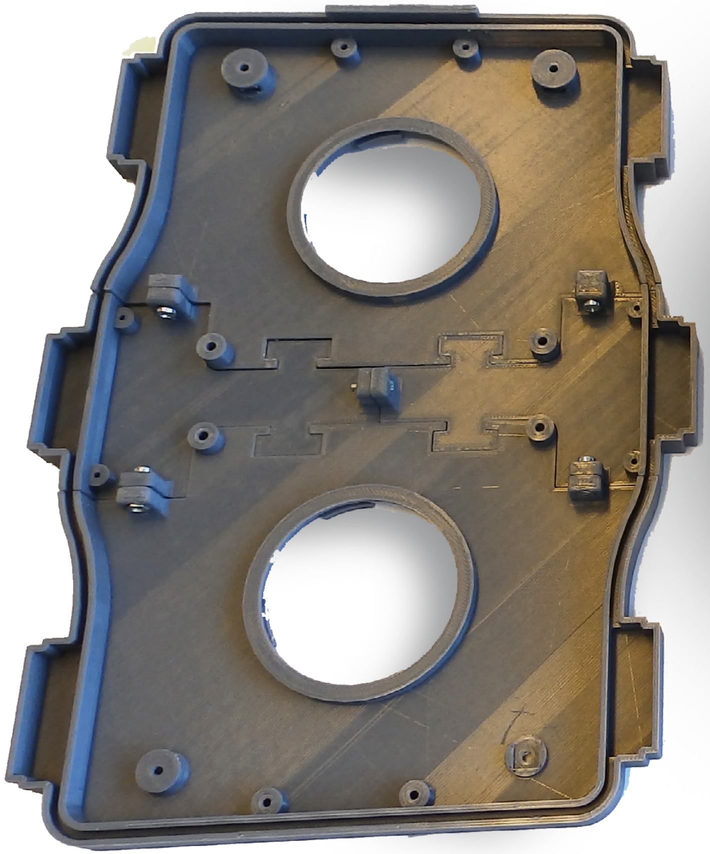
5.1 Redesign for mass production

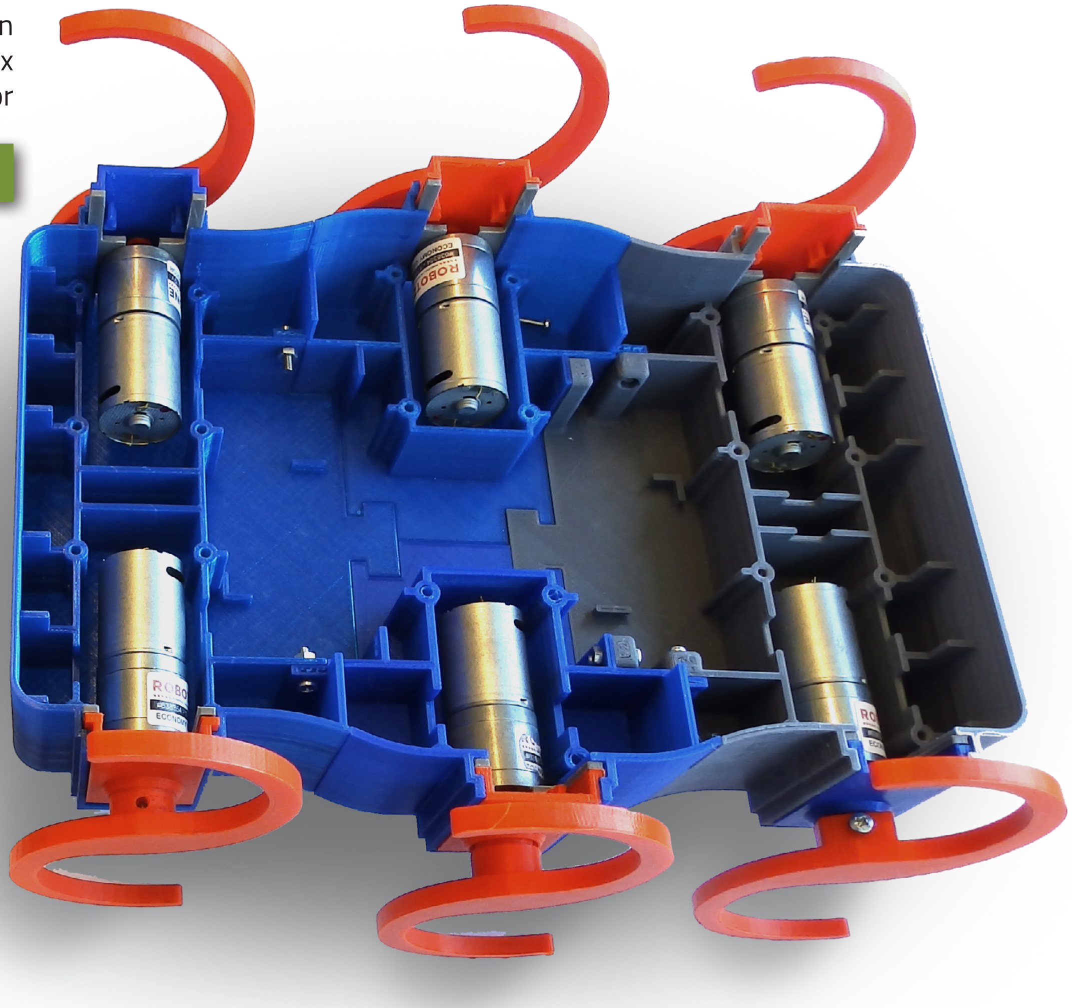
Prototype 1 is an integration of the motor module design with the third housing design. In total, 6 motor modules are placed in this housing. A lid is designed that locks the housing walls into place. The lid features two twist-and-lock module interfaces. This prototype requires a total of 120 hours of 3D printing, with the plastic parts weighing about 500 grammes. The motors add another 500, bringing the total weight of this prototype to about 1 kilogram. This still excludes batteries and electronics.

From a mechanical perspective this prototype is a success. The interaction between motor modules and the body is flawless. Within a minute all six modules can be installed in the body and the lid be closed. As such, the motor module and interface with the body are considered to be verified as suitable solutions for DeciZebro.

This design is, however, not yet suitable for mass production. Requiring 120 hours of printing time means only 1 prototype can be made within a reasonable timespan. Upscaling to 10 is difficult using this design, since no production techniques (other than 3D printing) exist that can reproduce this design.

Figure 5a: Prototype 1





Translation to series production

Having successfully demonstrated an implementation of a motor-module based approach, the design must become suitable for series production. To achieve this, it must be possible to create identical copies of Zebro that perform in a reliable way and can be produced at acceptable costs. Zebro consists of many parts, each of which must either be bought off the shelf or produced. Within this paragraph, the main production decisions are covered. These are, subsequently:

- Choice to use metal extrusion for the body framework
- Choice to use laser cutting for the body top and bottom
- Choice to use 3D printing and later on Injection molding for legs and motor module parts

5.1.1 Metal Extrusion of Body Framework

The choice to extrude the body of Zebro instead of injection molding was based on several key arguments:

- Metal extrusion molds will cost about €10,000 in total for DeciZebro. This can be afforded by the team. Injection molding is likely to cost 10x this amount, which is simply not possible within the team's context
- Metal extrusion allows the framework of the Deci to be produced cheaply and from aluminum, allowing lightweight rigidity, excellent durability and excellent heat dissipation
- The top and bottom of Deci can be produced using other techniques, such as laser cutting or stamping. 3D printing the framework (which would be extruded) takes only 40 hours. This means series of 10 robots can still be produced and made to exactly resemble the final Deci if it would be extruded (except that the profiles would be plastic, instead of aluminum). This means the production process of extrusion can be prototyped and fine tuned using 3D printing and laser cutting. This helps to close the gap between single prototypes and large series, which would be much more challenging if the design would be optimized for injection molding, since printing times would remain high.
- The current design of Deci is already suitable for extrusion, requiring only simple adjustments. Overall, the current shape is optimal for extrusion; a complete redesign would be needed in order to facilitate injection molding
- Extrusion is known for its excellent form closures / dependable mechanical interfaces, which are important in a modular approach product. Profiles can be clicked together, building shapes. As such, extrusion is the more modular approach, allowing different profiles to be combined and/or reused in other shapes.

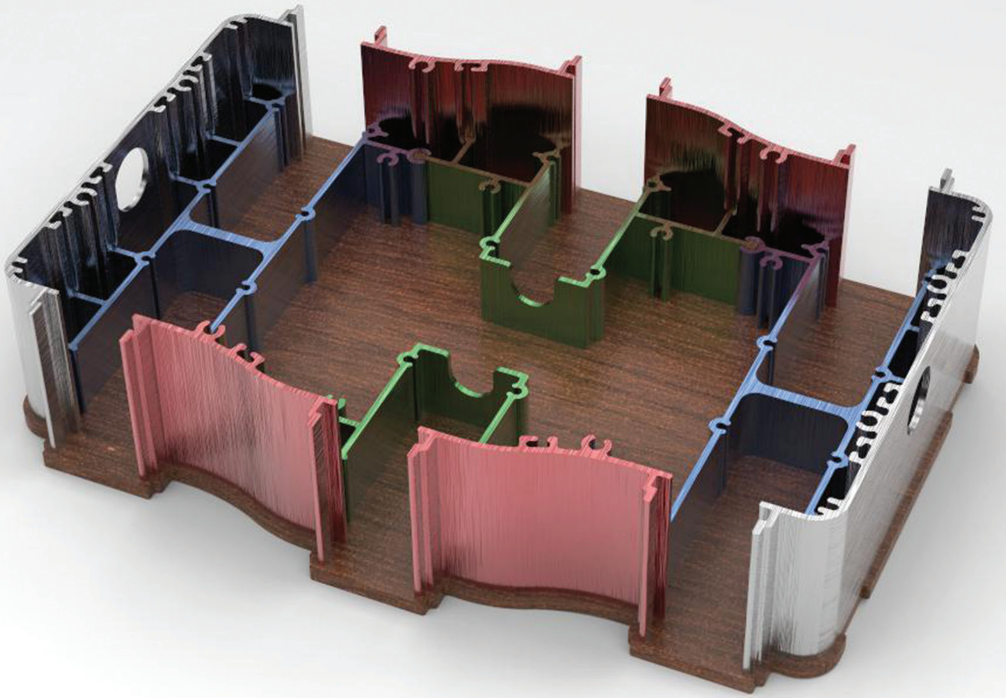
As such, Deci is redesigned for metal extrusion. This has implications on the design, requiring careful consideration and testing in order to maintain structural integrity whilst following the design rules set forth by aluminum extruders. These are, most importantly:

- The circumscribed circle of extrusion profiles should be as small as possible
- Sharp corners cannot be produced; corners should be filleted
- Profiles should be as symmetrical as possible
- Cavities should be avoided.
- Profiles should have a uniform height, so that it can be cut from the extrusion profile in one sawing move. This avoids the need for expensive tooling
- Wall thickness should be as uniform as possible
- The amount of unique profiles should be kept to a minimum to keep mold investments as low as possible.

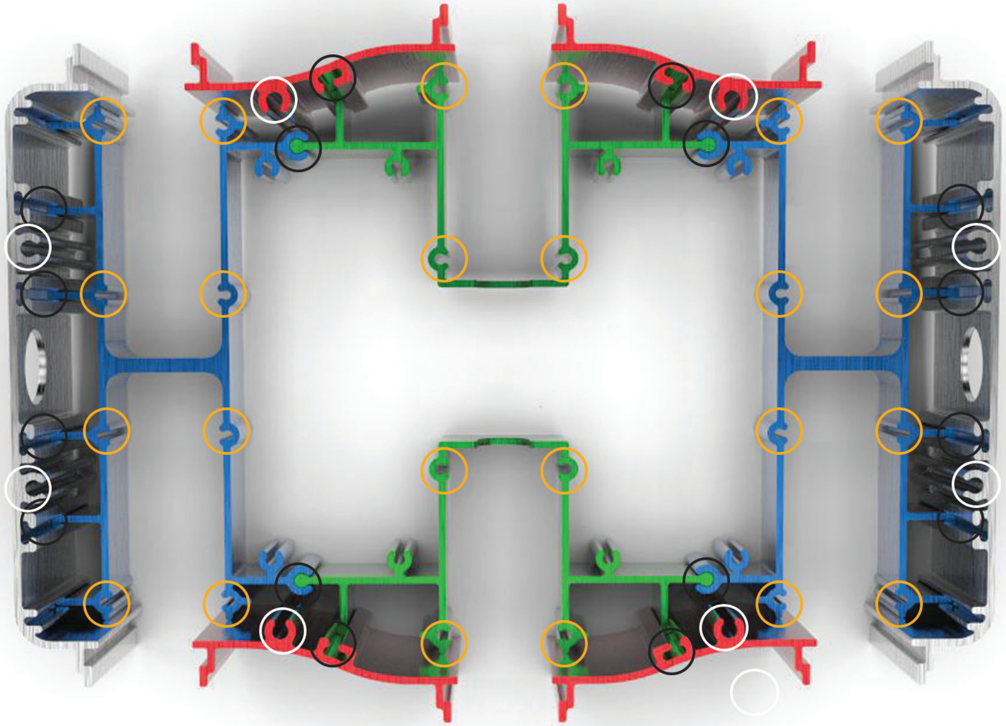
Extrusion Profiles

Taking into account these guidelines the frame of Zebro was redesigned for extrusion molding. Because the design of Zebro was already symmetrical over both the x and y axis, the entire framework could be split up into 4 unique extrusion profiles. In total the outer wall of Zebro (56mm high) consists of 6 profiles; 2 large profiles at the front and rear, and 4 smaller ones in the center. The inner framework consists of 4 profiles, two outer ones and two inner profiles. The profiles are joined using ball joints and T-joints, where the profiles are slided into each other over the Z-axis. Using this process the entire frame can be joined together in under 1 minute per Zebro. The profiles also allocate holes for PCB mounting and optional slots for bolts that fasten the top, bottom and profiles. (Figure 5b)

Figure 5b: Redesign for extrusion



- Inner Frame S (2)
- Inner Frame L (2)
- Outer Frame S (4)
- Outer Frame L (2)



- Motor PCB Connection
- Profile connection slide
- Top/Bottom plate bolts

The clicking together of profiles was prototyped using 3D-printing. In total, the frames took about 7 hours to print. 12 complete sets were printed (Figure 5d,e), after having optimized the clearances for optimal sliding.

Along with an expert from SAPA extrusions, one of the largest extrusion molders worldwide, the prototyped profiles were verified to be moldable. Furthermore a cost estimate was made. In total, the mold costs were placed at €8000 in total. Along with this, a total of €4000 of start-up costs are needed. This brings the total investments before extrusion can commence to €12,000. After this, material and tooling costs are to be taken into account. These are estimated to be around €5-10 per Zebro for all profiles. Any length of profiles can be extruded, so the more Zebro´s are produced in one go, the lower the investment costs per Zebro will be.

Figure 5c: Extrusion die with billet in and profile out

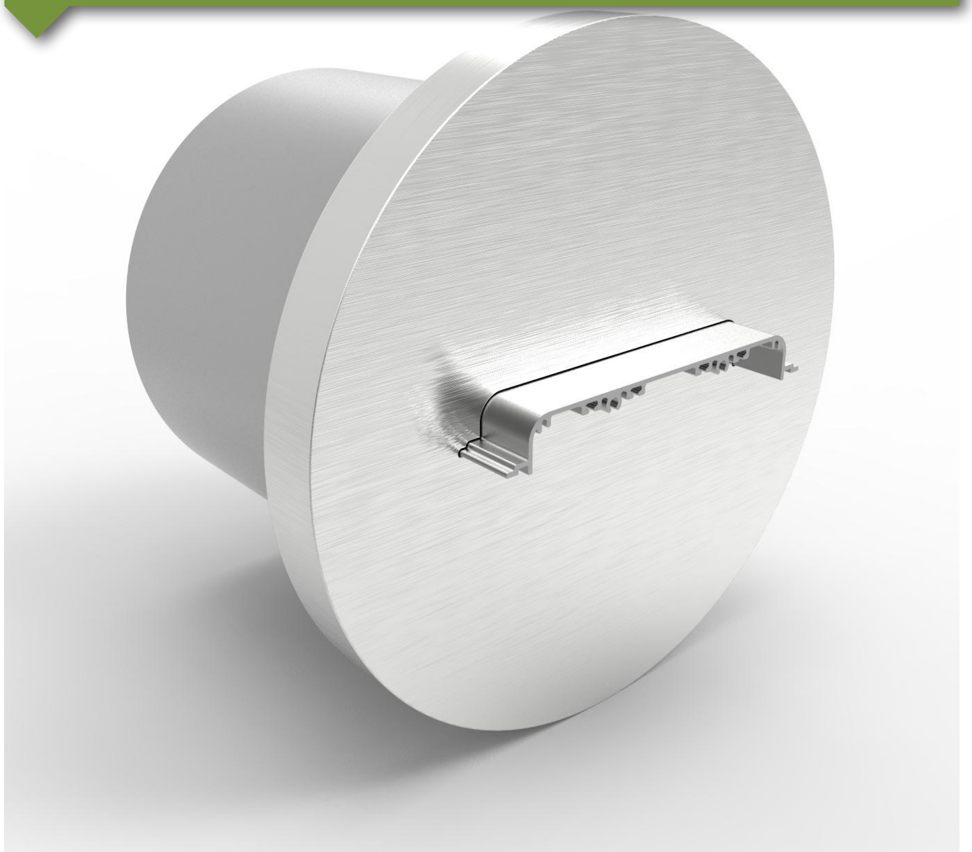
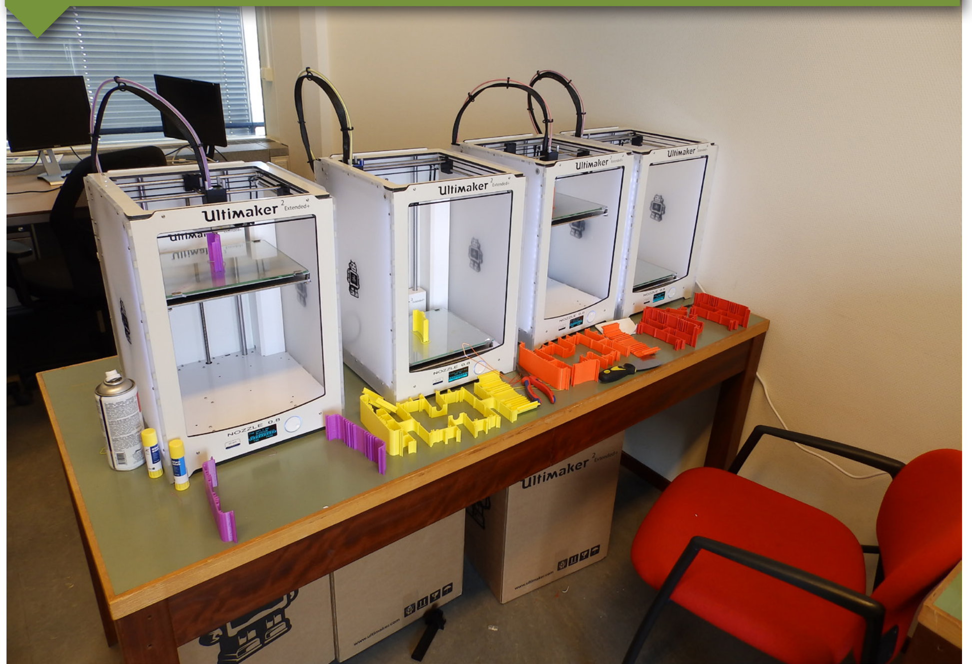


Figure 5d: 3D printed sets of parts

Figure 5e: 3D printers in operation



5.1.2 Laser Cutting

The extrusion profiles need to be locked in place. To lock them, the top and bottom of Zebro can be used. Using laser cutting these two plates are cut. Two millimeter deep slots are engraved in which the profiles are locked into place. These grooves can be seen in figure X. By locking the profiles in between the top and bottom plates, the need for mechanical fasteners such as glue or bolts/screws is avoided. By using 4 snap-fit clamps at the front and back of Zebro, the top and bottom plate are pushed together, locking the profiles.

In Figure 5f the interaction between the two module slots at the top of Zebro and the modules themselves can also be seen. The modules are fixed in place through a twist-lock The module is inserted from the top (bottom, in figure 5f), and twisted 10 degrees to lock it.

The motor connections plates are also laser-cut from aluminum. This means the motor will be able to dissipate heat easily through the aluminum and means the motor can be securely locked into place.

Finally, the encoder wheels are also laser-cut. Laser cutting is the only process that can create the tiny slits needed; tests with 3D printing failed (See section 4.2.3)

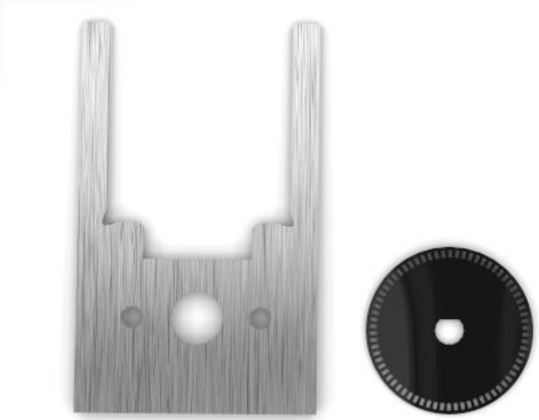
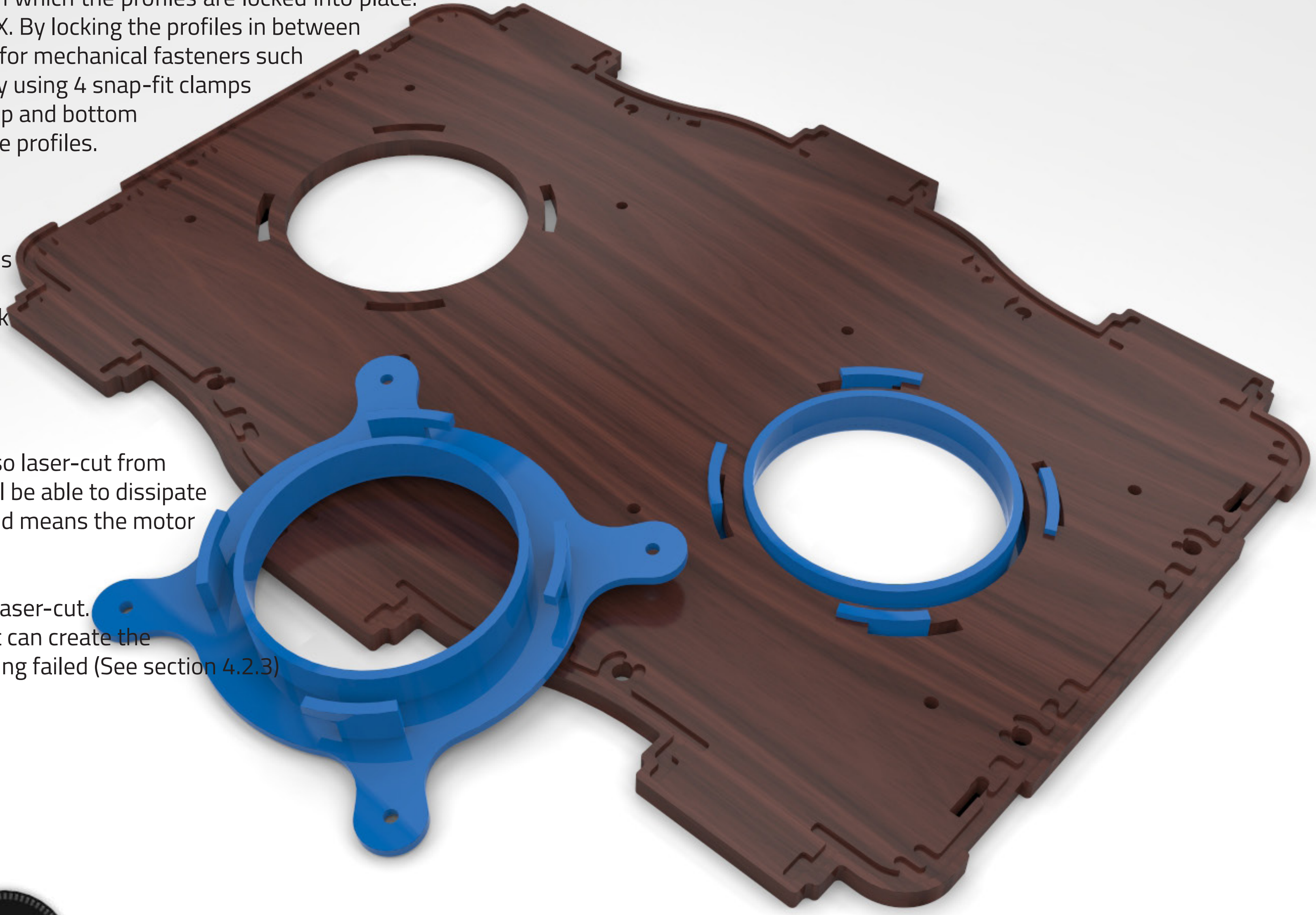


Figure 5f: Top plate with groove and module interaction



5.1.3 Injection molding

Injection molding is the manufacturing process of choice when it comes to the five parts shown below (Figure 5g). Injection molding is one of the most widely applied manufacturing process, being responsible for a large portion of all plastic products. With injection molding plastic granules are molten and injected into a close chamber consisting of two mold halves pressed together with great force. After a short cooling period (typically <1s) the mold is opened and the plastic product is ejected, and the cycle is repeated.

Being relatively expensive, injection molding will only be profitable in large series (10,000+), with typical mold costs for parts as small as these ranging between €5,000 and €30,000. All parts are easily moldable, requiring only two mold halves. An example of such a mold is given in figure X. The Leg Hub (second from the left) will be more difficult to produce, requiring two slides from the side.

For smaller series, these parts could all be 3D-printed. The printing times are, from left to right: 6m, 11m , 14m, 9m, 30m. Effectively, this would allow one 3D printer to print enough parts for 2 to 3 DeciZebro's per day.

Figure 5g: Injection molding parts and mold design

5.2 Final Design

The final DeciZebro (figure 5h, 5j) features a design optimized for series production. The robot weighs a total of 1800 grammes (Figure 5h) and measures 27x21x15 centimeters. It operates on a 14.4 Volt battery capable of providing enough power for at least 1 hour of continuous operation. The robot can be opened up within seconds by removing the four snap-fit clamps. After this, the motor modules can be replaced or taken out in seconds, by simply pulling them from their form closures. Two module slots are featured at the robots top, onto which modules can be secured using a twist lock, also found on camera lens caps. The robots legs are snap-fitted onto the leg hubs, meaning the robot can easily be transformed from single legs to double legs, and different legs can also be designed to fit on the robot.

DeciZebro is designed to look friendly and simple. Its rounded shapes and combination of warm colors with wooden top and bottom help to achieve this.

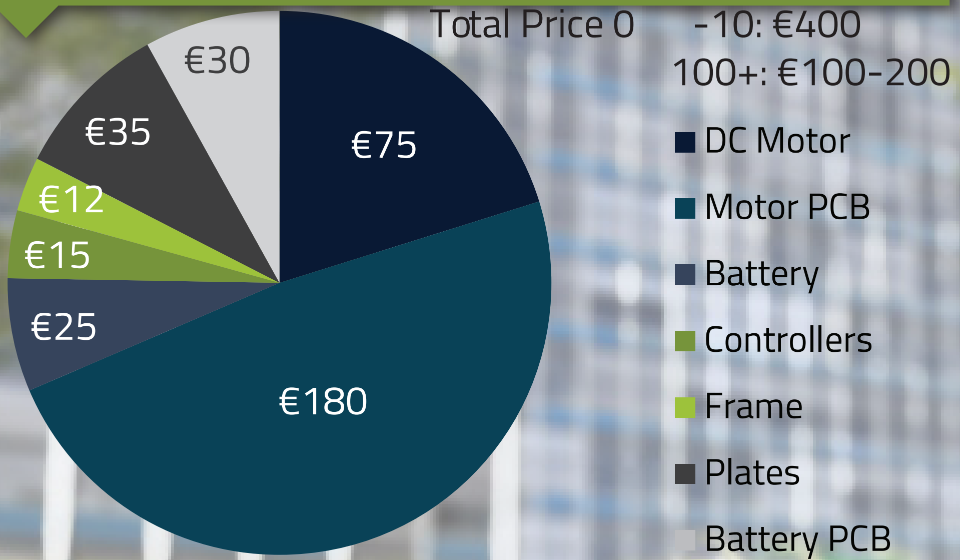
A series of 10 robots were prototyped. The prototype is produced using 3D printing and laser cutting. The total printing time per robot is about 20 hours with the right printer settings. In total, about 290 grammes of plastic are used. For the top and bottom, walnut wood is used. The total laser cutting time is about 40 minutes.

Structurally, the robot is very strong. It supports up to 90 kilograms on its top with non-snap fit legs. This was verified by letting a 80-kilogram person stand on the robot. For the snap-fit variant, the supported weight is about 20 kilograms before the legs snap off.

The total cost per series 10 prototype was about €400 including all electronics. For a series of 100 robots, the estimated price is between €150 and €200

Figure 5h: One of the series 10 robots

Figure 5h: Price and weight distribution



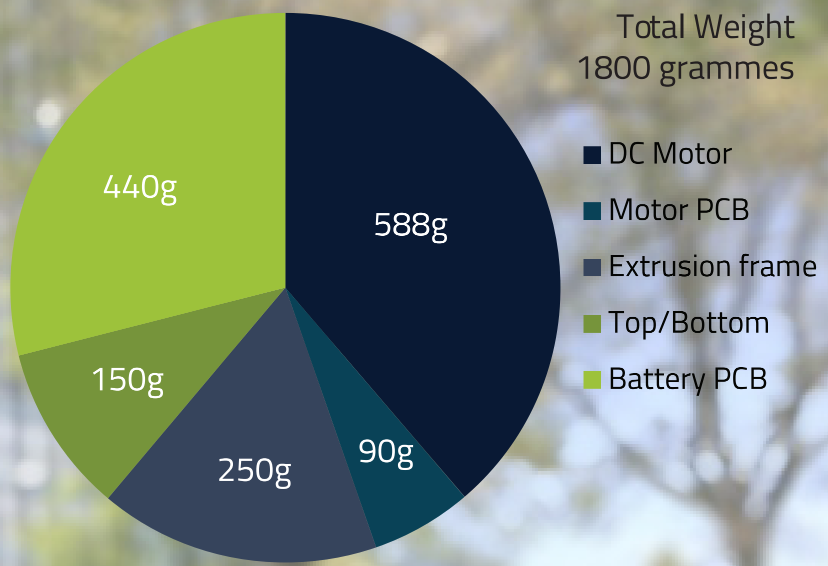


Figure 5j: Simulating a swarm with the series 10

5.2.1 Parts

DeciZebro has 153 parts (Figure 4k), of which 25 are unique. Of these, 11 are bought off the shelf. The other 14 need to be manufactured specifically for this robot. Of these, 4 parts are manufactured using metal extrusion. 4 parts are manufactured using laser cutting, 4 using injection molding or 3D printing and 2 are electronic components.

Each Zebro is equipped with 6 motor modules. Each module consists of 20 parts and weighs about 150 grammes. The estimated assembly time per module is 6 minutes. In figure 5l and 5m the internals of Zebro can be seen. In figure 5L the wiring diagram is shown, with the red/black wires showing the power connections, and the yellow wire showing the I2C data bus connections. The picture does not show the motor PCB to motor power cables.

The total assembly time per robot is estimated at 1 hour. For a detailed assembly schematic the reader is referred to appendix B. Furthermore, the reader is referred to the part catalog for production details and other information.

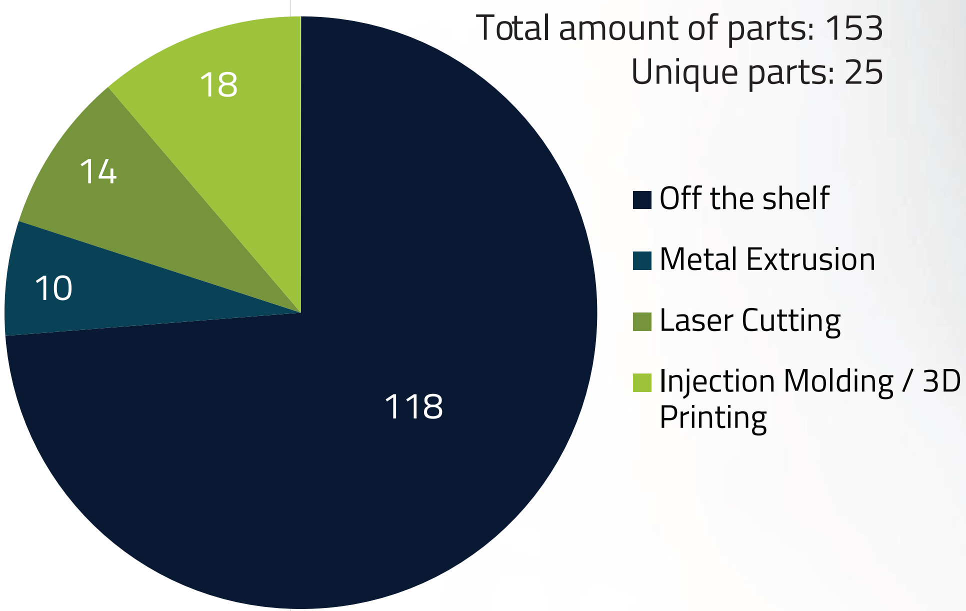


Figure 5l: Parts & Manufacturing methods

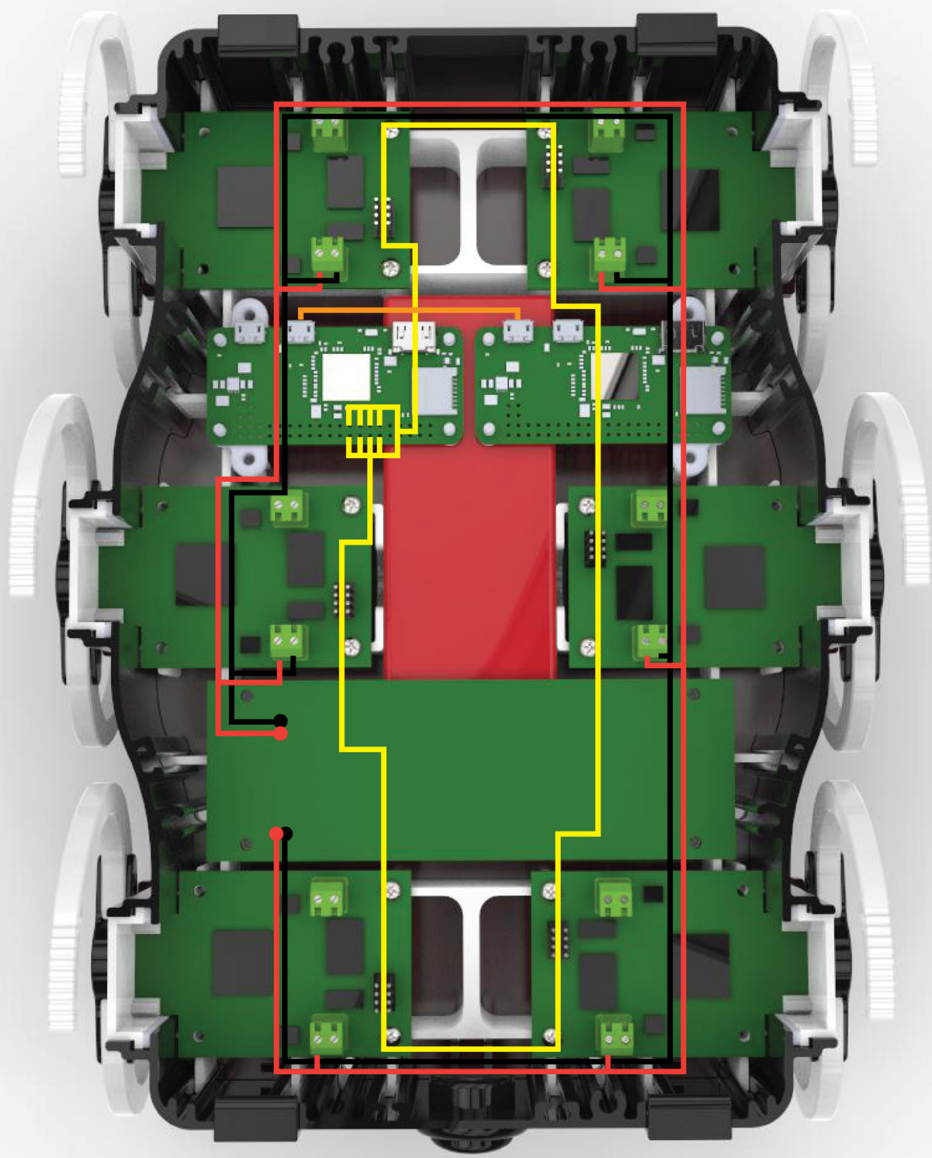
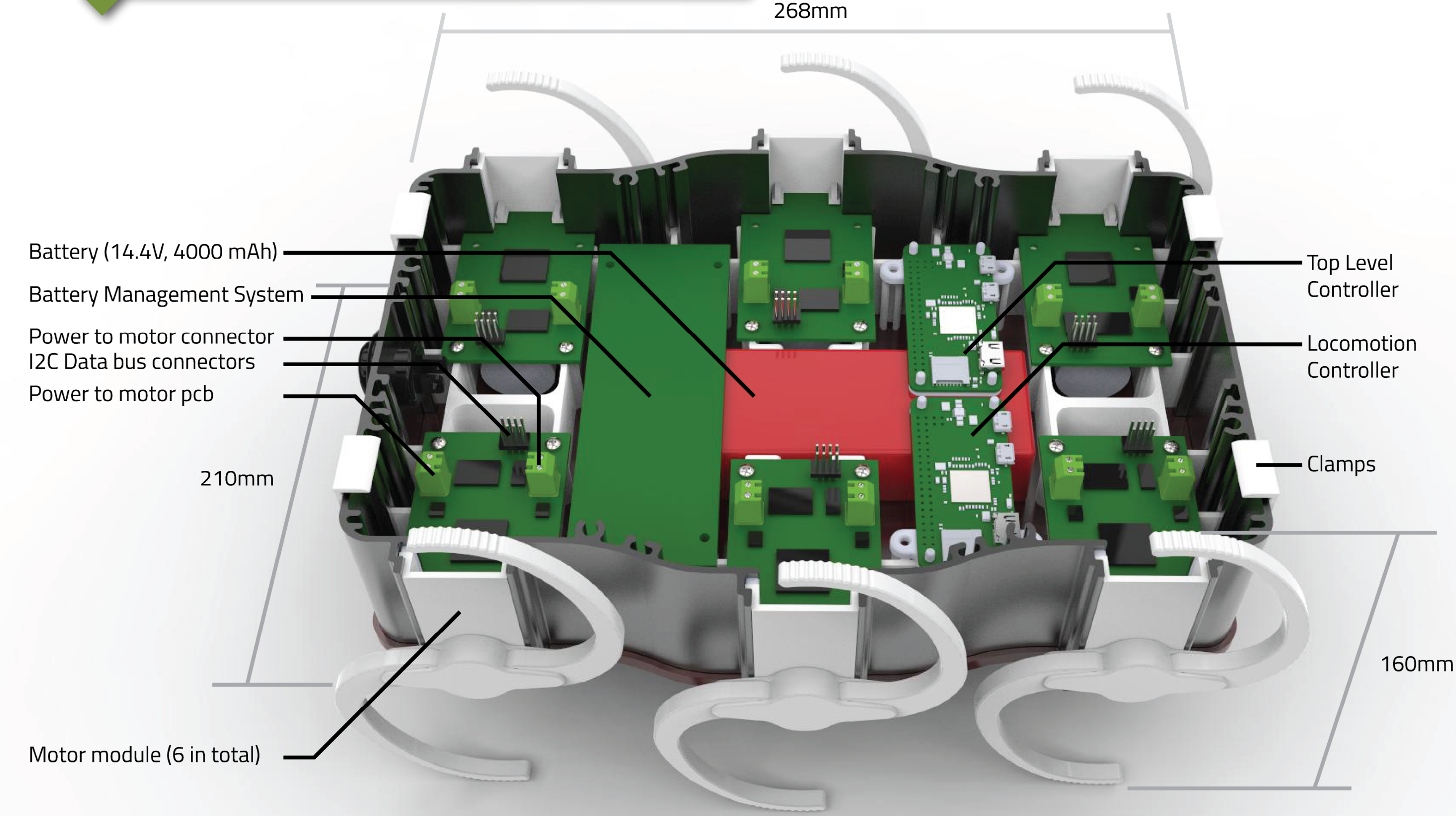


Figure 5m: Parts & Manufacturing methods

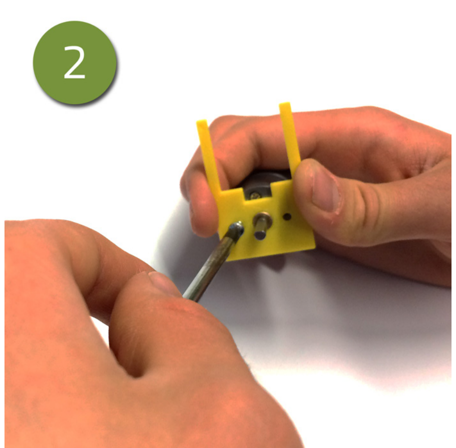


5.2.2 Assembly

Assembly of one complete DeciZebro takes about 1 hour. Within this assembly scheme only the mechanical assembly is covered; wiring of the electronics is not covered here. Wiring is included in the 1-hour figure. A detailed assembly overview is given within appendix A.

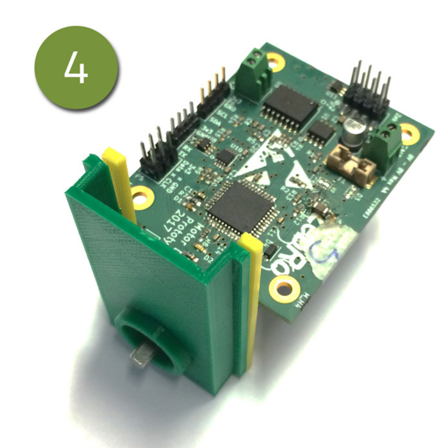
1. Motor Module Sub-Assembly

1. Gather 2 M3 6mm screws, the motor plate and the DC motor



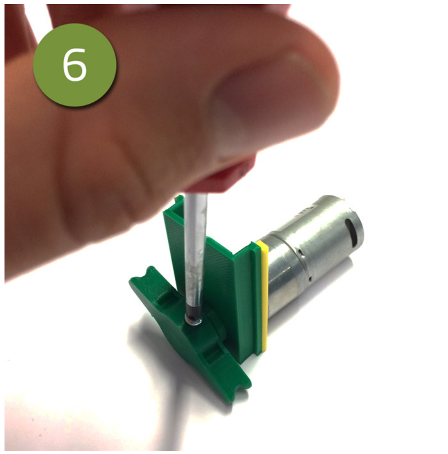
2. Screw the motor plate onto the motor

3. Slide the encoder wheel onto the motor D-Axis



4. Place the Motor PCB and the Motor Module Front

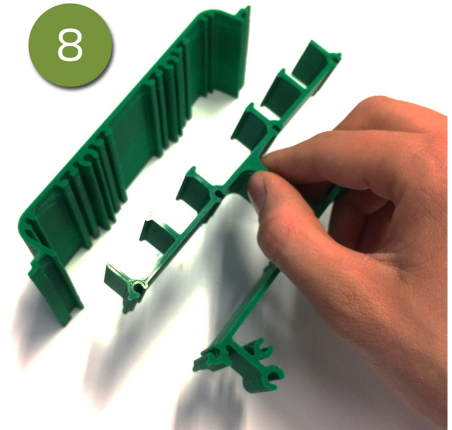
5. Insert Hex Nut into Leg Hub, screw in M3 12mm screw



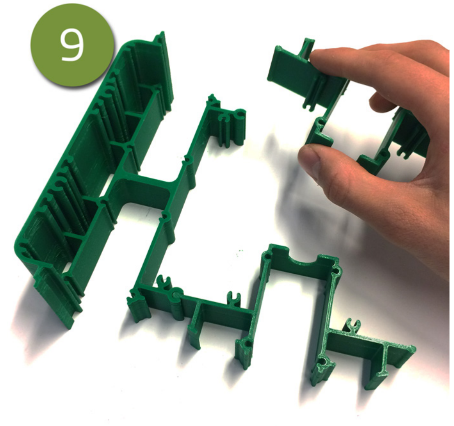
6. Fasten screw onto Motor axis to secure Leg Hub

7. Click the legs onto the motor hub - Motor module finished!

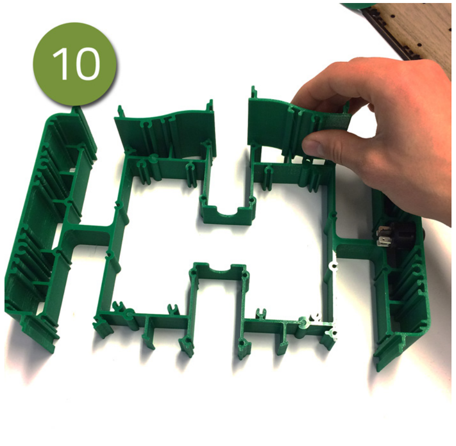
Repeat this process 6x, to assembly 6 motor modules



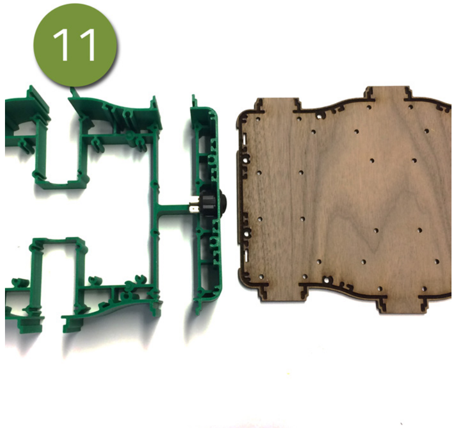
8. Slide Inner Frame L into Outer Frame L



9. Slide Inner Frame S into Inner Frame L (x2)

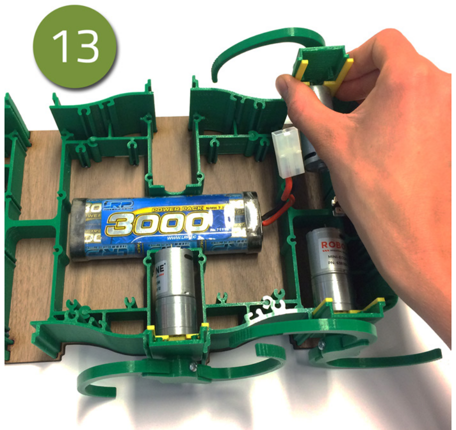


10. Slide in Outer Frame S (x4)

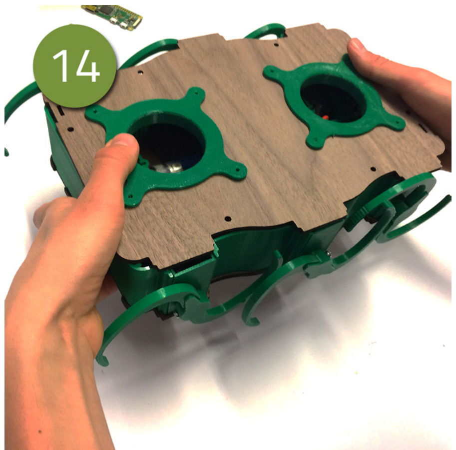


11. Take the bottom plate

12. Click the framework into the slots provided in the bottom plate



13. Click the battery into place and slide in the 6 motor modules



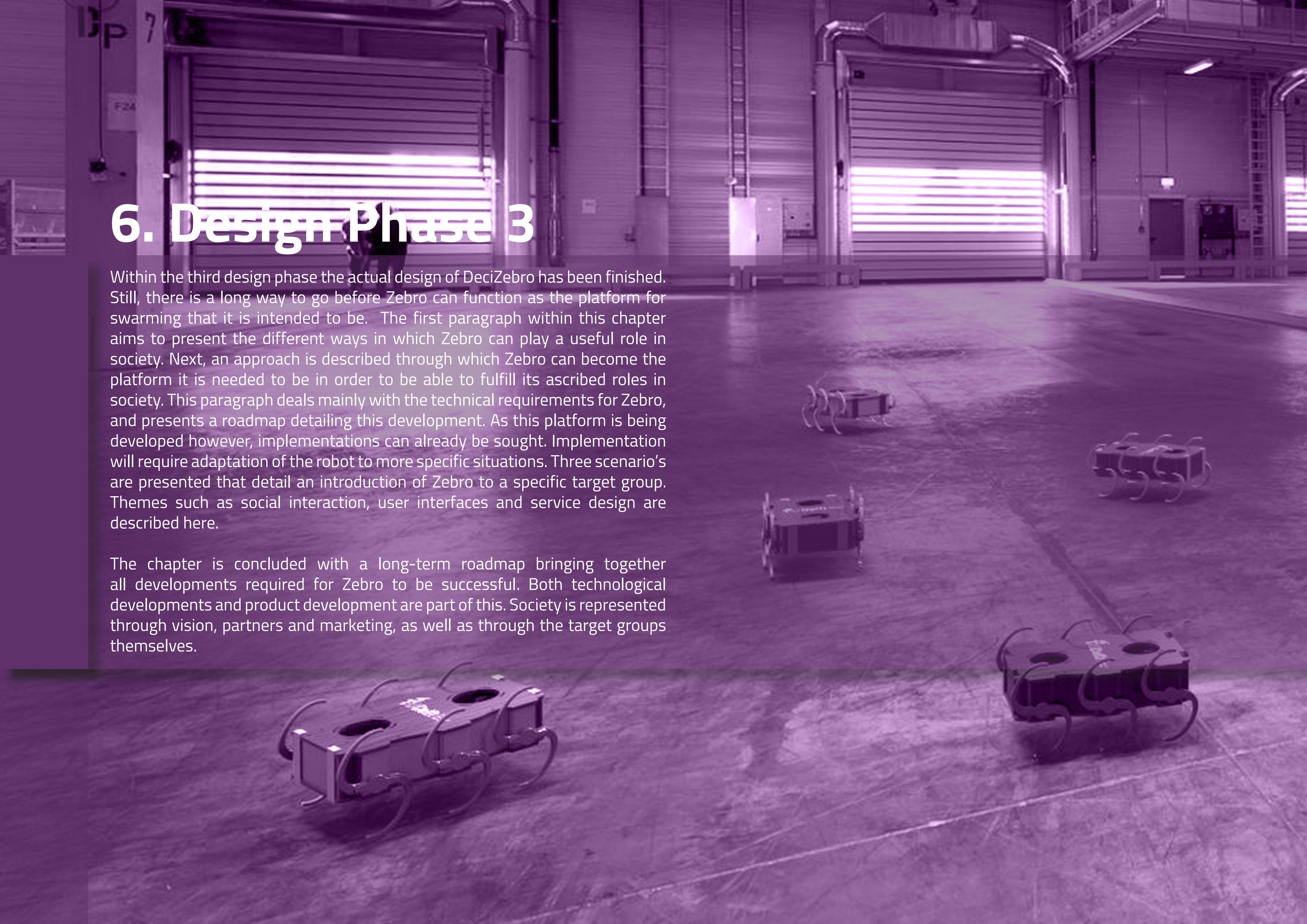
14. Click the top plate onto the robot

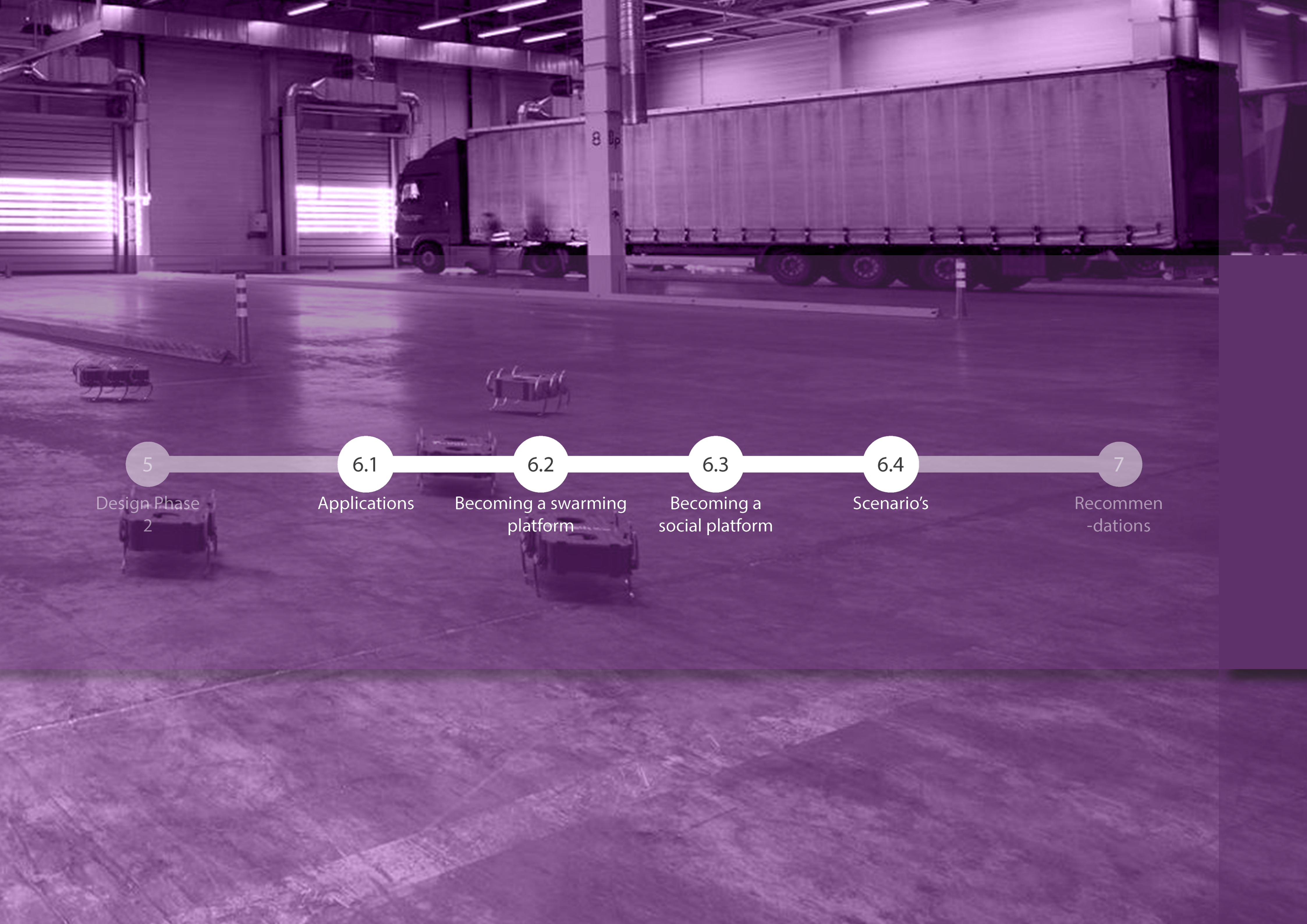
15. Click the clamps onto the sides - Finished!

6. Design Phase 3

Within the third design phase the actual design of DeciZebro has been finished. Still, there is a long way to go before Zebro can function as the platform for swarming that it is intended to be. The first paragraph within this chapter aims to present the different ways in which Zebro can play a useful role in society. Next, an approach is described through which Zebro can become the platform it is needed to be in order to be able to fulfill its ascribed roles in society. This paragraph deals mainly with the technical requirements for Zebro, and presents a roadmap detailing this development. As this platform is being developed however, implementations can already be sought. Implementation will require adaptation of the robot to more specific situations. Three scenario's are presented that detail an introduction of Zebro to a specific target group. Themes such as social interaction, user interfaces and service design are described here.

The chapter is concluded with a long-term roadmap bringing together all developments required for Zebro to be successful. Both technological developments and product development are part of this. Society is represented through vision, partners and marketing, as well as through the target groups themselves.





5
Design Phase 2

6.1
Applications

6.2
Becoming a swarming platform

6.3
Becoming a social platform

6.4
Scenario's

7
Recommen-dations

6.1 Zebro Applications

6.1.1 Characteristics of swarming

The first two design phases were about designing a Zebro suitable for swarming. This meant that the robot had to be mass producible as well as modular. Just as important as the physical design of Zebro however, is the strategy to implement it in society. The potential of swarming robotics is great but so far it has not been realized. The question that is asked within this chapter is, therefore;
How can swarming robots be applied in our society in a useful way?

In order to be able to answer this question a step is taken back. Swarming has 5 distinctly unique characteristics that allow it to be relevant. By examining these, a strategy for implementation can be based on the unique selling points afforded by swarming behavior.

Autonomous
First of all, swarms are autonomous. This means they are meant to operate independently of human interference or oversight. This is a competitive advantage over current systems that do require this human involvement. Moreover, it means Zebro swarms can also operate autonomously in area´s that are dangerous to humans. Examples include search and rescue missions, clearing minefields or exploration missions to remote territories (including interplanetary missions)

Simplicity & Homogeneity
Because Zebro's are inherently simple and a-specific due to their modular nature, they are much less expensive then specialized robots created for a single purpose. The heterogeneous nature of the robots allows swarms to be scaled up or down at will, without any coding or settings to be changed.

Collective Animal-like behavior
Because Zebro's work together they can do much more then they could on their own. Together the Zebro's can cover large swaths of terrain. Data can be shared across the swarm and verified by multiple sources. Any interesting event detected by an individual may attract the entire swarm, thereby increasing sensing density near interesting events.

Interaction
Zebro's can interact with their environment and show social behavior. Furthermore, they can interact with each other and react to each other. If different Zebro's are given different personalities, possibilities for researching social robotics arise.

Figure 6a: Characteristics of swarming

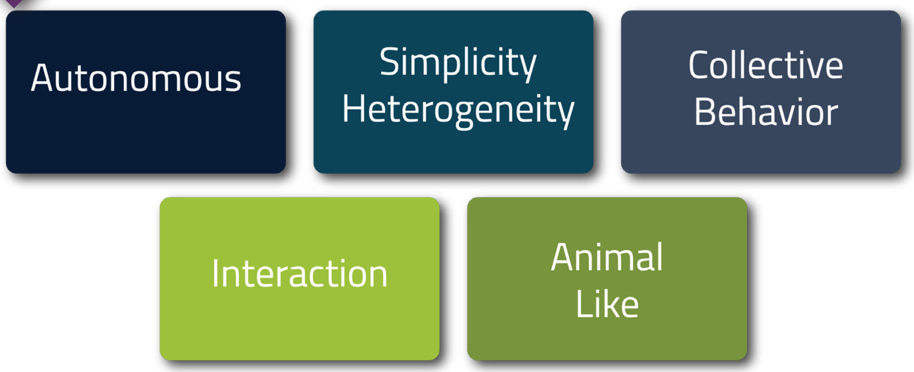
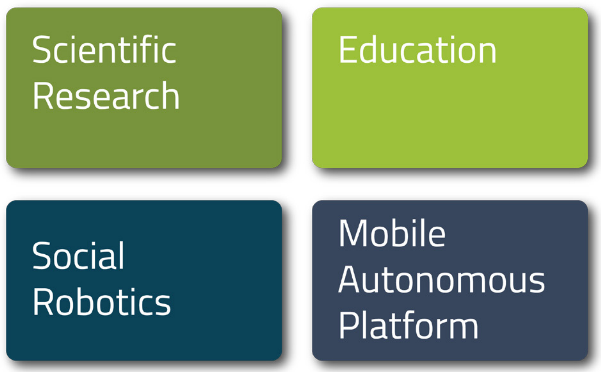


Figure 6b: Area's of application



6.1.2 Applications for swarming

Four main categories of application are identified. They represent broad categories of implementation that are distinctly different from each other. The first, scientific research, aims at implementing Zebro as a platform for experimentation with animal-like behavior and swarming, but also as a platform for social robotics research. The educational direction aims at bringing the simple design of Zebro to young people in order to let them engage with robotic technology and learn to program and create modules themselves. Zebro swarms can also be implemented with the specific goal of showing social behavior and entertaining people. This direction has a high potential for changing public perception of robotics in the early stages of implementation. Last of all the Zebro has great potential for implementation within companies through its capabilities as a mobile autonomous sensor network.

Education
Using Zebro as an educational platform can help bring robotics down to an understandable level for a new generation. Zebro is designed to be easy to assemble. About 16 soldering connections are necessary for the entire robot to function, and these soldering connections can come pre-assembled. As such, the robot is suitable to be assembled by children. Wiring is the most difficult part and could be done by youths 14 and up. By letting scholars assemble the robots themselves and see how each component fits together and forms the robot is a key step in involving them into the nature of robotics. If assembled, students could interact with the code. This could be done on several levels. Students could be asked to write code themselves, for example specifying a certain walking gait, or allowed to interact with the code on a visual interface basis. For example, an application that allows students to use drag and drop blocks to create a walking gait could be created.

When assembled, students could switch the robot on and see how the robots together form a swarm and start exploring the building. Camera modules could be added, allowing students to follow a live feed from the robot. The program could be offered along with a 3D printer, allowing students to make custom modules to be placed on Zebro. Making the robot their own is the key ingredient in this.

Safety issues are very important, as well as making sure the students understand the assembly guide and

Social Robotics
The main goal of social swarming is to create swarms capable of meaningful interaction with humans, eliciting surprise, being entertaining and changing perception of robotics.

Interaction is a very broad term and can therefore be defined broadly. In this specific case, interaction is regarded as meaningful when there is mutual understanding between the robot and the human it is interacting with. This understanding need only to be at a very low level and can be as basic as Zebro understanding when a human approaches, reacting to it by acting 'scared' and move backwards, the human interpreting this as the Zebro being scared or alarmed.

The first step to realize interaction is to allow Zebro to be able to perceive humans. This can be done in many ways, for example by detecting the heat signature of humans (IR) or using optical tracking (Camera). Once the Zebro is able to identify humans, it should be able to detect whether the human is approaching or moving away. The approach velocity and acceleration could also help Zebro to specify its responses. This input has to be converted to behavior. Locomotion can be used to physically move Zebro away or towards humans. Lighting could convey an emotion (quick blinking and red might mean panic, blue agitation and green happiness. Finally, the behavior shown by the Zebro must be understandable to humans to complete the interaction. In order to be able to understand Zebro, Zebro should consistently show the same kind of behavior in response to the same human actions.

The goal of social robotics is first of all to change the perception of robotics in general. Robots are often unresponsive to humans. If they are responsive, they have been specifically designed to be a 'social robot', coming with human-like face characteristics and being dedicated to being 'social'. DeciZebro is first and foremost a swarming robot, comparable to swarming animals. Animals have their own business and live their own lives, yet they do interact with humans if they are in the vicinity. This kind of spontaneous interaction that results logically from circumstances is a type of interaction that can unique be brought about by swarming robotics.

The first emotion that Zebro can trigger is one of surprise and next of curiosity. Watching a Zebro swarm move by should also be entertaining. As such, Zebro swarms could be featured in Zoo's or at other public events. The PicoZebro's could be featured as 'aquaria' of robots, whilst the large Zebro's could roam around. They could serve as delivery agents, for example bringing around drinks or refreshments

Mobile Autonomous Platforms
Zebro can enable companies to take a new approach to gathering sensor data. Zebro swarms can quickly and flexibly measure any parameter the client requests. By using their swarming behavior to explore a given environment, and by being equipped with a sensor module reflecting the clients wishes, the environment can be mapped in regard to the measured variables. The Zebro´s could either work event-based or provide continuous support. Zebro's would compete with static sensors, but have several specific advantages over them:

- Static sensors require manual installation.
- Static sensors require maintenance and battery replacements. If a sensor fails, the data stream stops.
- Static sensors can never cover an area as accurately and dynamically as a swarm can.
- Up or downscaling static sensor networks requires human interference

Scientific research
As a platform for scientific research, Zebro can help the field of swarm robotics advance. By providing a platform which is fully functional when locomotion is concerned, and which is ready for module implementation, research can advance more efficiently. The multi-disciplinary nature of the robot allows many different engineering disciplines to use the robot for their research.

6.2 Becoming a swarming platform

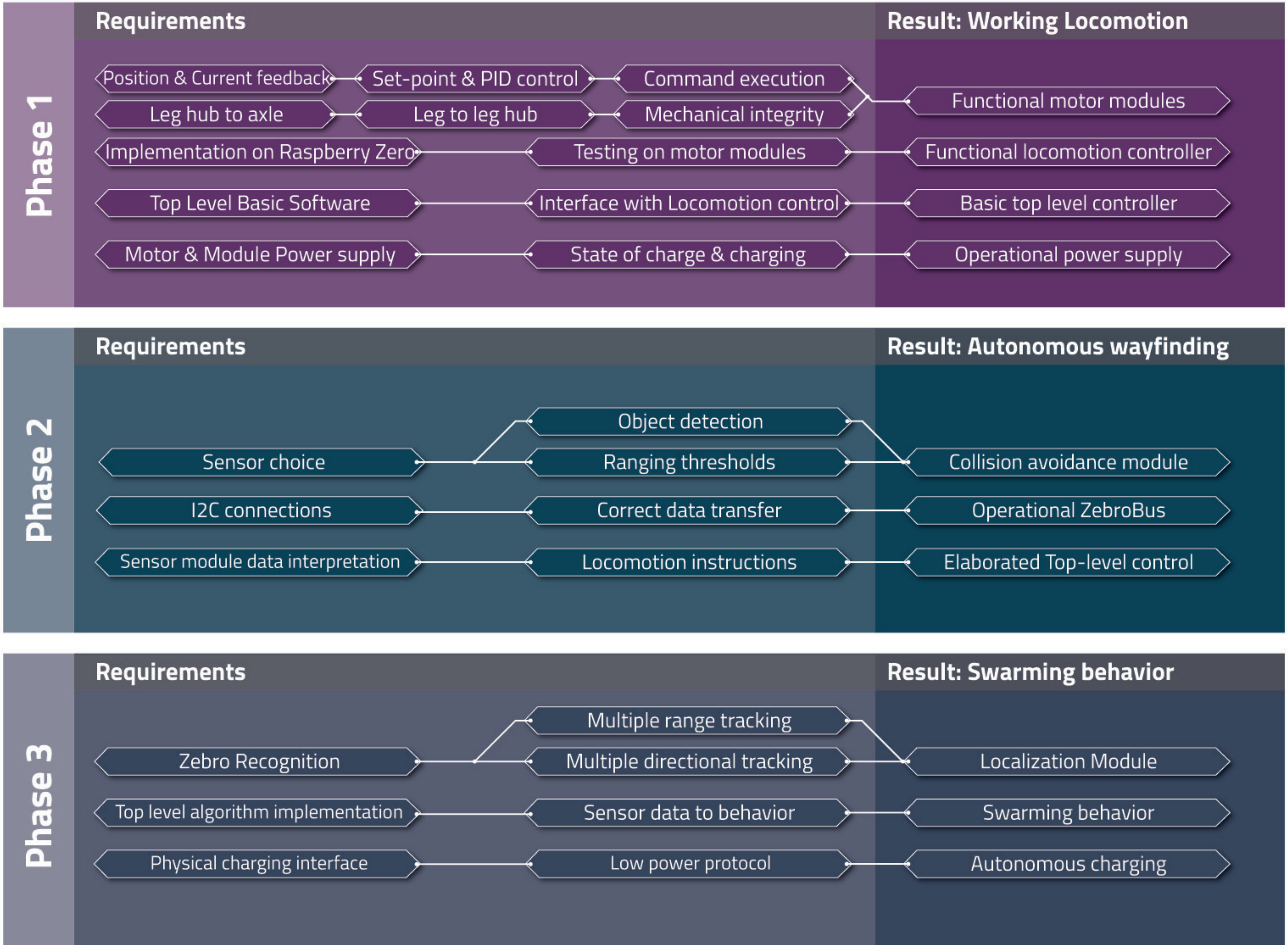
In order to become a robotic platform suitable for the aforementioned markets Zebro needs further development. Several key requirements have not been met, as they were outside of the scope of this project. However, being the bridge between different engineering disciplines, industrial design engineering can provide a framework for the realization of the key requirements outside its domain.

In order to be able to swarm, key requirements that still need to be met are:
1. Motor module electronics need to become fully functional
2. A locomotion controller must be implemented and tested
3. A top level controller must be implemented and tested, along with the ZebroBus I2C communication protocol
4. A reliable I2C interface with modules must be made, and the top level controller must be programmed in such a way as to be able to interact with these modules
5. A power supply system must be successfully implemented and verified according to safety standards, lifetime and charging methods

To be able to fulfill these requirements, a 3-step process is recommended, consisting of 3 project phases. Phase 1 is about making sure Zebro becomes a fully functional locomotion platform. During this stage the motor modules are finalized so that the electronics are verified and mass producible. Furthermore, software is written and implemented to actually run the electronics.

During phase 2 the Zebro takes a first step toward becoming an autonomous platform through autonomous way-finding. At the end of this stage, Zebro should be able to maneuver any environment autonomously, not hitting any objects.

During phase 3 the sensors and software is adapted to allow Zebro to recognize other Zebro's and engage in swarming behavior. This means the results of phase 2 have to be applied and adapted to the specific situation of swarming. After this, Zebro can be modified for any situation by simply adapting the modules used in its two module bays.


Phase 1
Requirements
Result: Working Locomotion
Position & Current feedback
Set-point & PID control
Command execution
Leg hub to axle
Leg to leg hub
Mechanical integrity
Functional motor modules
Implementation on Raspberry Zero
Testing on motor modules
Functional locomotion controller
Top Level Basic Software
Interface with Locomotion control
Basic top level controller
Motor & Module Power supply
State of charge & charging
Operational power supply
Phase 2
Requirements
Result: Autonomous wayfinding
Object detection
Sensor choice
Ranging thresholds
Collision avoidance module
I2C connections
Correct data transfer
Operational ZebroBus
Sensor module data interpretation
Locomotion instructions
Elaborated Top-level control
Phase 3
Requirements
Result: Swarming behavior
Multiple range tracking
Zebro Recognition
Multiple directional tracking
Localization Module
Top level algorithm implementation
Sensor data to behavior
Swarming behavior
Physical charging interface
Low power protocol
Autonomous charging

6.3 Becoming a social platform

Robotic swarming offers unique possibilities for experimentation with social robotics. It is important to understand the way Zebro can help function not only as a platform for testing the physical behavior of swarming, but also for testing the social behavior of swarms. This paragraph concisely introduces the topic of social swarming.

Products are meant to serve people. The same applies to robotics. Since its rise robotics has taken over many dangerous or repetitive tasks from humans. As such, robots have mostly manifested themselves as machines performing tasks. This is in line with Oxford's definition of a robot:

A machine capable of carrying out a complex series of actions automatically (Oxford Dictionary, 2017)

In popular culture, however, robots are often presented as having a personality. This personality does not necessarily equate to physical human likeness, as robots like R2D2 from Star Wars demonstrate. Nonetheless, many robots have been shaped to look like humans (called humanoids). In films like I Robot, humanoid robots rebel against humans and take over. This dystopian view is shared amongst many films, notably including The Matrix series and Terminator. Along with the advance of Artificial Intelligence (AI), the threatening character of human-like robots is strengthened.

Still, many projects are currently underway worldwide to replicate humans in the form of robots. These are either focused at recreating humans from a mechanical perspective (Atlas, Boston Dynamics) or the social aspect (Erica, Hiroshi Ishiguro). Surprisingly, however, robots do not often take the form of animals. The Zebro project is breaking ground in this respect, hoping to introduce robots as animals. Reasons for this choice are, notably:

- Animals are accepted as being part of society and are present in our day to day lives
- Animals interact with humans, creating mutual understanding
- Animals are, with exceptions, not threatening to humans.
- Swarm robotics lends itself to comparisons with the animal kingdom and shows groups of robots can function in a similar fashion as groups of animals
- The way DeciZebro walks means it is instinctively classified as an animal
- When classified as an animal, people expect behavior matching that classification. Animal behavior is much easier to replicate then human behavior. This explains the 'uncanny valley' principle in robotics where, if a robot is almost human-like but fails to fully convince, people experience the robots as being creepy and strange. Whereas replicating human behavior in robotics is still far off, replicating animal behavior is more likely

Figure 6d: I Robot (20th Century Fox, 2004)

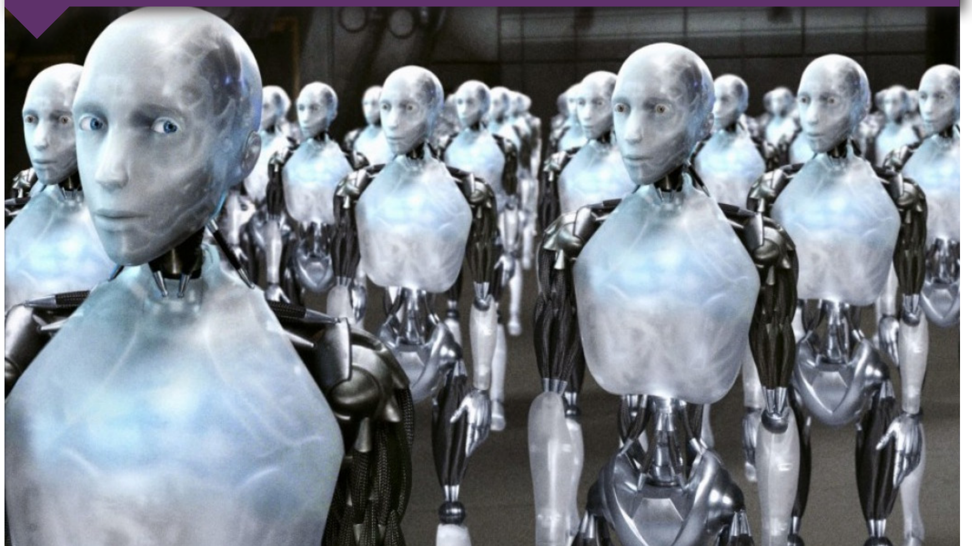
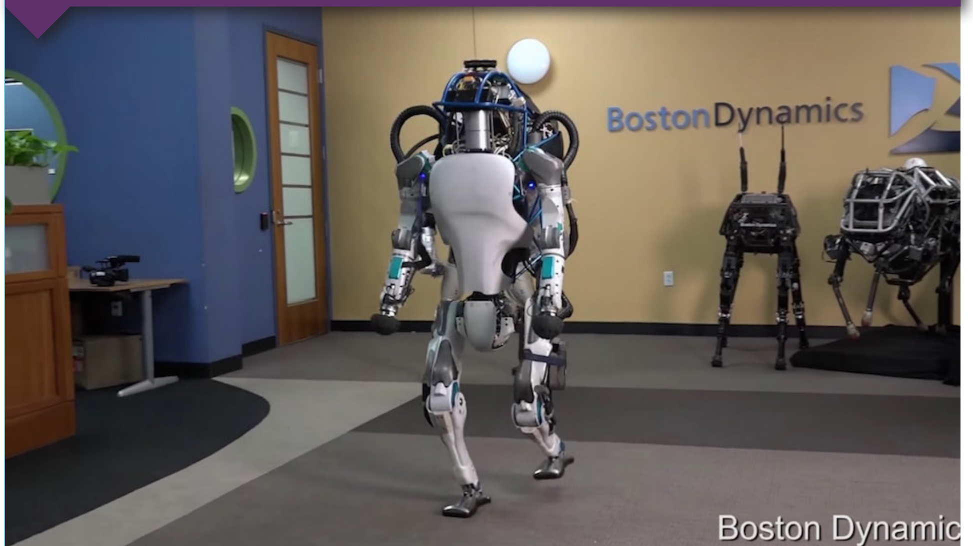


Figure 6e: Atlas (Boston Dynamics, 2016)



to succeed soon. As discussed in paragraph 4.1, animal swarms operate on simply principles which can be implemented in robotics right now.

By establishing that DeciZebro should be experienced as an animal, further specifications can be made and be translated into future design decisions. Several questions must be answered:

- What typifies individual animal responses to humans? How does this vary across different species, and to which species should DeciZebro be likened?
- What does and what does not make animal behavior insightful?
- What typifies collective animal behavior, and how can this be translated into robot swarming behavior?

These are questions that must be answered by future designers. As soon as Zebro starts to be introduced to society and starts to interact with humans, its design and behavior will need to reflect human-animal interaction.

Animal interaction

Before interaction with animals can be investigated, two categories of animals need to be specified. The first category consists of animals that are not aware of human presence. This does not mean they cannot detect objects around them, but means that they do not perceive them as humans. Insects make up the bulk of this category. Animals falling into the second category recognize the presence of humans and adjust their behavior likewise. Whereas an ant is not aware of the danger of a human being, but simply considers it an object blocking its path, rabbits or ducks perceive the size and presence of humans and are attracted or repulsed.

Replicating swarm behavior as demonstrated by ants would simply require DeciZebro's to interact with each other and avoid hitting environmental obstacles. This means there is no real interaction between human and robot. Replicating behavior as shown by ducks or rabbits means the robot must be able to identify humans and adjust their behavior. They might show curiosity, hesitation or restraint, keeping a certain distance, fleeing or coming closer. The words used here are hinting at Zebro having a certain degree of character embedded in its programming

In order to be able to execute these personalities, robots need to:

- Be able to sense humans
- Be able to sense distance
- Be able physically act in accordance with programmed personality

Insightful Behavior

If a robot would have a personality, it would need to make this personality visible to its viewers to achieve interaction. Humans would need to understand the robot. To do this, several approaches can be taken:

- Anthropomorphism: humans tend to attribute human traits, emotions and intentions to non-humans if they recognize features from themselves in these non-humans. To facilitate this, robots could be designed like humans. For example, robots could have a distinct front and back, featuring eyes on the front.
- Using visual and audio cues: DeciZebro could make its intended movements insightful using, for example, blinking LEDs. Much like a car has indicators to show the intended direction.
- Action-reaction: one of the most effective ways of establishing interaction would be to directly react to human behavior. For example, taking a step back when a human comes one step closer.

In short, DeciZebro needs to be able to communicate. It can do this through movement and through light/audio. It must not use these faculties randomly, but base them on sensor data.

Collective Animal Behavior

The sum of a group of Zebro's should result in collective, emergent behavior. This means that the sum of individual characters of robots could help build a dynamic social entity. Some robots in swarm might be more curious, whilst others might be more apprehensive. The possibilities for experimentation are countless and offer great potential for the advance of the field of social robotics.

6.4 Scenario's

As shown in paragraph 6.1, Zebro can have fulfill many positive contributions to society. Implementation is currently not yet possible due to technical limitations, for which a short-term development plan was suggested in paragraph 6.2. Within this paragraph, three scenario's are provided that assume the results as presented in 6.3 are achieved. This means these scenario's are based on DeciZebro being able to autonomously navigate its environment and show swarming behavior. Each scenario focuses at a different target group and helps to explore the way society could benefit from a robotic swarming platform like Zebro.

By deliberately presenting concrete scenario's, the designer and reader are challenged to envision Zebro in an actual context. It puts to the test the claim of Zebro's added value opens up possible development paths of the Zebro platform. The scenario's are mere suggestions, and serve a purpose of triggering future designers who will work with Zebro.

6.3.2 Scenario 1: Disaster response

This scenario is based on the premise of the Zebro platform functioning as a mobile autonomous sensor cloud. The scenario is representative for any application of Zebro involving it functioning as an autonomous sensor cloud. These applications may include, but are not limited to;

- Hazardous area exploration / mapping (including disaster response, minefield clearing, radioactive areas, i.e. Fukushima, space exploration etc.)
- Event based sensing (smoke detection, gas leak detection etc)
- Constant monitoring (air quality, security patrol)
- Mechanical tasks (ground sampling, transport)

In these situations a swarm of Zebro's would be outfitted with a specific module capable of monitoring the data a client would wish to measure. If necessary, certain parameters would be programmed into the swarm, restricting its movement for example. A swarm would be released into the designated area along with a docking station for charging.
The most likely scenario for a business model in the case of autonomous sensor clouds, is that the ZebroSwarms would be offered as a product service system. Clients would not buy the actual product, but buy the service of being able to deploy a swarm for a certain amount of time.

Specific scenario
Directly after an area is hit by a natural disaster, including earthquake's, tsunami's or hurricanes, a swarm of Zebro's is dispatched to the location. A total of 100 robots are released. Together, they spread out over an area of about 50x50 meter and start exploring the area. Being equipped with sensors to detect life-signs, the Zebro's immediately notify a supervisor when a positive signal is found. The supervisor can verify the data and dispatch a rescue team. After several hours the Zebro's need to be recharged. They can do so via a solar panel module or by returning to a charging station.

In this situation the Zebro swarm can effectively cover a large area to detect life-signs.


Figure 6f: Disaster response scenario

6.3.2 Scenario 2: On the streets

This scenario is based on the idea of social robotics. This scenario is representative for situations where interaction between Zebro and people can help achieve certain goals.

In this scenario, each Zebro is equipped with a trash bin module. The Zebro's are released in touristic area's and are attracted to humans. This means that at any location where there are a lot of people, there will be more Zebro's. As such, the density of trash bins is increased near area's with many people. This means there will also be more trash bins at places where more trash is generated.

The surprise at finding out the robots are attracted to people, and the surprise of interacting with the robots, is likely to at least generate great attention towards proper waste disposal.

The scenario of social robotics is promising and offers many possibilities for research. It is for this reason a special paragraph has been dedicated to this topic (Paragraph 6.4)

Figure 6g: An example of a social robotics scenario

6.3.3 Scenario 3: Educational platform

Being easy to assemble, Zebro could be a platform upon which a next generation could be brought closer to future technology and be made enthusiastic about it. Through the use of graphical interfaces the programming of Zebro could be made insightful and children could be able to build and program their own robots which can then act together as a group using the swarming principle.

Figure 6h: DIY assembly in a educational scenario

Recommendations

Within this section a range of recommendations is presented. These recommendations serve as guidelines for future designers that will work on this project. Much work still needs to be done before Zebro can start to fulfill the promises brought on by the concept of autonomous swarm robotics. Recommendations are grouped here by topic.

R1: A focus on platform stability

At the time of writing, DeciZebro is not yet walking. Although it can be said with certainty that it will, the struggles to get it working were great. If Zebro is to become a swarming platform, its locomotion system should work flawlessly. It is recommended that the roadmap presented in paragraph 6.2 be implemented, in order to assure the working of the locomotion system. Only if this can be assured can Zebro be used as a platform to experiment on.

R2: Expertise

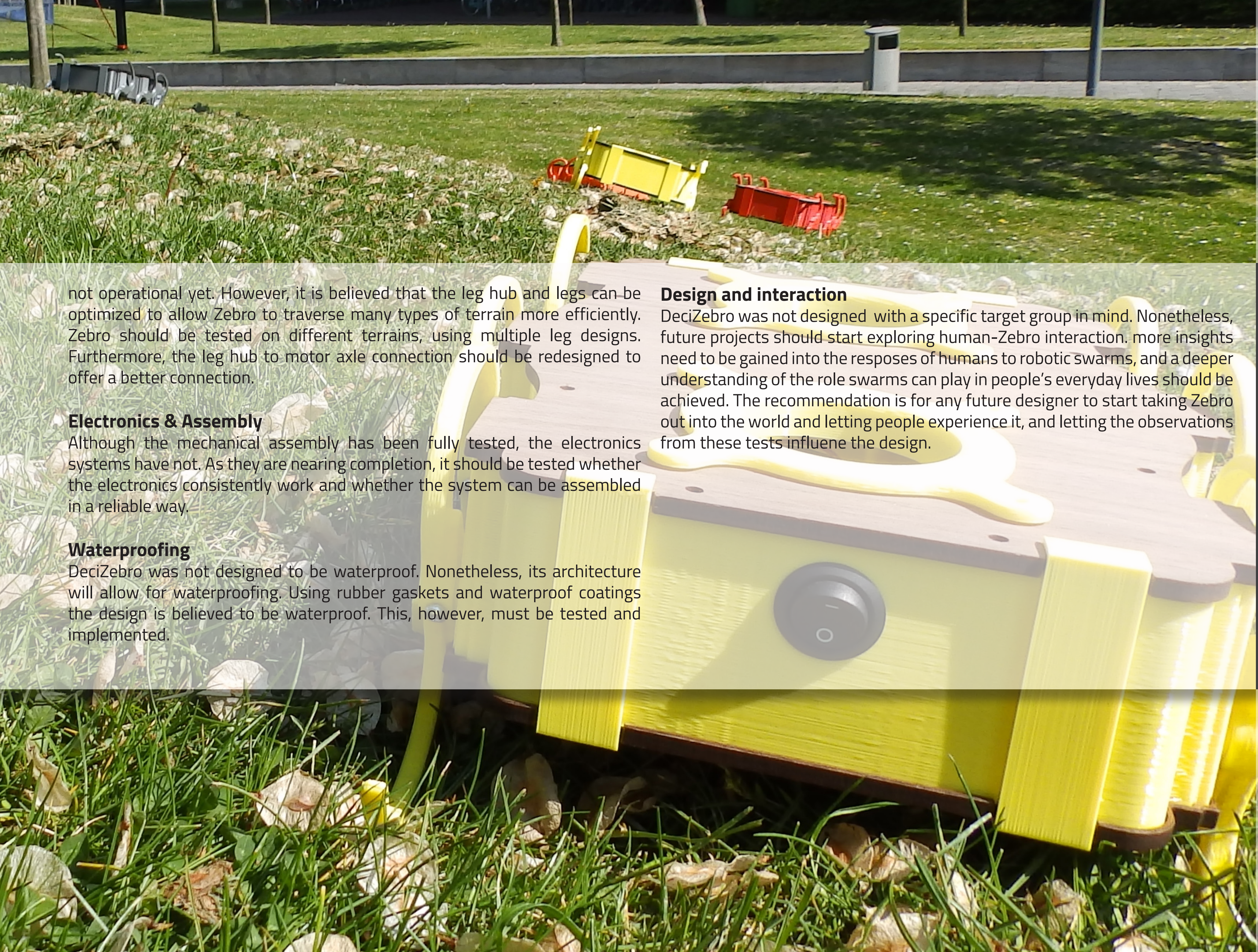
One of the main setbacks during this project originated from a lack of key expertise and skill. Much of the work involved the design of printed circuit boards, the soldering and testing of prototype boards, and the programming and debugging afterwards. These practical skills are often not part of the curriculum of TU delft projects. This meant aligning individual/TU goals with the need for a working robot was very difficult. It is paramount that the learning objectives are matched to the practical skills required to design Zebro. This may result in closer cooperation with students from applied sciences and vocational education (MBO).

R3: Partnerships

Once swarm testing can commence and results are positive, partnerships with companies should be initiated in order to cover initial investments for mass production. Producing the series of 10 robots was stretching the limits of 3D printing possibilities, requiring a full week of printing on 10 3D printers. For larger series, investments will be needed to start the process of metal extrusion.

Leg redesign

The current design of the legs and their attachment to the motor axle via the motor hub have not been field tested, due to the fact the electronics were



not operational yet. However, it is believed that the leg hub and legs can be optimized to allow Zebro to traverse many types of terrain more efficiently. Zebro should be tested on different terrains, using multiple leg designs. Furthermore, the leg hub to motor axle connection should be redesigned to offer a better connection.

Electronics & Assembly

Although the mechanical assembly has been fully tested, the electronics systems have not. As they are nearing completion, it should be tested whether the electronics consistently work and whether the system can be assembled in a reliable way.

Waterproofing

DeciZebro was not designed to be waterproof. Nonetheless, its architecture will allow for waterproofing. Using rubber gaskets and waterproof coatings the design is believed to be waterproof. This, however, must be tested and implemented.

Design and interaction

DeciZebro was not designed with a specific target group in mind. Nonetheless, future projects should start exploring human-Zebro interaction. more insights need to be gained into the resposes of humans to robotic swarms, and a deeper understanding of the role swarms can play in people's everyday lives should be achieved. The recommendation is for any future designer to start taking Zebro out into the world and letting people experience it, and letting the observations from these tests influene the design.

Afterword

This report has described the six-month process of a graduation assignment from the faculty of industrial design engineering. It provided a relatively chronological description of the entire process. It is in this afterword that I would like to shortly reflect, as a designer, on the project. I will do so by addressing the three main pillars of my studies: Industrial Design Engineering.

The first few weeks of this project were challenging. After having spent 5 years at the faculty of IDE, one gets used to its approach to projects. Being mostly like-minded, the students at the faculty understand each other and follow the same general principles of being user-driven and operating in a systematic, problem-solving way. The approach at the Robotics Institute stood into sharp contrast with this, focusing rather on the technology and not on the user or application. It took several weeks to get adjusted to this approach, and to get used to the way other engineering disciplines work. It has been a valuable lesson to learn how to work in a multi-disciplinary cooperation. It is often said that IDE students form the bridge between disciplines, and it was during this project I learned what that means. To help engineers bring their technology driven-approach to a producible, marketable and desirable product.

The role of design in this is key. I've started to discover how design is the bridge between the technology-driven engineering and actual user. How design helps to bring technology to its full potential, molding it in such a way that it matches the needs in society.

I've learned a lot about team management. About aligning personal goals with team goals, and about understanding each other and working together. About facilitating useful and constructive dialogue through the use of mock-up models and visuals. About having an open-minded approach toward technology and other engineering disciplines, and about learning from them.

The role of industrial production (IP) within this project was crucial. A technology may have incredible potential, yet without economically viable mass manufacturing a product may never reach the world outside of the office. IP is relevant from the start of a project and must be considered concurrently with other design issues. This approach allowed me as a designer to consider important production questions early on in the process, avoiding stalemates later on. By deciding, as a starting point, series production will take place and

setting very ambitious goals, the eventual result now includes a design that is ready to be taken towards mass production. One of the biggest challenges in this respect was the role of electronics and software. During this project the design and manufacturing of the required electronics was delayed frequently, with unknown bugs plaguing the prototyped electronics. Where the initial expectation was to have walking robots within the first 3 months of the project, this turned out to be, at best, within 3 months after the project. Software engineering, electronics engineering and design are radically different fields, and principles applying in the field of IDE do not always apply to these other fields. Managing the uncertainties involved with electronics design and programming is something I struggled with, and learned much about.

Finding solutions for problems is something I have enjoyed greatly. The design decision tree (appendix B) gives some insight into the thousands of design decisions that were made in order to come to the current design of DeciZebro. Although this design is far from being finished, it will pave the way for a first robotic platform suitable for testing of swarm robotics. It is my personal hope that many will continue the development of this robot, and that many applications may be found. That, one day, the potential of swarming robotics may realized for people to benefit from. That the use of (natural) resources within this project will also be justified in that sense.

This project has been a great opportunity and joyful experience. To discover what is means to be a designer, and to discover the value designers bring to the table is valuable. What is more, the experience of working with students from many different backgrounds and disciplines towards a single goal has been a pleasure. In the end, it is the people behind a product that make it the process itself as well as the final result worthwhile.

With great thanks to the Zebro team, my coaches and the TU,
Mattijs Otten

Appendix A: Implementation Roadmap

On the next two pages you will find an implementation roadmap for de DeciZebro concept. In it a timeline is proposed spanning the period of May 2017 to January 2019. The roadmap serves as a general guideline toward the implementation of DeciiZebro in real-life contexts. The eventual goal, as sketched here, is to implement DeciZebro in one or multiple of three markets; the educational market, the consumer market or the business-to-business market. This timeline, along with the roadmap proposed in paragraph 6.2, allows the reader of this report to gain some sense of the timescale involved in this project.

The roadmap consists of two halves. The bottom halve deals with the feasibility of DeciZebro, and is all about the developments that are necceasary in order for Zebro to be relevant to society and, more specifically, its intended target markets. The feasibility side consists of two parts: technological developments and product developments. Technological developments concern the development of technologies or know-how that do not yet exist, but are required to enigneer the product. For example, swarming algorithms do not yet exist (or are not available publicly) and require research in order to be developed toward a product or be implemented in a product. Another example is charging. Allthough many charging techniques exist, none has been optimized for DeciZebro. The technological development would, in this case, be to first choose suitable charging methods, and then to adapt existing know-how to the specific context of Zebro. Only after this has been done can an actual charging station be designed.

The product development map deals with actual product development. It is here that the products or modules are developed that will eventually be introdduced into the market. This includes the design of DeciZebro, its constituent parts, but also additional modules and applications. For example, in order to accomodate the consumer and educational markets, the design of software interfaces that allow users to easily program Deci may be needed.

Zebro and the topic of swarm robotics is new to society. As such, people have no preconsisting knowledge on which to base their evaluation of Zebro. The market therefore needs to be educated in regard to the possibilities afforded by swarm robotics. For this, the vision behind Zebro must become very clear. If

this vision is clear, the concept can be demonstrated to society. In order to gain exposure, Zebro must start making many public appearances. Special events could be schedualed, TV appearances made and interviews given. Through demonstrating Zebro, the hope is to find partners willing to be involved in the development of the robot. The TU Delft will not be able to commercialize the robot, its primary concern being education and scientific research. It is therefore neccesary that at some point investors and development partners come aboard.

A suggested approach would be to demonstrate the Zebro wherever possible, and see whom it attracts. The novelty and fun-factor of Zebro makes it an eye catcher likely to attract many companies. If the vision and unique selling points of Zebro are clear, the expectation is that the right partners will be found.

Three possible markets are specified within the roadmap. The first is the hobby market or general consumer market. For this market the robot may not yet be ready for swarming, but be able to perform many sensor tasks. Being modular, an open-source approach could be taken, along with a crowdfunding campaign such as Kickstarter. Through this market, early revenue can be made in order to further the development of actual swarm robotics. These would be needed in order to enter the business to business market and the educational market.

The timspan suggested is rather arbitrary and based on the experience of the author of this report during this 6-month project. The current goal is to have Zebro become a fully functional locomotion platform within 3 months, after which swarm experimentation should start. From this point on it is very difficult to say how fast the technology will develop. What can be said is that, if needed, DeciZebro is close to being ready for full-scale mass production. If the right customers can be found, Zebro can start to be introduced to society.

6.3 Roadmap

Adoption

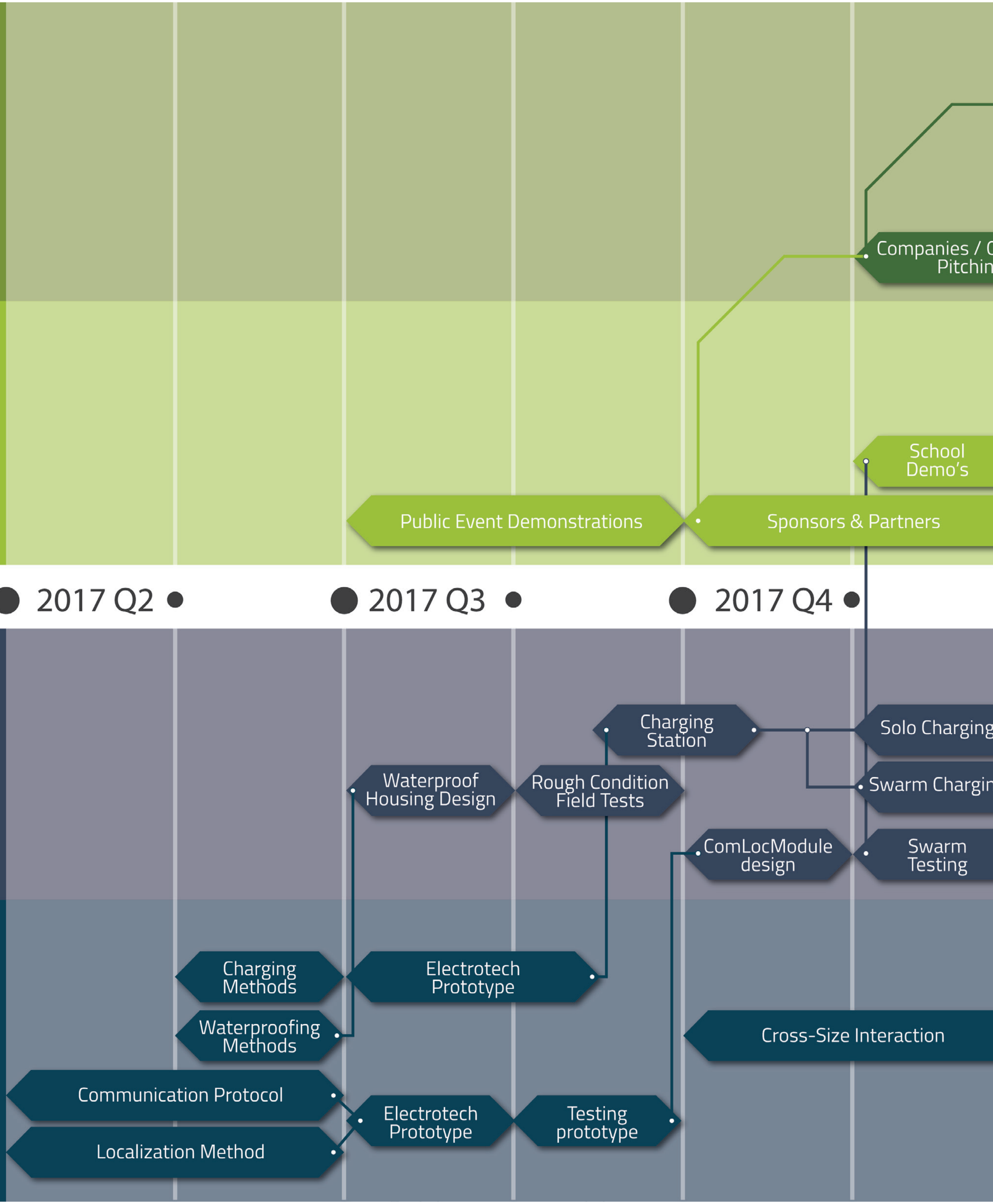
Market
Target market that Zebro marketing efforts are targeted at, and appropriate sales channels

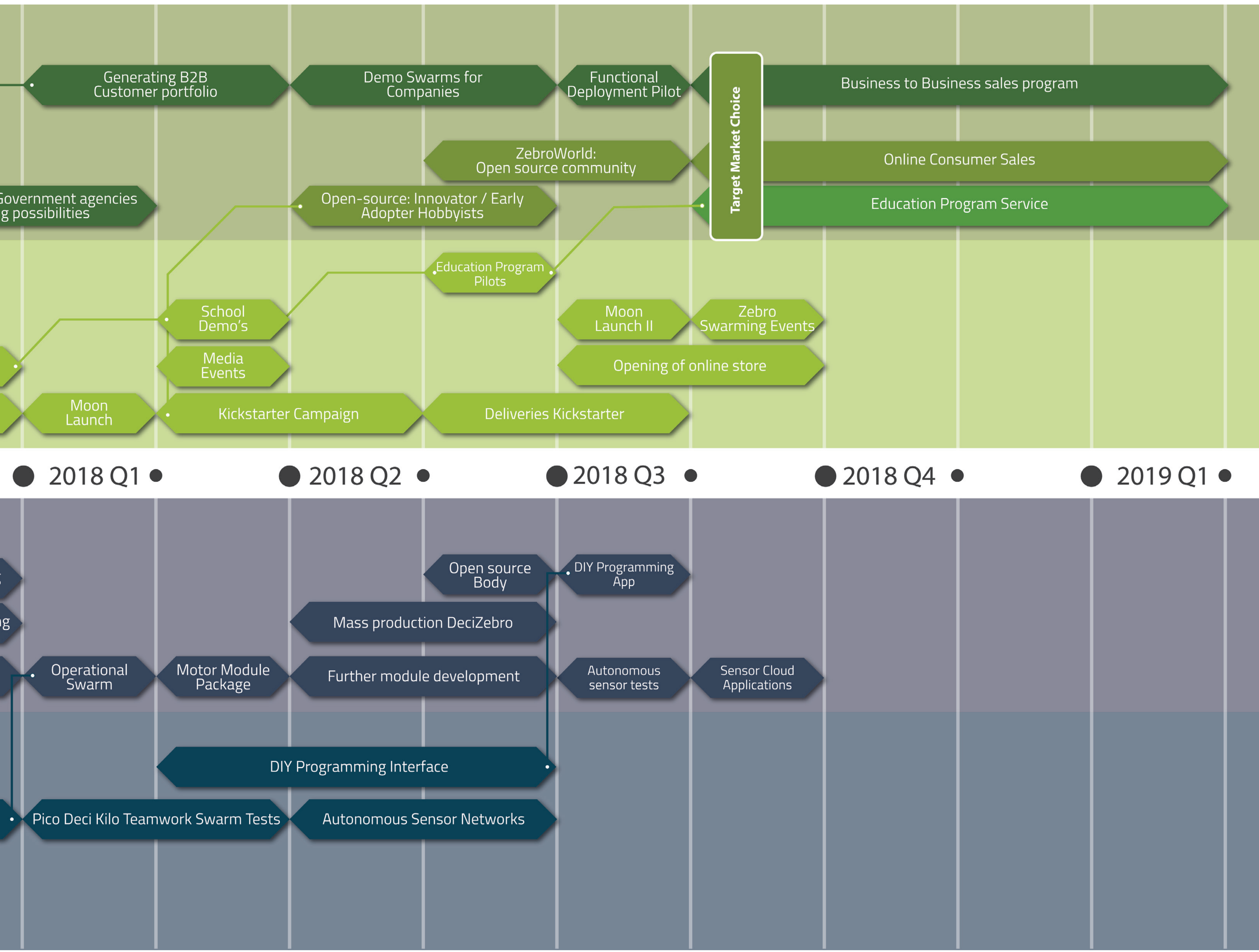
Vision, Exposure, Partners
The way (autonomous) robots are perceived in society. The emotions, feelings and opinions people hold towards robots such as Zebro

Feasibility

Product Development

Technology Development
The progress needed to fuel the creation of value, the perpection of the public and the role robots fulfil. In terms of technological advances and new possibilities




Generating B2B Customer portfolio
Demo Swarms for Companies
Functional Deployment Pilot
Target Market Choice
Business to Business sales program
ZebroWorld: Open source community
Online Consumer Sales
Open-source: Innovator / Early Adopter Hobbyists
Education Program Service
Education Program Pilots
School Demo's
Moon Launch II
Zebro Swarming Events
Media Events
Opening of online store
Moon Launch
Kickstarter Campaign
Deliveries Kickstarter
2018 Q1
2018 Q2
2018 Q3
2018 Q4
2019 Q1
Open source Body
DIY Programming App
Mass production DeciZebro
Operational Swarm
Motor Module Package
Further module development
Autonomous sensor tests
Sensor Cloud Applications
DIY Programming Interface
Pico Deci Kilo Teamwork Swarm Tests
Autonomous Sensor Networks

Appendix B: Technical Data Package


E
B
A
⌀60
75
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG

A1. Part list

Part ID	Description	Off the shelf Y/N	Supplier/Production	€ (series 1)	€ (series 100)	Weight (gr)	Amount
Motor Module							
M001	DC Motor	Yes	Servocity	14	10	98	1
M002	Encoder Wheel	No	Laser Cutting (Laserbeest)	0,6	0,6	1	1
M003	Motor PCB	No	PCB Manufacturer (EPR)	30	15	15	1
M004	Plate	No	Laser Cutting	1	0,2	3	1
M005	Front	No	3D printing/Injection Mold	0,1	0,1	10	1
M006	Leg Hub	No	3D printing/Injection Mold	0,1	0,1	5	1
M007	Leg	No	3D printing/Injection Mold	0,1	0,1	10	2
M008	Ferrite ring	Yes	Conrad/Mouser/Farnell/RS	0,61	0,4	2	1
M009	IDC Connector	Yes	Mouser/Farnell/RS	0,25	0,15	1	1
M010	M3 Metal Screw 6mm	Yes	Hardware stores	0,1	0,04	1	6
M011	M3 Metal Screw 12mm	Yes	Hardware stores	0,05	0,03	1	1
M012	M3 Hex Nut	Yes	Hardware stores	0,05	0,03	1	3
			Total per module	46,96	26,75	148	20
			Total per Zebro (6x)	281,76	160,5	888	120
Body							
B001	Outer Frame L (2)	No	Extrusion	3	2	66	2
B002	Outer Frame S (4)	No	Extrusion	3	2	56	4
B003	Inner Frame L (2)	No	Extrusion	3	2	64	2
B004	Inner FRameS(2)	No	Extrusion	2	1,5	38	2
B005	Top Plate	No	Laser Cutting	17,5	5	75	1
B006	Bottom Plate	No	Laser Cutting	17,5	5	75	1
B007	M3 Metal Screw 35mm	Yes	Hardware stores	1,8	6	30	12
B008	Clamps	No	3D printing/Injection Mold	0,05	0,05	2	4
			Total per Zebro	47,85	17,5	406	28

Part ID	Description	Off the shelf Y/N	Supplier/Production	€ (series 1)	€ (series 100)	Weight (gr)	Amount
Other							
O001	Battery	Yes	Conrad/Hobbyking	25,29	15	437	1
O002	Top Level Controller	Yes	Raspberry Pi Zero	11	11	5	1
O003	Locomotion Controller	Yes	Raspberry Pi Zero	5,5	5,5	5	1
O004	Flatcable	Yes	Mouser/Farnell/RS	1	0,5	10	1
O005	Battery Management	No	PCB Manufacturer (EPR)	30	20	20	1
			Total per Zebro	72,79	52	477	5
			Total per Zebro	402,4	230	1771	153

Weight per Zebro : 1.771kg
Parts per Zebro : 153
Unique parts per Zebro : 25

Excluding Assembly:
Price per Zebro, series 1 : €402,4,-
Price per Zebro, series 100 : €230,-
Estimated per Zebro, 1000+ : €150-200

A2. Assembly Scheme

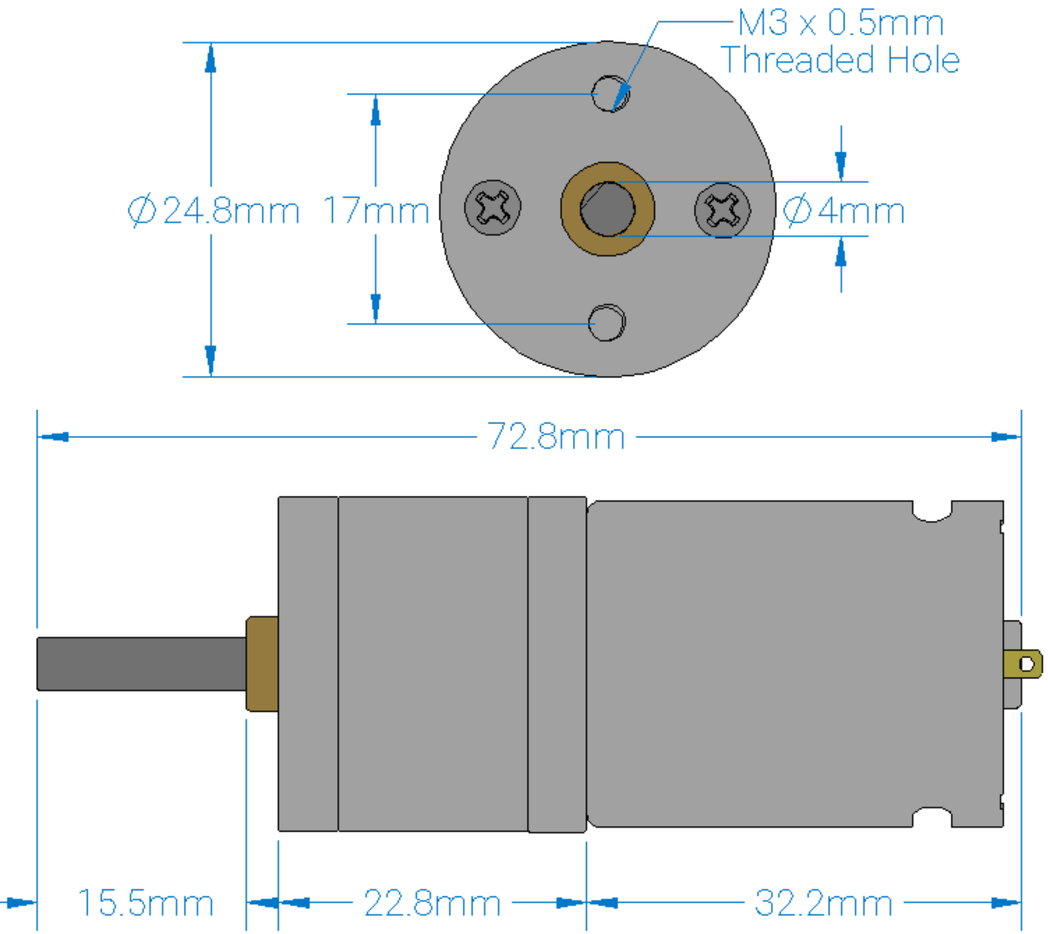
*** The assembly scheme is based on actual timed tests of DeciZebro assembly, but is not fully representative and should be viewed as a general guide, providing a sense of the order of magnitude of time required. The final time is not expected to deviate more then 25%**

Step #	Part ID	Additional Parts	Description	Time (s)	Tools
Motor Module Assembly					
1.	M001	Wire, Shrink Wrap	Solder + and - wires to motor contact points	60	Soldering Iron, Heat Gun
2.	M008		Wrap wires around ferrite ring	20	
3.	M004	M010, M001	Screw Plate into Motor	45	Electric Screwdriver
4.	M002	M001	Slide encoder wheel onto motor axle	20	
5.	M003	M004	Slide motor PCB onto plate	20	
6.	M003		Wire motor power wires to board	60	Electric screwdriver
7.	M005	M004	Place motor front onto plate	20	
8.	M012	M006	Insert Hex Nut into Leg Hub	15	
9.	M011	M006	Screw M3 Screw into Leg Hub	30	Electric Screwdriver
10.	M006	M001	Slide SubAssembly 2 onto motor axle	30	
11.	M011	M006	Fasten Screw onto motor axle	30	Electric Screwdriver
			Total (Minutes)	5,83333333	
Final Assembly					
12.	B001	B006	Click profiles into bottom plate	30	
13.	B002	B006	Click profiles into bottom plate	30	
14.	B003	B001	Slide in profile	60	
15.	B004	B002, B003	Slide in profile	60	
16.	MM	S3	Slide in motor modules	60	
17.	O001	S3	Place battery	20	
18.	O001	O005	Connect Battery to BMS	60	
19.	O004	M003	Connect power to Motor PCB	300	
20.	O002	S3	Install controller	60	
21.	O003	S3	Install controller	60	
22.	O004	O002, O003	Connect power to controllers	120	Electric screwdriver
23.	O004	M003, O002, O003	Wire I2C Bus	300	
24.	B007	M003	Fasten Motor PCBs	300	Electric screwdriver
25.	B005		Place Top Plate	60	
26.	B008	B005, B006	Fasten Clamps	30	
			Total (Minutes)	25,8333333	
			Grand Total	60,8333333	

A3: Part Detailing

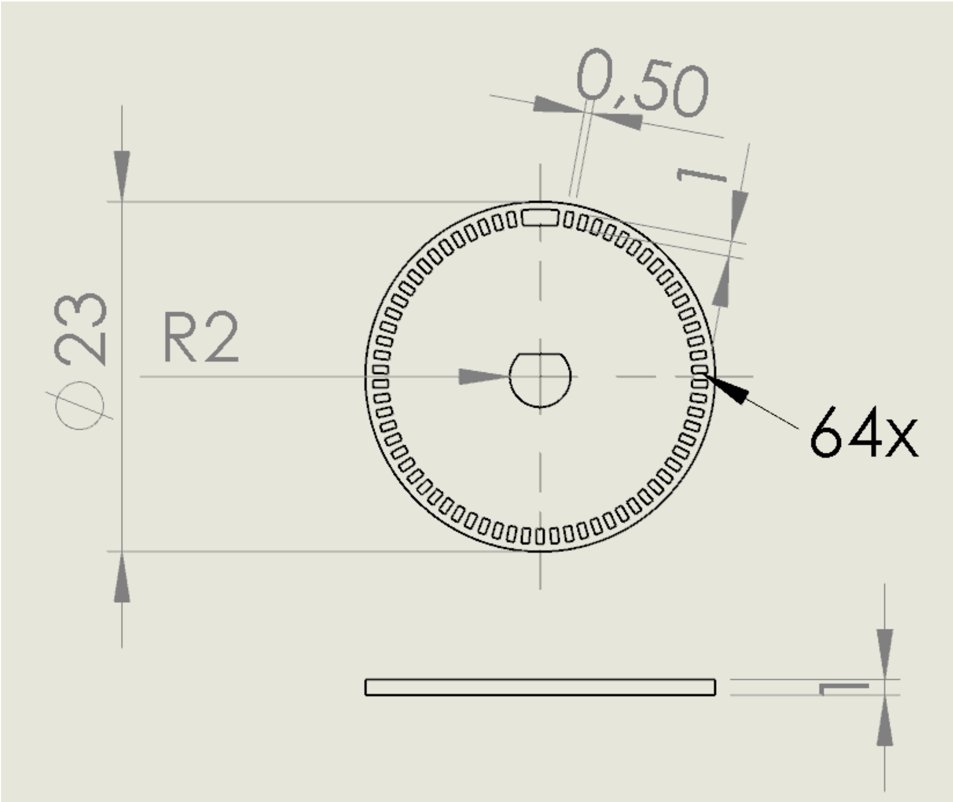
M001: DC Motor

Type: brushed direct current motor
Specs: 170 RPM, 22.04kgf/cm, rated for 12V, 3.8A stall current



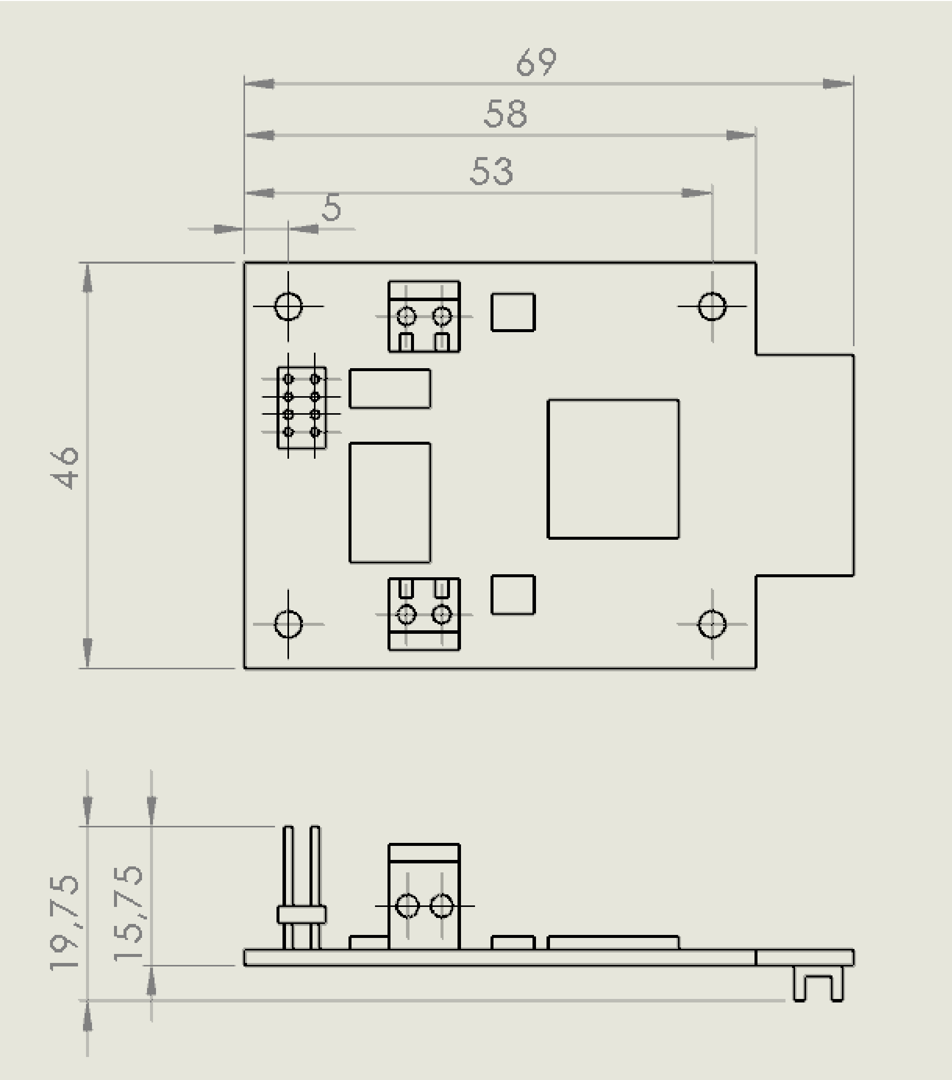
M002: Encoder Wheel

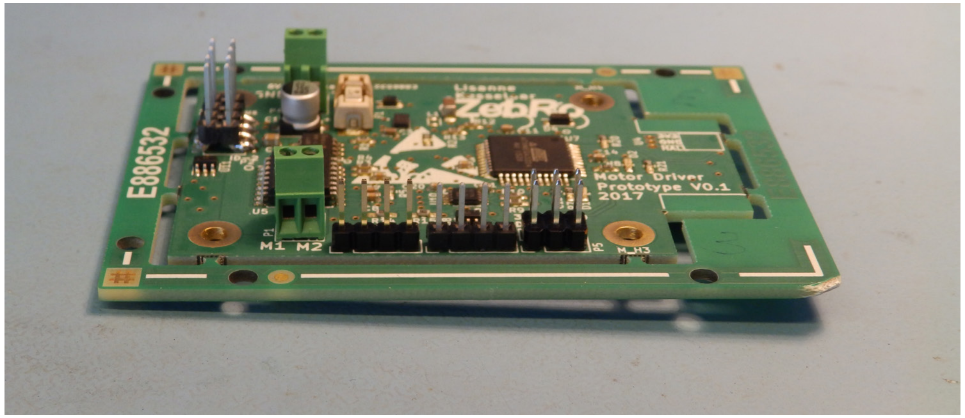
Material:	Perspex
Production process:	Laser cutting
Required tolerance:	0.05mm
Function:	Provide optical encoding of motor axis position
Further information:	



M003: Motor PCB

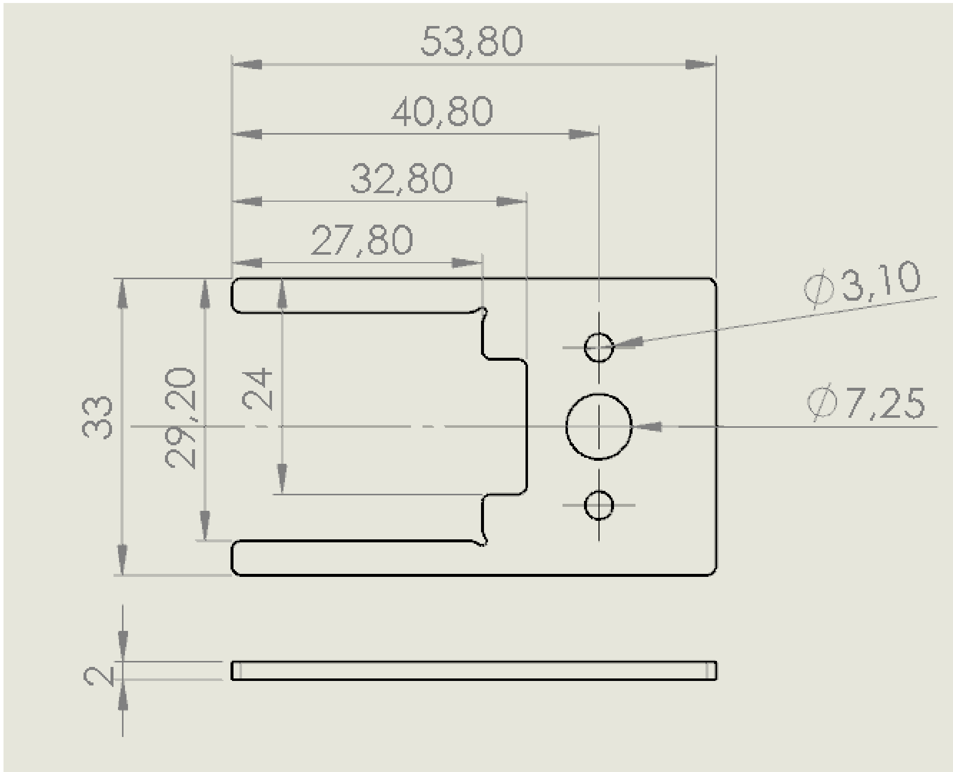
Material: PCB material
Production process: PCB Manufacturing (outsourced)
Required tolerance: /
Function: - Provide full H-bridge motor control, temperature feedback and positional feedback, and communication with the rest of Deci
Further information: Designed by Lisanne Kesselaar





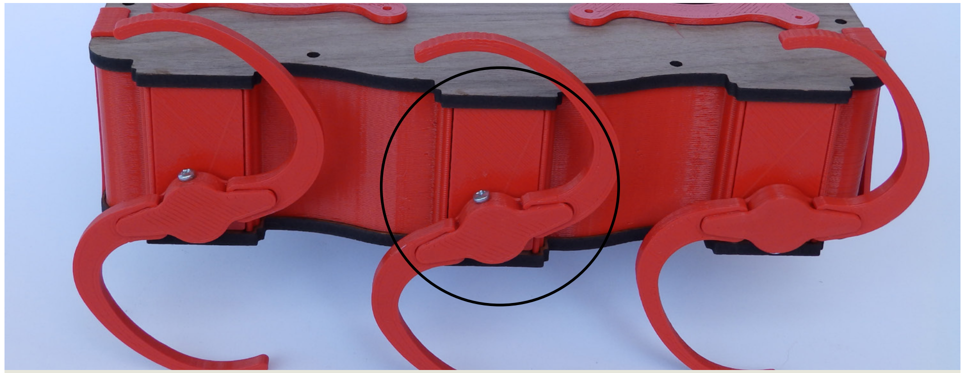
M004: Plate

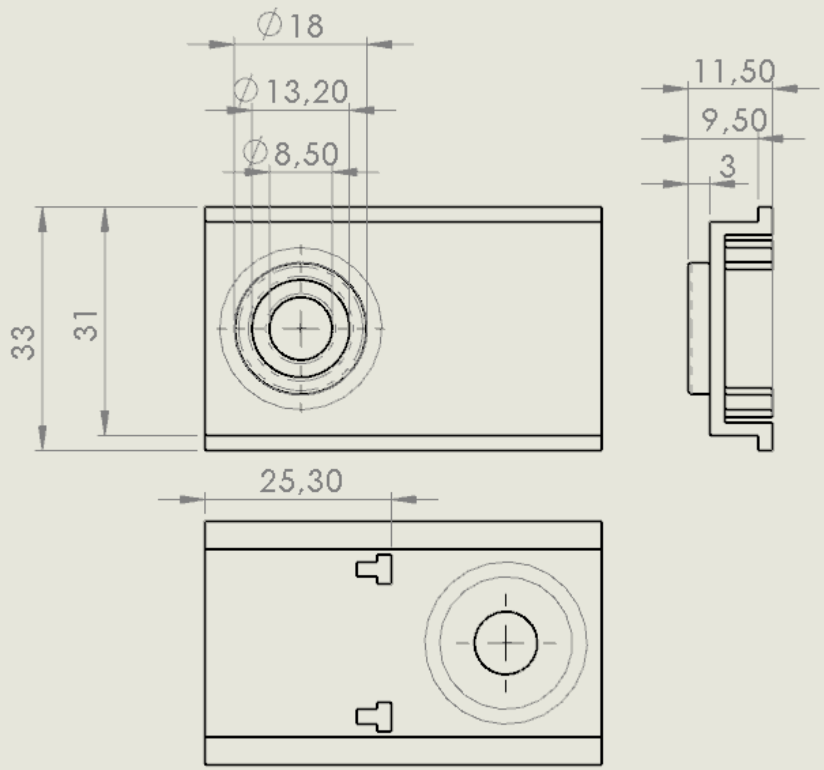
Material: Aluminum 6000 Series Alloy
Production process: Laser cutting
Required tolerance: 0.05mm
Function: Locking DC motor in place (connection with 2 M3 screws)
Further information: /



M005 Front

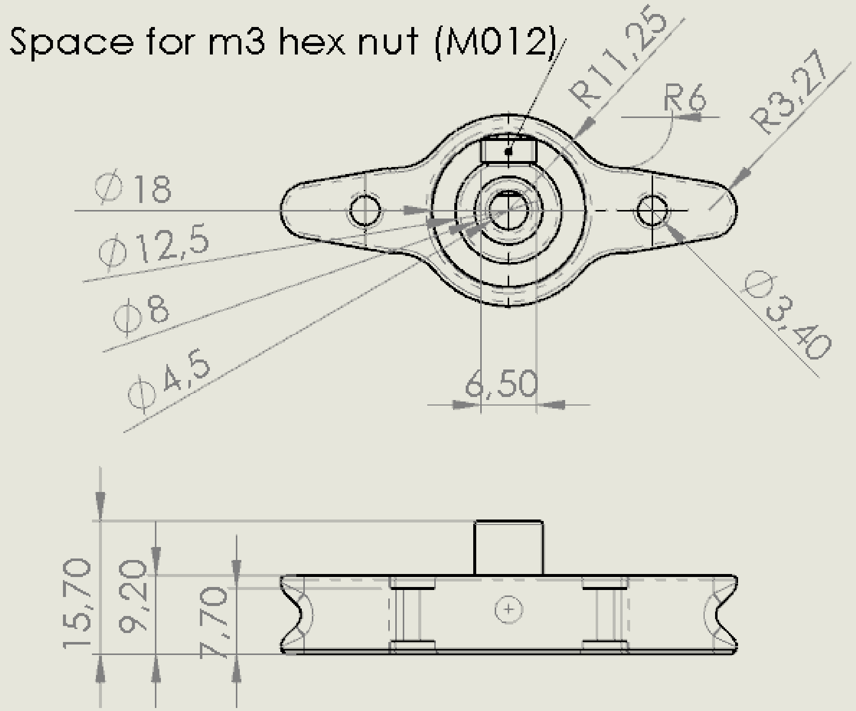
Material: PLA/PE/PP/ABS
Production process: Injection Molding (PE/ABS/PP)/ 3D Print (PLA)
Required tolerance: 0.05mm
Function: Watertight seal with outer wall of housing
Further information: Printing time: 16m(0.8nozzle), 52m(0.4)





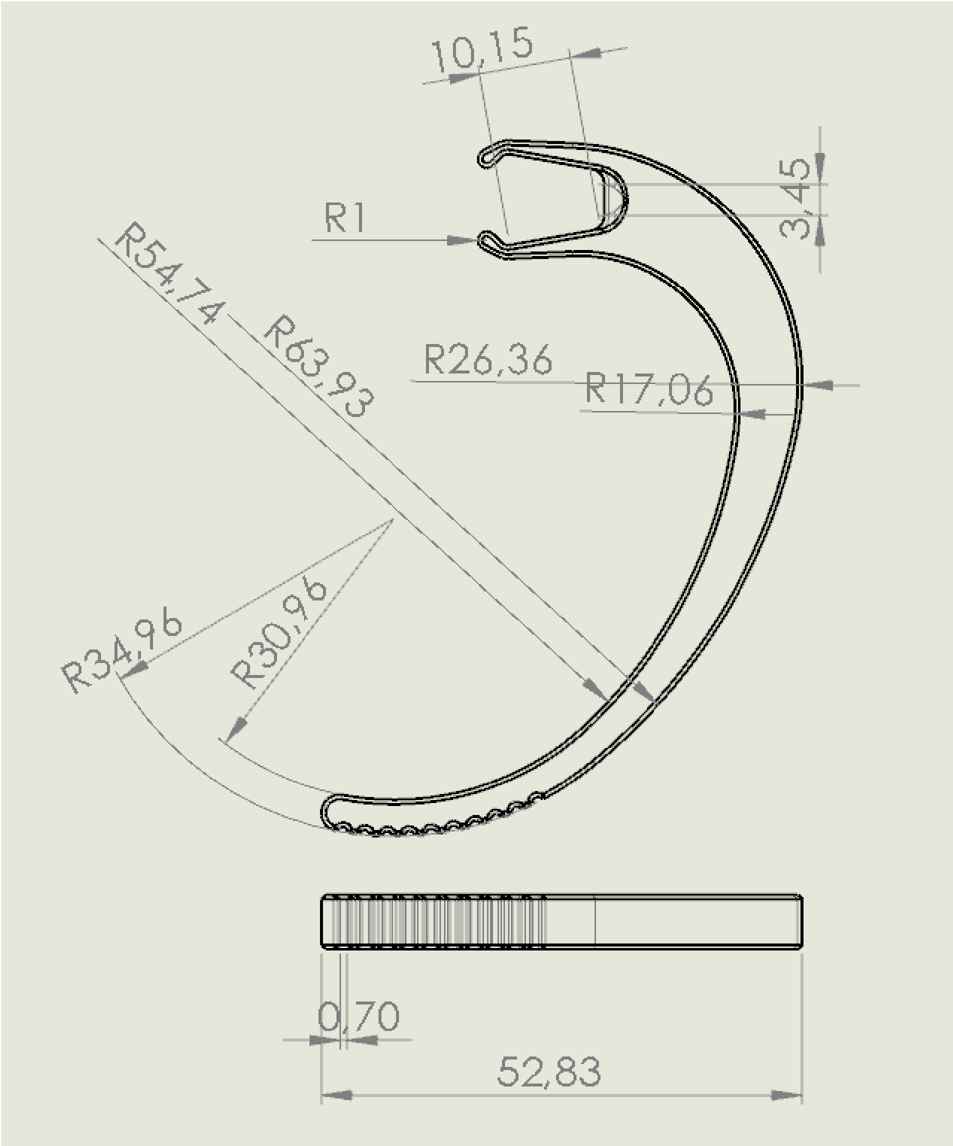
M006 Leg Hub

Material: PLA/PE/PP/ABS
Production process: Injection Molding (PE/ABS/PP)/ 3D Print (PLA)
Required tolerance: 0.05mm
Function: Hub for legs, secured to motor axle
Further information: Printing time: 12m(0.8nozzle), 40m(0.4)
Designed by R. Buitenhuis



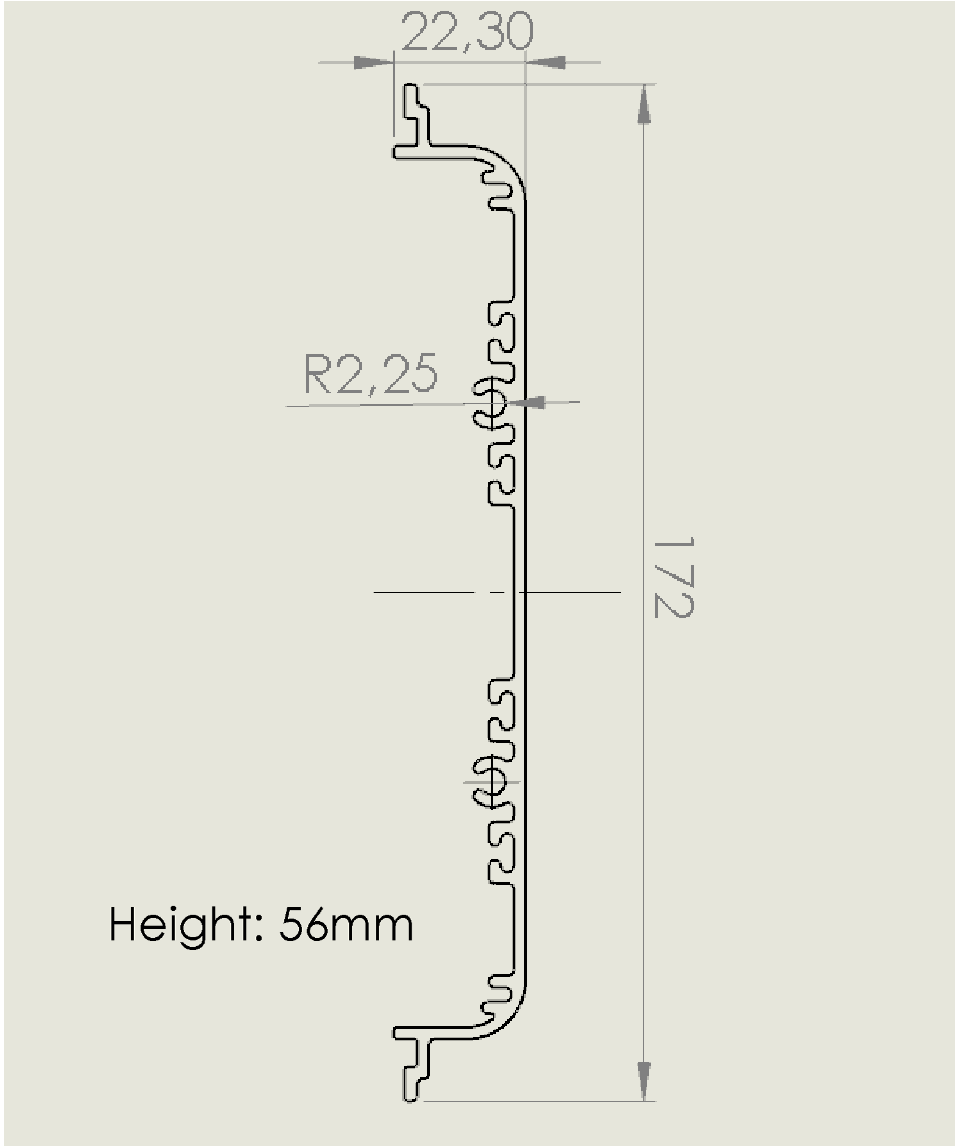
M007: Leg

Material:	PLA/PE/PP/ABS
Production process:	Injection Molding (PE/ABS/PP)/ 3D Print (PLA)
Required tolerance:	0.05mm
Function:	Snap-fit leg
Further information:	Printing time: 5m(0.8nozzle), 15m(0.4)
	Designed by R. Buitenhuis



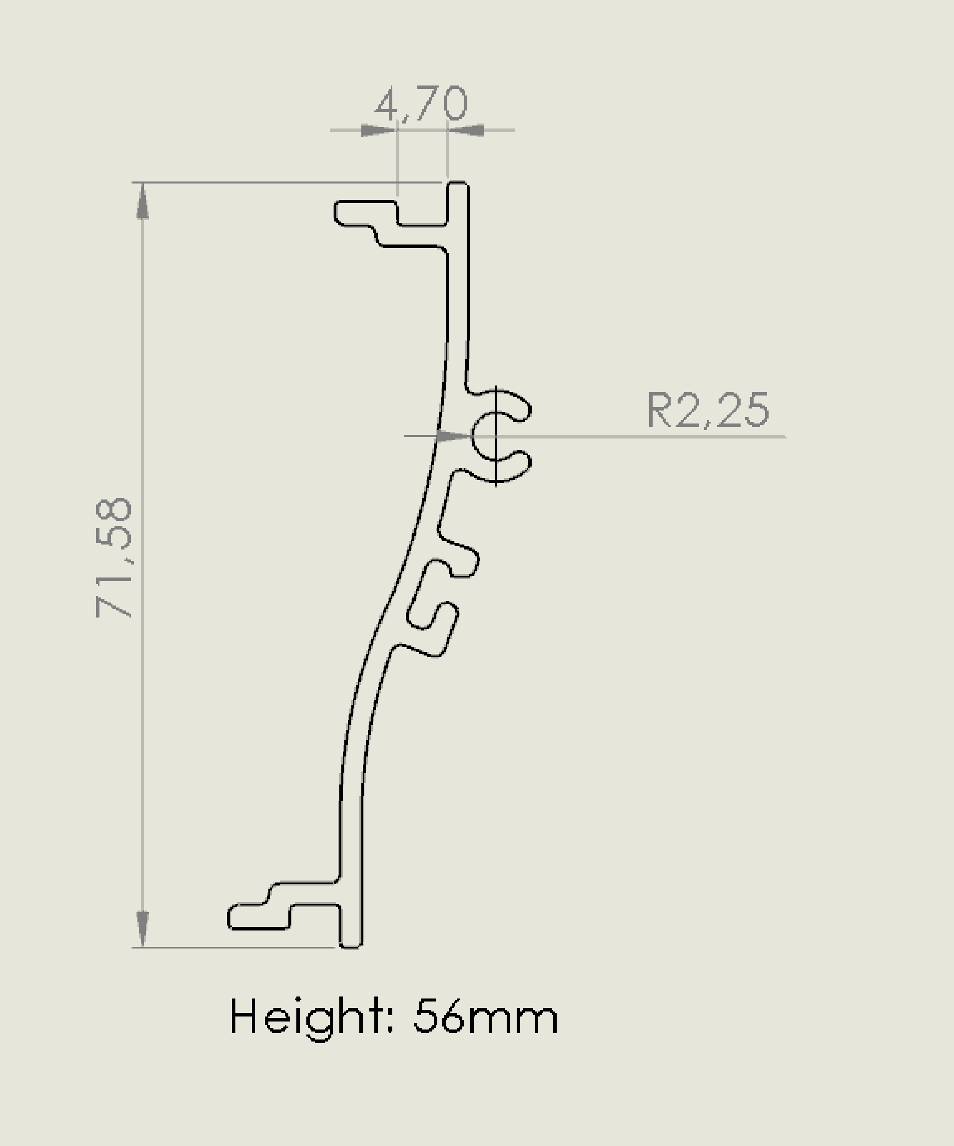
B001: Outer Frame L

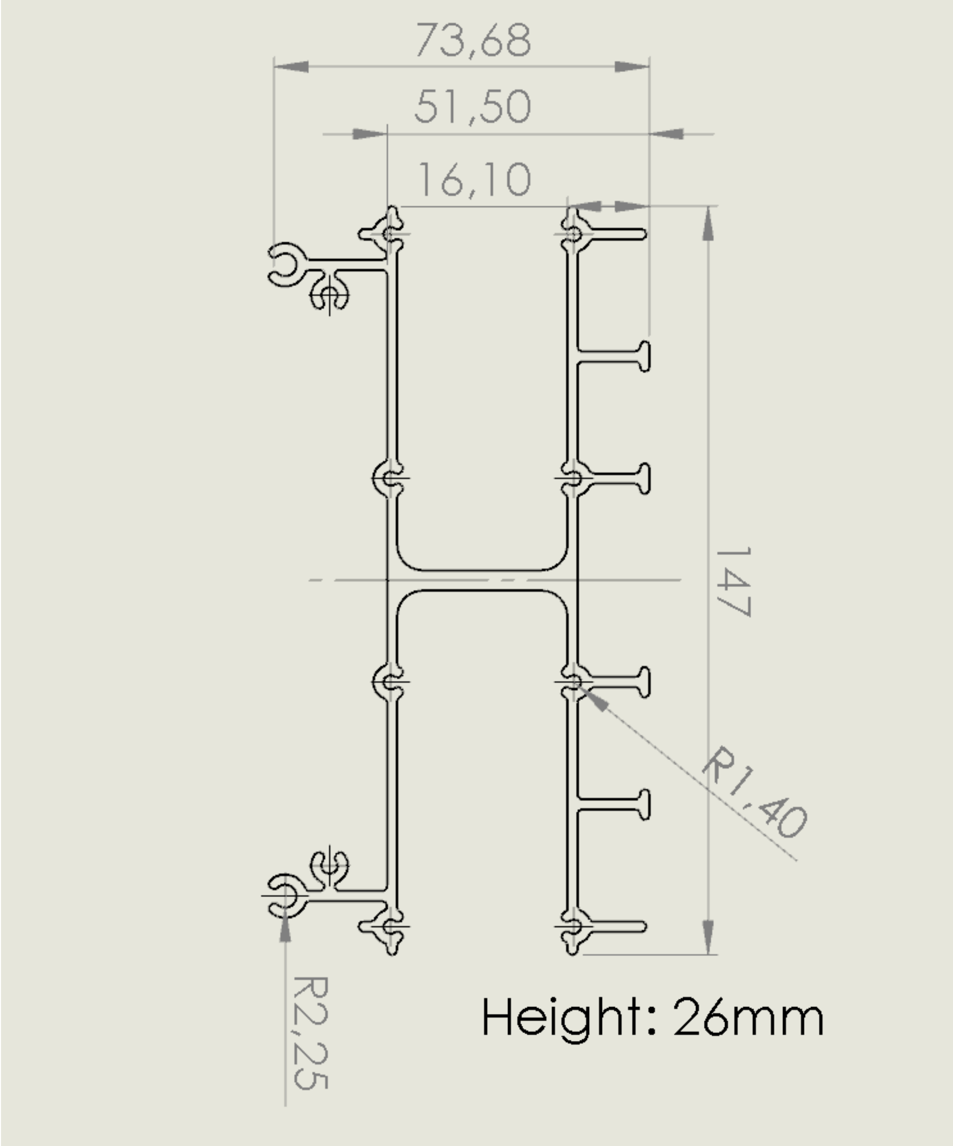
Material:	PLA/Aluminum 6060
Production process:	3D Print / Metal Extrusion
Wall Thickness:	2mm (Print) / 1-2mm (Extrusion)
Required tolerance:	0.1mm
Function:	Robot outer frame
Further information:	Printing time: 30m(0.8), 125m(0.4)



B002: Outer Frame S

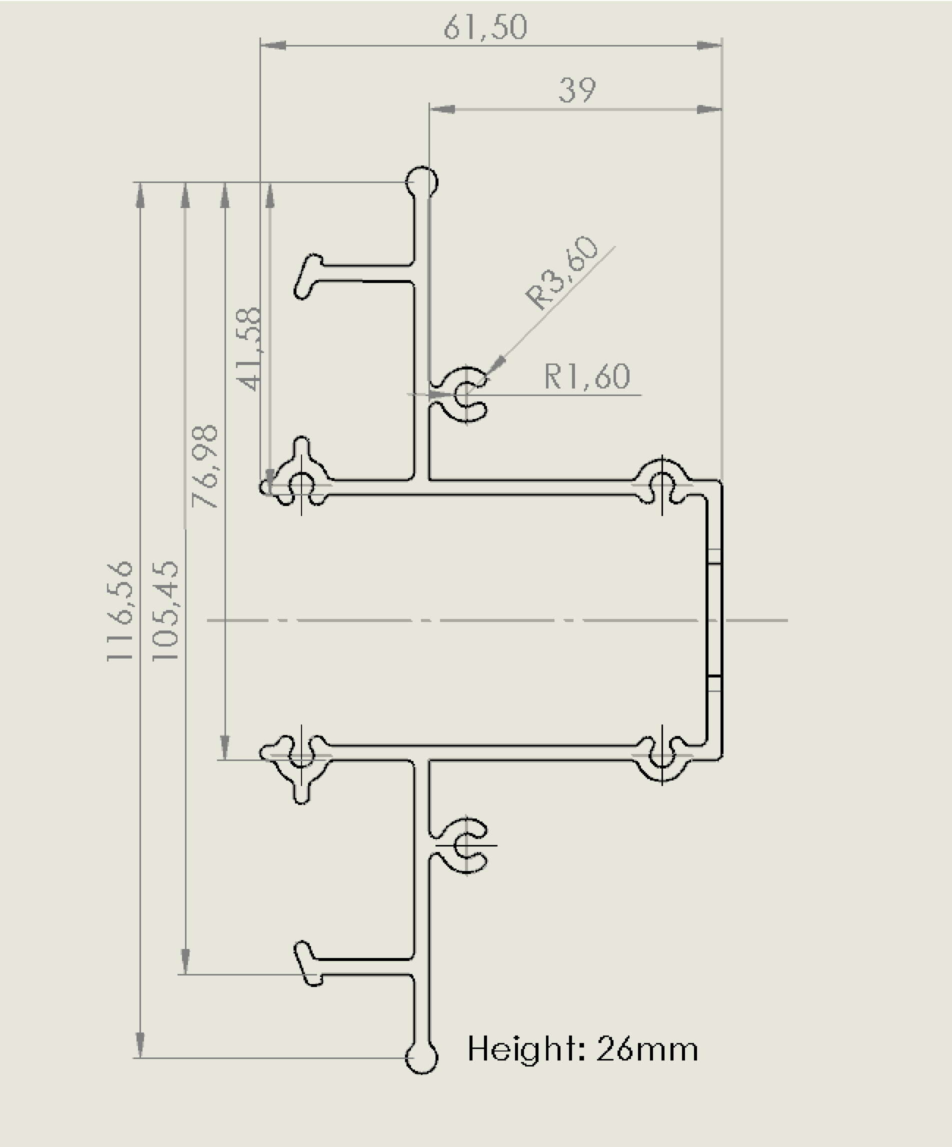
Material:	PLA/PE/ABS
Production process:	Injection Molding (PE/ABS)/ 3D Print (PLA)
Wall Thickness:	2mm (Print) / 1-2mm (Extrusion)
Required tolerance:	0.05mm
Function:	Robot inner frame
Further information:	Printing time: 30m(0.8), 125m(0.4)





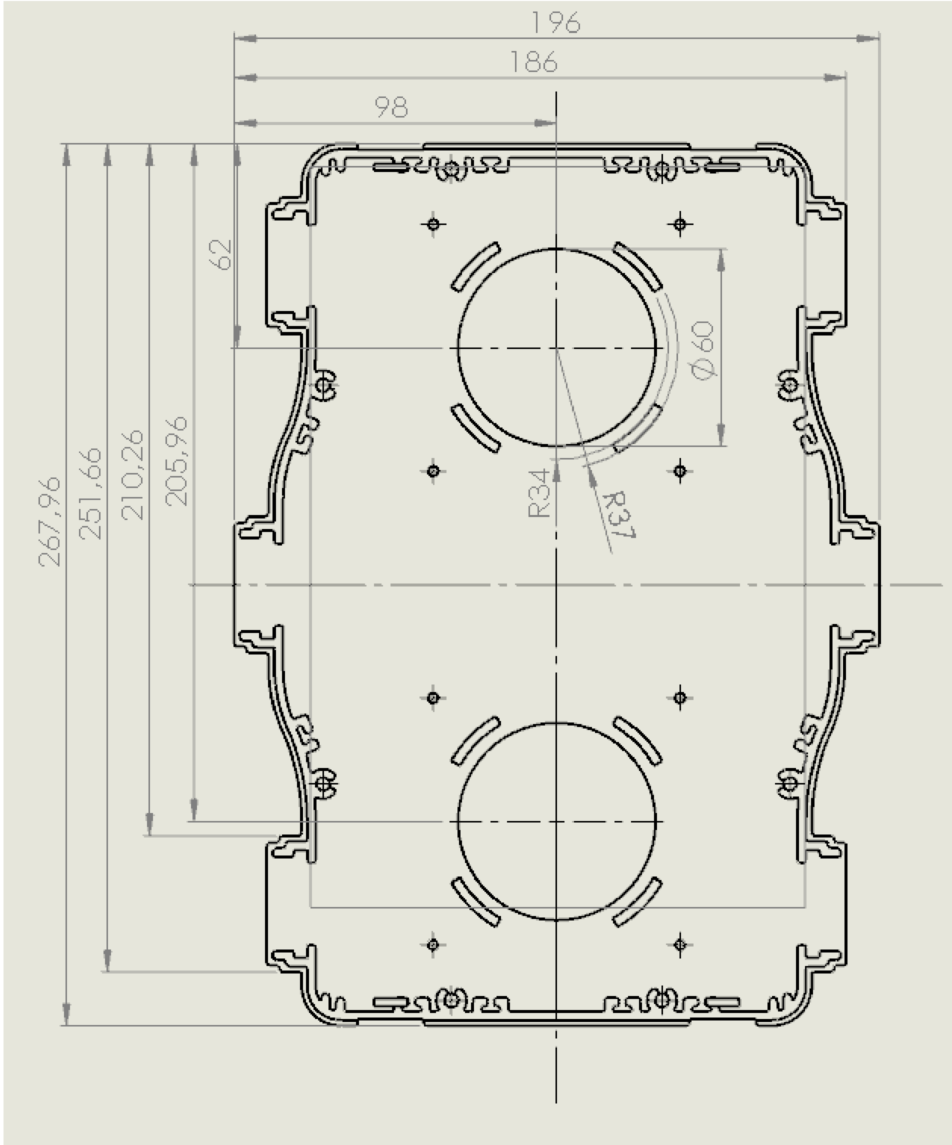
B004. Inner Frame L

Material:	PLA/PE/ABS
Production process:	Injection Molding (PE/ABS)/ 3D Print (PLA)
Wall Thickness:	2mm (Print) / 1-2mm (Extrusion)
Required tolerance:	0.05mm
Function:	Robot inner frame
Further information:	Printing time: 15m(0.8), 52m(0.4)



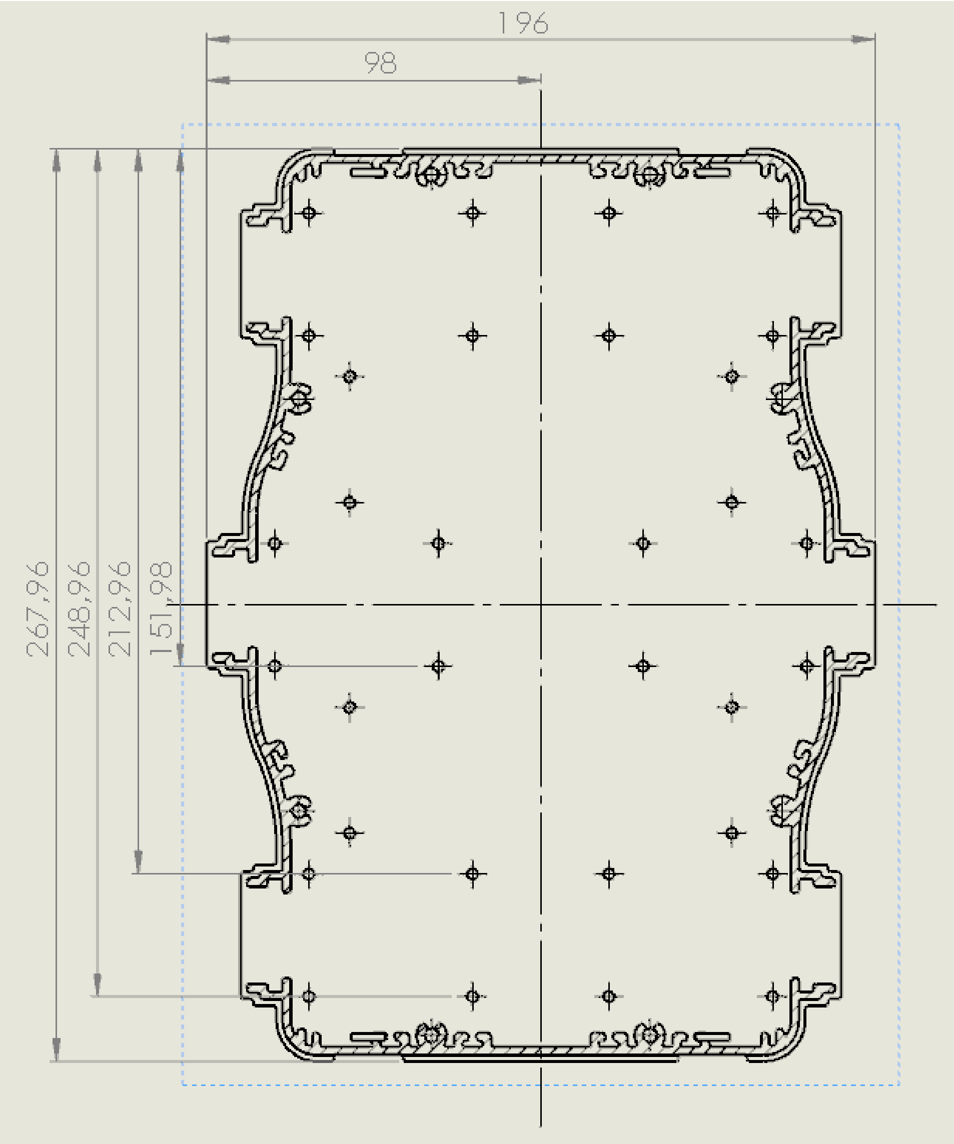
B005. Top Plate

Material:	Triplex / Acrylic
Production process:	Laser cutting
Thickness:	5mm (3.5mm in groove)
Required tolerance:	0.05mm
Function:	Robot Top plate
Further information:	Cutting time (30m). 2 module interfaces.



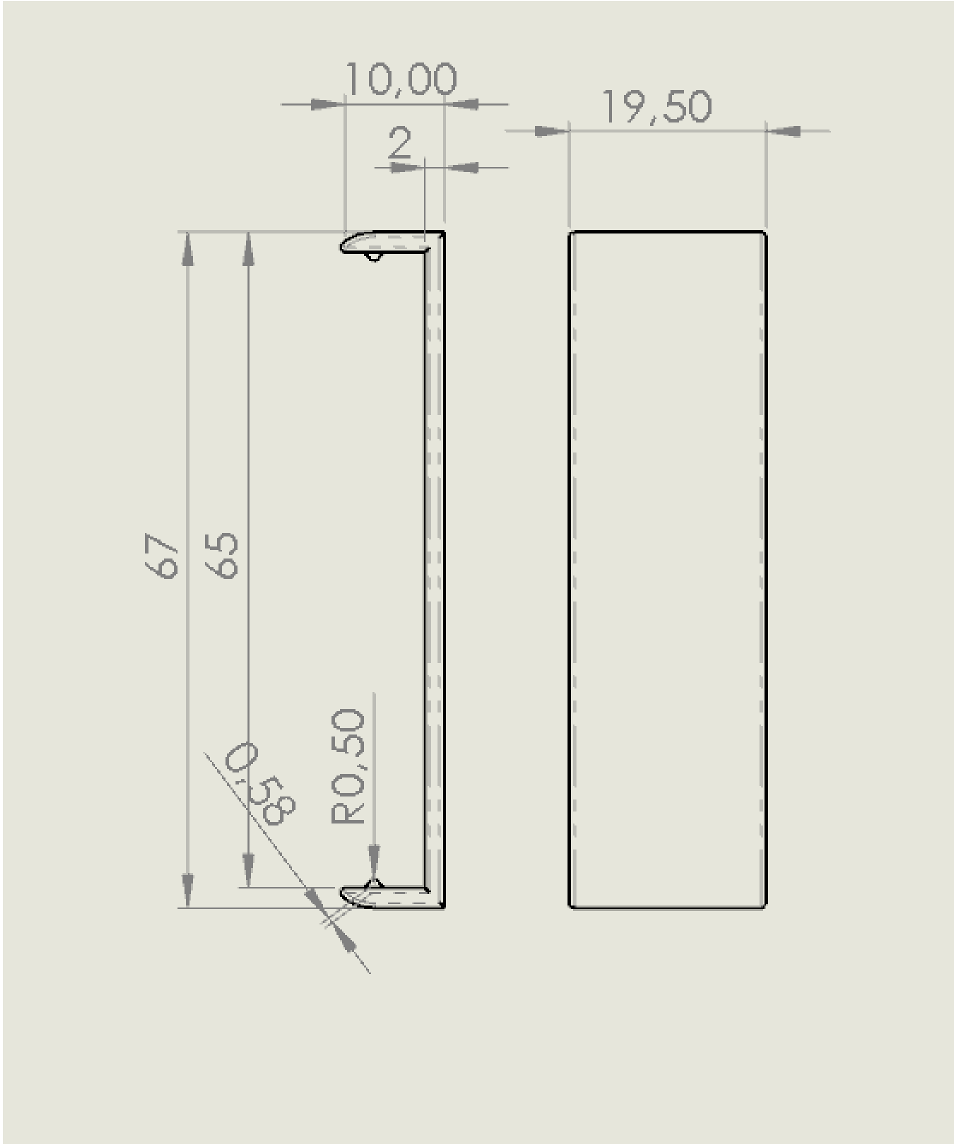
B006. Bottom Plate

Material:	Triplex / Acrylic
Production process:	Laser cutting
Thickness:	5mm (3.5mm in groove)
Required tolerance:	0.05mm
Function:	Robot Top plate
Further information:	Cutting time (30m).



B008. Clamps

Material:	PLA/ABS/PE
Production process:	3D Printing / Injection Molding
Wall Thickness:	2mm
Required tolerance:	0.05mm
Function:	Secure top and bottom plate to each other
Further information:	Printing time: 3m (0.8), 12m (0.4)



Decision Tree

Within this appendix an overview of important design considerations and decisions are given in a (semi) chronological fashion. This appendix is meant to provide extra insight into the design process and help answer any questions the reader might have. Furthermore, it serves as a future reference for redesigns and further developments on DeciZebro. It is by no means a complete overview.

1. Avoid Soldering

- Observation: Only series production robot is CampZebro, which is difficult to assemble and requires many time consuming soldering connections
- Conclusion: Soldering connections significantly slow down assembly process and increase likelihood of errors
- Decision: Any mass producible robot should require the least amount of soldering connections possible, preferably none

2. Alternatives to Hall Sensors

- Observation: Zebro's struggle to walk because detecting the leg position is difficult. Current system using Hall Sensors is not yet working properly
- Conclusion: Zebro has been working with Hall Sensors for a long time, yet they still do not work correctly. Hall sensors currently require 3 soldering connections per sensor.
- Decision: Alternatives to Hall Sensors should be investigated

3. Reconsider use of Servo Motors

- Observation: Current motors (servomotors) are barely strong enough to lift the CampZebro. For their size, they are operating at the maximum of their capacity. Larger Servos are available, but do not reach the desired speeds
- Conclusion: The closed system package of servo motors means they deliver less speed and torque for the same volume and weight. When weight is kept equal, regular DC motors outperform Servos
- Decision: The use of servomotors should be reconsidered and viable alternatives should be investigated.

4. High RPM needed

- Observation: Other 6-legged robots and predecessors of Zebro walk more efficiently by 'jumping'; by rotating their legs fast enough, the impact of the legs bends them and then releases this elastic energy, allowing the robot to jump slightly. This type of walking is much faster and more efficient then regular walking
- Conclusion: For the new Zebro design to be as functional as possible, its intended motors should be powerful and fast enough to facilitate this type of walking
- Decision: minimum motor RPM should be 150 (no load)

5. Torque per leg needed

- Observation: SwarmZebro weighs about 800 grammes. The new Zebro could way up to two times this amount.
- Conclusion: Assuming the weight of the new Zebro is 1.5 kilograms, the torque per motor can be determined. The goal is to allow Zebro to be able to lift itself using only one leg
- Decision: if the length of Zebro's legs is known, the required torque per motor in order to lift a 1.5kg robot can be determined

6. Leg radius leads to motor torque

- Observation: Zebro is intended for both indoor and outdoor use. In order to traverse outdoor terrain it should be able to scale objects such as curbs
- Conclusion: most curbs have a maximum height of between 8-12 centimeters. Higher curbs are often curbs between large roads and pedestrian area's, which Zebro will not cross anyways. Lower curbs however, form boundaries between pedestrian area's, bicycle paths etc
- Decision: Zebro should be able to climb curbs of up to 12 centimeters high, which means its leg radius should be about 7 centimeters. This means the robot´s motors should provide 1.5kg of force over 7cm, which means it should provide at least 10.5kgf/cm

7. DeciZebro Size

- Observation: available motors that have the specifications needed (150RPM, 10.5kgf/cm+) are usually at least 5 centimeters long.
- Conclusion: accounting for extra space needed for the motors, the Zebro needs to be at least 15 centimeters wide to accommodate motors on each side of the robot to be lined up

- Decision: the new Zebro must be wider then its predecessors. Furthermore, in order to allow the leg radius of 7cm, it should also be longer. By making a small mock-up, it was decided the new Zebro will be between the size of an A5 and an A4, and likely to be closer to an A5)

8. Motor Modules

- Observation: in order to be able to quickly assemble/disassemble/repair/replace parts, the motors should be easily replaceable
- Conclusion: in order to make the motors easily replaceable, the motors should be considered as modules, in adherence to the modular design approach. The motor module as a whole should be quick to assemble and place into the robot. Preferably, only snap-fit/slide connections should be used
- Decision: the motor will be part of a motor module that clicks/slides into the body

9. Motor modules become leading in form-follows-function design

- Observation: several design attempts at creating a good looking body fail, because not enough is known about the inside of the robot to create the outside body
- Conclusion: instead of starting on the outside and working in, the inside mechanics of the robot should determine the outside looks.
- Decision: a form-follows-function approach is taken, whereby the motor modules are seen as the design drivers. The design of the motor module is leading in the design of the housing, since locomotion is the primary function of the Zebro housing. Since other design tracks are modularized they can be implemented later through simple module interfaces in the top and bottom of the robot.

10. Motor Choice and Encoding

- Observation: not many motors can be found that meet the requirements. 1 motor if found which is perfect, but it has no encoder. Adding an encoder triples the price of the motor
- Conclusion: the motor that is found is much stronger then required, and operates at the right RPM. This allows the motor to cope with higher weights then expected and increases design freedom. The encoder is very expensive, so other solutions must be found
- Decision: the DC motor from ServoCity is chosen, without the encoder. The decision is made to design a new type of encoding, either using Hall Sensors or preferable another method

11. Motor PCB is needed

- Observation: The motor will need electronics to drive it. There need to be temperature sensors and a full H-bridge to steer it. Furthermore, in order for the modules to be stand-alone, a microprocessor is required
- Conclusion: a printed circuit board specifically designed for the motor module is needed to provide the necessary electronics for operation
- Decision: a motor PCB needs to be designed and incorporated in the design of the module housing

12. New approach to module design

- Observation: the first few designs of the motor module feature enclosed housings as the module outer wall. This hinders assembly and makes production much more difficult. Furthermore, the enclosed nature of the module housing hinders cooling.
- Conclusion: If the module is inside the housing, it does not require a full waterproof housing itself. Only the seal with the outside wall of the robot needs to be watertight.
- Decision: the motor module will not feature a full housing around it. Only the front of the module needs to be joined with the housing of the robot. A design for assembly approach is taken that results in a design optimized for assembly.

13. Prototyping optical encoder wheels

- Observation: Hall Sensors still giving a lot of trouble in other Zebro's. Alternatives include having a pre-installed encoder on the motor; these can be bought of the shelf but cost at least as much as the motor, and these still operate based on magnetic fields. Research into alternative methods made me think of a computer mouse. It can detect position of mouse wheel.

- Conclusion: optical encoders, like those used on mouses, can provide accurate and dependable feedback and only require an slotted wheel to be slided onto the motor axle, and an optical encoder (sensor with a beam of light that is interrupted by holes in the encoder wheel).
- Decision: in order to achieve 8 bit encoding (as required, defined by previous groups), 256 measurements per rotation are needed. Because a double encoder can be used (with two slots), only 256/4 holes are needed in an encoder wheel. The decision is made to prototype encoder wheels with 64 holes.

14. Laser cutting the encoder wheels

- Observation: a series of 8 iterations on a 3D-printed optical encoder wheel shows that although the amount of holes can be printed on a wheel with a diameter of 2,5cm, the accuracy is not high enough. Tests with the chosen optical encoder show the pulses are not accurate enough. However, the tests do provide a proof-of-concept and show this method will succeed if a proper production method can be found
- Conclusion: another production method must be found. Off the shelf wheels are too expensive and do not fit the strict size constraints afforded by the motor module
- Decision: laser cutting will be used as an alternative prototyping method. A professional laser cutting company will be involved.

15. Puzzle pieces in order to facilitate prototyping

- Observation: 3D printing the housing of the robot is not possible on most conventional printers due to size
- Conclusion: either larger printers need to be found or design must be split into pieces
- Decision: the housing is split up into 'puzzle pieces' that fit neatly together. In this way, 3D printing is possible with regular printers

16. Securing the motor

- Observation: The motors are capable of delivering up to 3 kilograms of force onto the ground. This means there will be significant forces acting on the motor through the leg. The motor will tend to rotate around its axle (torsion).
- Conclusion: The motor must be secured in a dependable and torsion resistant way and attached to the housing in a non-permanent way (so that the modules can still be slided in and out in a fast way)
- Decision: The motor has two screw-holes at the front. A metal plate is screwed onto the motor, with the motor axle going through it. The plate, being metal, allows the motor to dissipate its heat quickly. The entire plate is slided into the body and is thereby locked into place on all four sides (3 sides before the lid is placed on, 4 with the lid on). The motor will dissipate the torsion forces onto the plate which, through its large contact area, will transfer these forces to the housing in a dependable way.

17. Sliding of modules

- Observation: by sliding the modules into the housing from the top, a watertight seal can be created that does not hinder quick assembly or causes complicated clicking fingers etc.
- Conclusion: simple sliding is sufficient for Zebro. Snap-fits over complicate the design
- Decision: sliding is used to place the modules into the housing

18. Structural integrity prototype

- Observation: The first prototype is not rigid enough
- Conclusion: The section lines along which the printed parts are joined should not meet at a single point. Furthermore, the walls in between which the modules slide in are not rigid enough, and flex so that the modules are not secured anymore
- Decision: a redesign of the housing needs to be made where the printed parts are joined in a different way. Furthermore, the design must be far more rigid along its x and y planes. This can be done by adding ribs.

19. Waterproofing legs and sidewalls

- Observation: waterproofing is a very difficult thing to do, especially with a product consisting of so many parts and that has to be modular.
- Conclusion: waterproofing this design of Zebro is not possible. However, designing the robot in such a way that it is splash-waterproof is possible. This can be done using U-seals which could be fitted with rubber lining
- Decision: this version of Zebro is not designed to be fully waterproof, but should be able to keep functioning when subjected to droplets/small amounts of liquid.

20. Securing leg on axle

- Observation: in order to be able to transfer the forces on the leg onto the motor axle, a secure connection between both is needed. The legs are plastic which is not very tough and wears out. The motor has a D-axle, so the legs can be fixated on the D-axis. Testing with plastic prints however shows that the flat surface that slides on the flat part of the D quickly wears out and the legs start rotating
- Conclusion: a metal-to-metal connection is necessary in order to secure the leg. This means that some kind of insert is needed that slides into the plastic leg and secures the leg onto the D-axis.
- Decision: a space for a hexagonal nut is made inside the leg. A bolt is screwed through this nut onto the D-axis, which is perpendicular to the screw orientation. The nut is pulled tight against the plastic by the fastening of the bolt and is locked in place. This is tested and proves to work.

21. Securing motor PCBs

- Observation: in order for the sensors on the PCB (temperature sensor and photo-interrupter) to work properly, the PCB must be solidly fixed to the housing.
- Conclusion: A connection is needed between the PCB and the housing. Because the PCB is flat and the only option for altering it is adding holes, a mechanical fastening (screw or bolt) is needed. This means the module will slide out and in as easy as before, because the nuts need to be fastened/unfastened
- Decision: since no other option is available, 4 holes are made in the PCB for a bolt to pass through. Also, 4 holes are allocated in the bottom of the robot through which the bolts can pass. Optimally, only two of the four holes will need to be used for fastening, but to avoid ordering the PCBs and printing the body and then finding out 4 holes are needed, all 4 are accommodated.

22. Printing time prototypes

- Observation: the current prototypes (fully made of plastic) take over 140 hours to print per robot. This is so high that only single prototypes can be made
- Conclusion: in order to be able to at least produce a series of 10 robots, and thereby prove potential for series production, the robot should be redesigned to allow this printing time to go down.
- Decision: it is at this point that an actual final mass manufacturing process needs to be chosen, and the Zebro can then be redesigned for this process, and the prototyping methods be adjusted for a series of 10.

23. Choice for production process

- Observation: the ribbed and rectangular shape of the housing design allows for easy decoupling between the ribs/walls and the top/bottom of the robot.
- Conclusion: the rectangular shape does not reflect the design possibilities afforded by injection molding. However, the design does not need the design freedom afforded by injection molding. The 2D nature of the walls and ribs is perfectly suitable for metal extrusion, and this also allows the top and bottom to be manufactured with a different process. This allows the prototyping process to improve; now, only 20-40h of printing is left per robot, and the top and bottom could be laser-cut

24. Implications of Extrusion

- Observation: extrusion is a 2D process, so any changes in the variation of profiles in 3D are not possible anymore. This presents challenges, for example between the different heights of different sections of the housing. Milling can be used to change the 3D shape of the extruded profiles, but this is expensive
- Conclusion: the housing needs to be split up into different profiles. There

should be as little unique profiles needed as possible, because for each new dies will be needed, and these are expensive.
- Decision: the housing of Zebro is split up into as little as possible unique profiles

25. Room for battery and battery type
- Observation: The chosen DC motors operate optimally and 12V and, on average, will draw about 0.6A per motor when walking. The goal is to be able to walk at least 1 hour on a single battery charge.
- Conclusion: At least a 4-cell battery is needed to supply a high enough voltage (12V); 3-Cell batteries only provide 11.1V. Furthermore, if the average amperage per motor is 0.6A, 6 motors will draw 3A. Adding in all modules will bring this to 4A. In order to walk for 1 hour, at least a 4000 mAh battery is needed.
- Decision: A 4000 mAh 4-cell battery will need to be found that fits the size criteria (150mm x 44mm x 26mm)

26. Room for controllers
- Observation: Zebro will need a locomotion controller and a top level controller in order to be able to walk and process sensor data.
- Conclusion: sufficient space is required to facilitate the placement of these controllers, which are basically small computers such as the Raspberry Pi
- Decision: The Raspberry Pi Zero has enough computational power to function as a locomotion or top level controller. The needed space is allocated and mounting holes are placed in the body to accommodate two of these.

27. Module interface
- Observation: the locomotion and communication modules need to be positioned somewhere on top of Zebro and should be easy to install and to remove.
- Conclusion: a simple connection mechanism is needed that connects any modules to the top of Zebro
- Decision: the decision is made to use camera lens type connections, that twist into place and lock. (Bajonetsluiting, in Dutch). These are prototyped and found to be working

28. Need for wall locking
- Observation: The new design, based on extrusion, does not actively secure the sidewalls. The sidewalls are now sandwiched between the top and bottom plate, but can still move outwards. If forces are put on the motor, the outer walls move and the motor modules can pop out. Furthermore, 8 bolts are currently needed to secure the top, wall and bottom.
- Conclusion: The sidewalls need to be secured so that they cannot move. Furthermore, the robot should be designed in such a way that the bolts are not necessary
- Decision: In order to secure the sidewalls they could be countersunk into the top and bottom plates. These are made by laser cutting, and by setting the laser at a low speed, deep and wide cuts can be made. If an offset of 0.2mm or so is taken from the wall profiles and this area is engraved to be 1 - 2mm deep, the profiles will be locked into place

29. Series 10 printing time
- Observation: The fully plastic prototypes took a total of 140 hours per robot to print. With the new design, based on extrusion, the top and bottom are laser-cut and do not have to be printed. This brings the total printing time down to about 40 hours.
- Conclusion: If 10 3D printers are used, it is possible to successfully print at least 10 full robots in one week
- Decision: 10 3D printers will be borrowed from the IDE faculty and used to print a series of at least 10 robots

30. Modular leg approach
- Observation: the double C legs make it difficult to assemble the robot. Furthermore, there are two function embedded in the leg right now: first, securing the leg to the robot, and secondly, the actual leg that has to walk. Using the current set-up, legs can only be used on 1 side of the robot, if placed on the other they are facing the wrong way.
- Conclusion: if the motor modules are to be fully modular, one should be

able to place them at any slot within the Zebro. This means the design of the leg should change so that it can fit at both sides of the robot. Loose coupling of the functions of attaching to the motor shaft and the leg itself could help with this.

- Decision: the decision is made to split the leg into a leg hub that is fastened onto the motor shaft, and a leg that is clicked onto the hub. This means that for each hub 2 legs can be clicked on, using a snap-fit connection. If the module is place at the opposite side of the robot, the legs are simply switched around, using the snap-fit connection to do this quickly.

31. Leg grip

- Observation: in order to be able to walk, the legs need to have sufficient grip on the floor. To achieve this, several methods can be used. Firstly, friction could be increased through applying a rough material onto the leg, like rubber. Secondly, friction could be increased by changing the surface of the leg, either by ribbing it or by making the contact surface greater
- Conclusion: once Zebro is operational the legs should be tested and a method to increase grip should be chosen
- Decision: because Zebro is not yet functioning, and because the legs can easily be redesigned at a later stage, the legs are not redesigned within the context of this project. The modular nature of the legs offers ample opportunity for redesign at a later stage

32. Connectors & Wiring

- Observation: all in all, many wires will be required to connect the different PCB's to the power grid of Zebro, and to the communication bus.
- Conclusion: it is important to test the wiring before final prototypes are made, to be able to say with certainty all connectors fit and there are no unforeseen problems
- Decision: by using the 6 prototype PCB's and by ordering the needed connectors, a test was done to verify all wiring fits within the frame of Zebro

33. Assembly

- Observation: assembling the prototyped Zebro's takes quite a long time. This means that assembly cost (man hours etc.) may be quite significant in respect to the total Zebro price
- Conclusion: a clear picture is needed of the assembly time of DeciZebro as is
- Decision: 5 DeciZebro's were assembled in succession, and the amount of time it took to assemble them was measured. (Results in appendix B)

References

Books & Articles

Bone, Q., & Moore, R. (2009). Biology of fishes (1st ed.). New York, N.Y: Taylor & Francis.

Boothroyd, G. & Alting, L. (1992). Design for Assembly and Disassembly. CIRP Annals - Manufacturing Technology, 41(2), 625-636. http://dx.doi.org/10.1016/s0007-8506(07)63249-1

Cornejo, A. & Nagpal, R. (2015). Distributed Range-Based Relative Localization of Robot Swarms. Algorithmic Foundations Of Robotics XI, 91-107. http://dx.doi.org/10.1007/978-3-319-16595-0_6

Lentink D, Jongerius SR and Bradshaw (2009) The scalable design of flapping micro air vehicles inspired by insect flight In:Floreano D, Zufferey JC, Srinivasan MV and Ellington CP (eds)Flying Insects and Robots. Springer-Verlag

Mankins, J. (2009). Technology readiness assessments: A retrospective. Acta Astronautica, 65(9-10), 1216-1223. http://dx.doi.org/10.1016/j.actaastro.2009.03.058

Sanchez, R. & Mahoney, J. (1996). Modularity, flexibility, and knowledge management in product and organization design. Strategic Management Journal, 17(S2), 63-76. doi:10.1002/smj.4250171107

Rubenstein, M., Cornejo, A., & Nagpal, R. (2014). Programmable self-assembly in a thousand-robot swarm. Science, 345(6198), 795-799. http://dx.doi.org/10.1126/science.1254295

Tang, D., Zheng, L., Li, Z., Li, D., & Zhang, S. (2000). Re-engineering of the design process for concurrent engineering. Computers & Industrial Engineering, 38(4), 479-491. http://dx.doi.org/10.1016/s0360-8352(00)00059-0

T.D. Seeley, R.A. Morse, P.K. Visscher (1979) The natural history of the flight of honey bee swarms, Psyche,, pp. 103–113

Wilson, E. (1978). Sociobiology, the new synthesis (1st ed.). Cambridge, Mass.: The Belknap Press.

Web

Beehive. (2017). Aetherforce.com. Retrieved 17 March 2017, from http://aetherforce.com/wp-content/uploads/2015/03/hive-15-11-bigger-but-less-bees.jpg

Boston Dynamics: Dedicated to the Science and Art of How Things Move.. (2012). Bostondynamics.com. Retrieved 1 January 2017, from http://www.bostondynamics.com/robot_rhex.html

DelfiSpace , 2013. Retrieved June 2017 from http://www.delfispace.nl/

Fish Photography. (2017). Blenderartists.org. Retrieved 17 March 2017, from https://blenderartists.org/forum/attachment.php?attachmentid=322193&d=1406042723

GrantDixon Photography. (2017). Grantdixonphotography.com.au. Retrieved 17 March 2017, from http://www.grantdixonphotography.com.au/lib_images/LIT-2933.jpg

How Bird Flocks Work. (2017). Howitworksdaily.com. Retrieved 17 March 2017, from https://www.howitworksdaily.com/wp-content/uploads/2015/07/wallpaper-of-a-flock-of-flying-birds-hd-bird-wallpapers.jpg

Insect Compound Eyes (2014), Retrieved June 2017 from http://indianapublicmedia.org/amomentofscience/files/2014/07/Compound-Eyes.jpg

INFRARED TRACKING SYSTEM. (2017). People.ece.cornell.edu. Retrieved 4 January 2017, from https://people.ece.cornell.edu/land/courses/ece4760/FinalProjects/s2004/rd73/476finalpro.htm

Intel Lights Up the Night with 500 'Shooting Star' Drones. (2016). Intel. Retrieved 28 December 2016, from http://www.intel.com/content/www/us/en/technology-innovation/videos/drone-shooting-star-video.html

Kod*lab : RHex. (2017). Kodlab.seas.upenn.edu. Retrieved 13 January 2017, from http://kodlab.seas.upenn.edu/RHex/Home

Meet Cozmo | Anki. (2016). Anki.com. Retrieved 14 January 2017, from https://anki.com/en-us/cozmo

Swarmbots (2005). swarmbots.org. Retrieved March 5, 2017 from http://www.swarm-bots.org/

Robot - definition of robot in English | Oxford Dictionaries. (2017). Oxford Dictionaries|English. Retrieved 14 May 2017, from https://en.oxforddictionaries.com/definition/robot

Swarmrobot | Open-source micro-robotic project. (2013). Swarmrobot.org. Retrieved 9 January 2017, from http://www.swarmrobot.org/publications.html

Zebro - six legged robot | TU Delft Robotics Institute. (2017). Robotics.tudelft.nl. Retrieved 13 March 2017, from http://robotics.tudelft.nl/?q=research/zebro-six-legged-robot

Zebro Light: Lightweight Mobile Hexapod Robot - Robotsquare. (2017). Robotsquare. Retrieved 7 March 2017, from http://robotsquare.com/2013/07/17/zebro-light/