Project description

Digga

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Abstract

In the event of an avalanche, 80 % of those who remain on the surface survive once it stops, while only 40 - 45 % of those partially or fully buried survive [1]. The search methods currently used from the overground are error prone. To facilitate search and rescue operations in extreme situations, we have considered a lightweight design concept for a bio-inspired robot construction. The integration of effective digging is inspired by the mole, the scale-supported movement of snakes in difficult terrain serves as a template for the drive. The methods of detection are based on the sonar of bats, leading to an ideal merge of desired functions for an effective search in disaster areas.

Introduction

Bionics, which involves applying the principles of biology to develop machines and systems for simulating or enhancing the functions of living organisms [2], is a field of learning that combines the biological effect and physical approach to create technology inspired by living organisms or natural mechanisms. Interdisciplinary cooperation is key to a successful bio-inspired prototype-creation. Therefore we are lucky to have a diverse group of two engineers, Björn and Simon, a biologist, Pamina, a robotics engineer, Marcus and a biochemist, Luca.

While Luca and Pamina were able to provide input with their scientific knowledge about nature’s phenomena for bioinspiration, especially in the first phase of finding ideas and designing the prototype. They supported the project in the prototype-building phase mainly by creating the presentation and writing the paper.

Björn and Simon constructed the prototype digitally as well as physically. Moreover, they found workarounds for the problems that occurred during 3D-Printing the individual pieces of the robot.

Marcus, before also writing the paper, compiled in the specific situation of algorithm for detection and communication, draft control of multiple ‘Digga’ robots in the simulated snow mountain environment when performing search and rescue operations.

Problem and process of development

For bio-inspired product development, there are two different ways, top-down (problem-driven), which the developer designs with the beginning of one technical problem and its requirements, and bottom-up (solution-driven), which gets inspired by natural existing phenomena. The problem, we searched a solution for, was the detection of buried people. Outdoor sports enthusiasts, such as mountaineers and skiers who explore wild snowy mountain terrains, are always at risk of encountering an avalanche, which has a devastating impact and destructive power. The chances of survival are further reduced for those completely buried. Specifically, 20% of fully buried individuals survive for 30 minutes, 13 % for 1 hour, 7 % for 2 hours, and 4 % for 3 hours. The leading causes of death during an avalanche include suffocation (65 %), collision (25 %), and hypothermia or shock (10 %) [1]. Due to the large area of snow rescue in mountainous areas, the low survival rate of deep burial and the high possibility of secondary snow disasters, it's therefore important to rapidly search for frostbitten skiers and minimize the risk of injury or death.

Even if our product was designed primarily for the detection of avalanche victims, it is also suitable for other disaster areas (landslides, earthquakes).

Our top-down approach (Figure 1) to product development involved starting with the overall goals of digging and searching and then breaking them down into smaller, more specific steps of modification inspired by nature, leading to the prototype of 'Digga'.

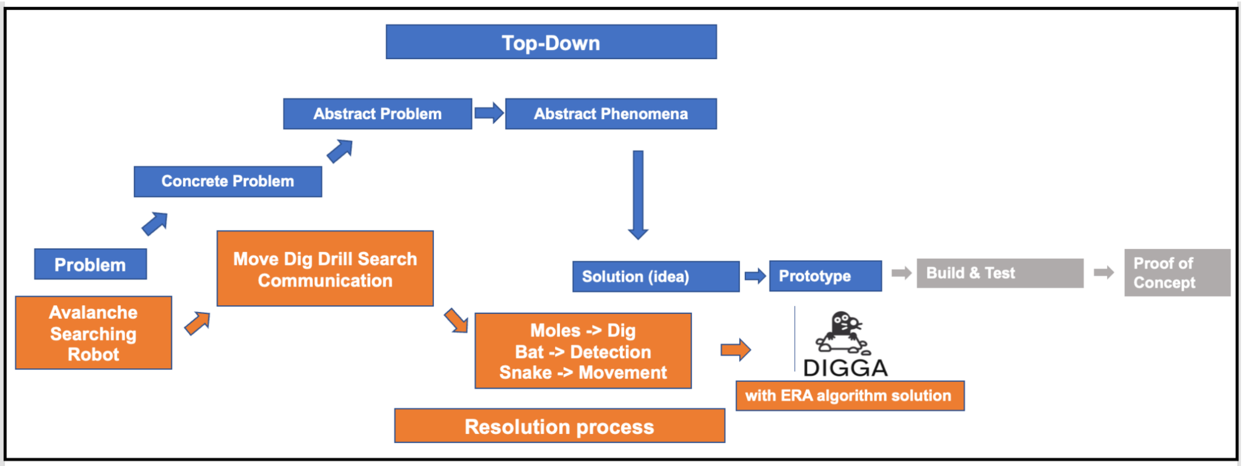

Figure 1. Top-down driven 'Digga' robot development

To design this robot, we did the following function integrations from the perspective of bionics within top-down product development. The operational area is to be imagined underground in large (mountainous) areas. In the case of avalanches, we must expect snow-water mixtures with dense accumulations. Due to the difficulties of carrying search-tasks in this environment out with manpower, it's possible to consider using a robot. To further discretize the Problem a function diagram was created (Appendix 1). To further abstract the problem, two "Problem Element" Bio-cards were created. One mainly for the function of movement underground and one for detecting buried persons. Then a thorough search of Biological databases and knowledge of the Bio-inspired members in our team, resulted in four Bio-inspired "Solution Element" Bio-cards, to fulfill some of Digga's functions. Mole-inspired paws and mole-inspired forelimb anatomy is used to generate a digging mechanism. Snake-inspired tracks on the chain drive increase traction and bat-inspired echolocation will help finding buried people. In the following section these concepts are alluded to.

After our functional analysis and biological principal search based on this specific problem context, we got inspired by the habits of the mole, because their palms work well with their stream-lined body shape to push the dirt away [3]. After they complete the action of digging (action F_a), according to the principle of Newton's third law of kinematics, this reaction of force (reaction $F_{r,b}$) from the underground solid material will be combined with the shoulder joint to the hand arm to form a torque (M_a), which provides a guarantee for them to move forward (Figure 2) [4]. To simulate the movement of the mole from a graphic kinematics point of view, we combine our shovel and swimming-like (cam-mechanism) movements. By designing 'Digga' we not only considered the bio-inspired design of the mole, we also combined certain behaviors of snake and bat, so that our main functions (digging, movement and detection) can be combined and maximize the effect of underground search. Then we designed the motor system that provides power to the rear of the robot to separate our kinematics and motor drive, because snake-drive is taken to design our chain drive and mid-mounted motor principle. To better adapt to the underground structure and enable the robot to better maintain its position in the underground environment, we use a snake-drive structure to design our chain drive. The snake-drive structure can realize crawling forward and all chain segments can participate in the motion process, to maintain the motion with optimal use of friction force (F_f). Additionally, the separate design thinking is better for design changes in testing and validation according to the V-Model [5] later. So far, we have been inspired by the movement of moles and snakes and realized the transformation/ combination of the 'Digga' robot functional modeling in/ with solution elements. In our actual manufacturing, we made several optimizations and improvements for the 'Digga'. This part will be described in chapters 3 and 4.

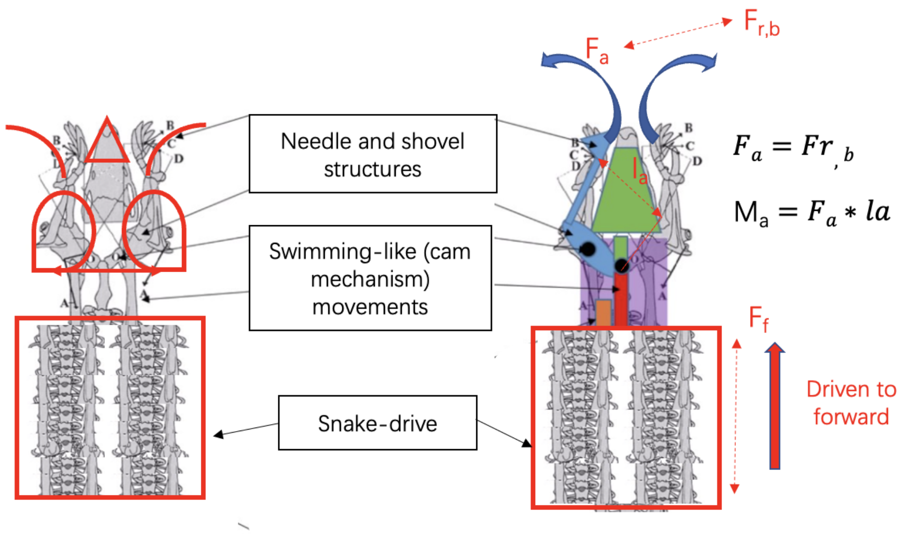

Figure 2. Motion Analysis and Synthesis

Another important function of our 'Digga' robot is how to find the target object, such as deeply buried human beings after the avalanche search and rescue. The underground environment can be dark, cramped, and hazardous, making it difficult to move around and conduct a thorough search. Specifically In avalanche searching, the snow can quickly bury someone or something. Moreover, the snow can also shift and change quickly, making it challenging to predict where the buried person or object might be located. In this case, the way bats transmit signals and hunt in nature comes into sight. Bats use their larynx to emit high-frequency, short-wavelength ultrasonic waves and then listen to the echoes reflected by objects through the auditory system, and the brain center analyzes and responds. This way of sending and receiving at the same time is what we need. However, in underground searching, materials with big density, e.g. soil, rocks, and other debris, can make it challenging to pinpoint the exact location of the person or object [6][7]. So we got inspiration from the echolocation of bats, replacing the ultrasound signal with electromagnetic waves generated by ground-penetrating radar (GPR). The reason to use the electromagnetic waves generated by GPR is that, due to the dielectric difference of the medium causing the difference in wave propagation, the period of sending and receiving the electromagnetic waves through the different mediums underground should also be different.

Requirements

According to the functional description in chapter 2, we made a list to integrate the problems, the abstract phenomena, and the solution idea. Because of the existing conditions in the workshop, limited funds, time and capacity, we cannot fully realize all the defined functions, the achieved principles are marked with green color, while those that were not covered are in red.

Table 1. Summary of functional modeling with solution elements

Abstract Problem	Abstract Phenomena	Solution idea
No secured paths and getting stuck	Mole-like movement helps digging.	Shovels with claw structure
Difficult to maintain position underground	Snake forward-movement with scales for friction	Chain drive with thorns
Will buried humans be harmed?	Seeing with the eyes.	Camera
Detection in extreme conditions	Echolocation used by bats	GPR Search & ERA
Potential limitation in wireless connection but I need of connection for networked control	Communication in low frequency	
Is drilling required when the underground environment is solid rock?	Sharp-billed animal's teeth can drill through soil	Install a drill on the head of the robot

After getting inspiration from nature, we design the corresponding objects using engineering principles with CAD. Before designing, we need to clarify the specific requirement list of solution elements, thus reducing the reversible process in the development. We calculate and research to obtain necessary values. We begin by determining the size of the robot, which helps estimate its forward speed and force. We also need to establish the effective range of the control and communication signals for the robot. Communication-related values should be specified.

Table 2. Requirements of development for Digga robot

ID	Description (Property/Requirement)	Variable/ Symbol	Value			Unit	Source
			min.	Exact/ Nominal Value	max.		
1	Signal effective range	f	10 M		2.6 G	HZ	Description of GPR SoftDig [8]
2	Signal propagation velocity	v	200		240	m/us	Tillard S, Dubois J C. [9]
3	Sufficient force to remove loose material	f			200	N	Procter E. et.al. [10]
4	Generate forward momentum	v			0.2	m/s	Procter E. et.al. [10]
5	Space to house sensors			0.5		m^3	Ayuso N. et.al. [11]
6	Round trip delay	t			25	s	Ayuso N. et.al. [11]
7	Penetration depth	d			18	feet	Ayuso N. et.al. [11]
8	Size of Digga robot	l x b x h		385.85 x 180 x 180		mm	Construction with CAD

This process was aided by creating so-called Bio-cards to help organize the Problem and solution elements.

Derivation for the solution element

After the analysis of the biological effect, functional modeling, requirement list and achievable possibility of the principle, the main three functions of the ‘Digga’ robot are derivated in Figure 3. All the bio-inspired solution elements were mathematically and physically evaluated and validated. In front of the biological effect in nature, the mole is very efficient at digging tunnels and “swimming” underground. Furthermore, the claws are optimized in shape to displace material ahead and the continuous row motion can even be achieved by the inverse cam principle. Getting inspired by the snake scale structure the forward momentum and skip prevention could be achieved with the chain-driven with thorns structure. To achieve the detection and communication we create the Evolutionary Rescue Algorithm, which integrates the calculation about the straight-line distance set, searching for the path set by Rapidly exploring random trees (RRT*) within the signal effective range and the cost comparison. Since then, the three main functions of the robot can be well realized according to the principle of bionics.

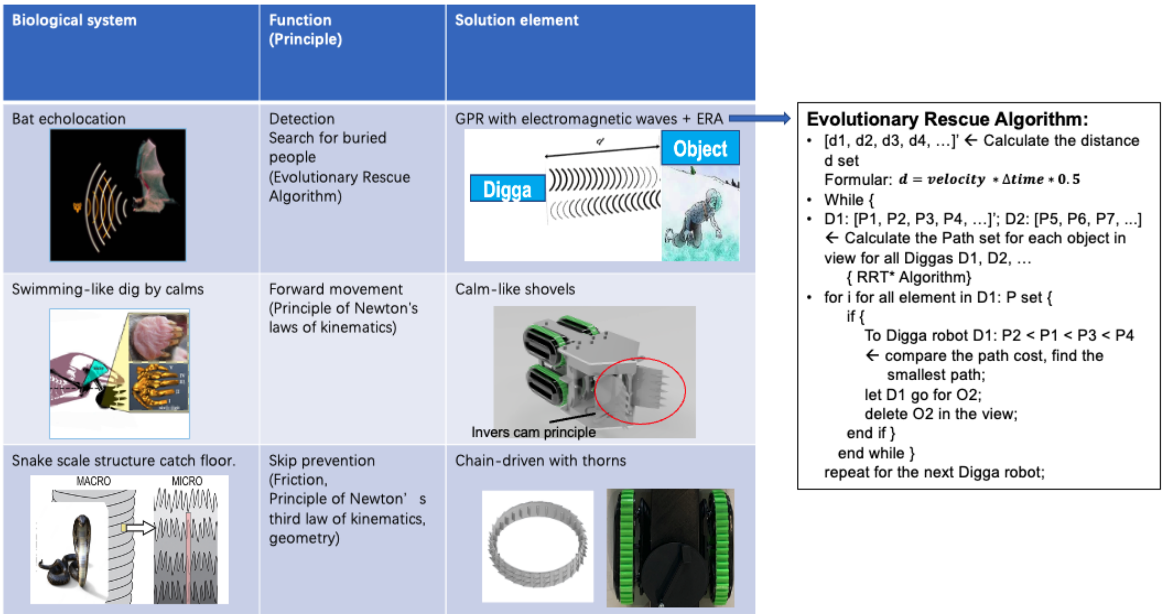

Figure 3. Derivation of the solution with the biological system and function

Application

Figure 4 shows the CAD model and the ‘Digga’ robot prototype printed by a 3D printer. Except for the wheels, motor batteries and bolts, the parts of the ‘Digga’ robot have been mainly manufactured by 3D printing. The outer protective layer was cut out of metal for stabilization and protection. The ‘Digga’ robot has an actual size of 385.85mm x 180mm x 180mm. The actual dimension can be found in Appendix 2. Primary straight-line control of the ‘Digga’ robot can be achieved by operating the remote handle externally and in the follow-up field test, the ‘Digga’ can realize the basic functions of the original functions stated in the function modeling.

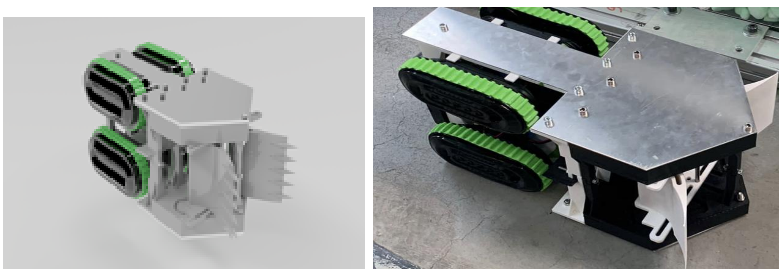

Figure 4. 3D model and prototype

Conclusion

By using a bioinspired Top-Down approach to solve the problem of detecting people underground, the ‘Digga’ robot has designed and manufactured, which uses detection methods underground rather than overground as currently applied. ‘Digga’ combines the biological advantages of moles burrowing, bats transmitting messages and snakes moving forward. The prototype was successfully built and is working as intended and the corresponding simulation has also been realized. Because of limited funds and time, we don't have microchips and it is not possible to deploy the algorithm part to the original system to achieve real detection and communication. Therefore, in the subsequent development stage of the product, the motor power of the central control rotation and translation needs to be increased by 4 to 5 times, and the ERA algorithm needs to be inherited to the chip and then built on the robot. Further an improvement to the guidance of the shovels could be implemented. The detection and avoidance of injuring people with the shovels require a camera at the front end. In addition, the size of the robot can be further reduced to achieve more efficient and flexible ground drilling requirements.

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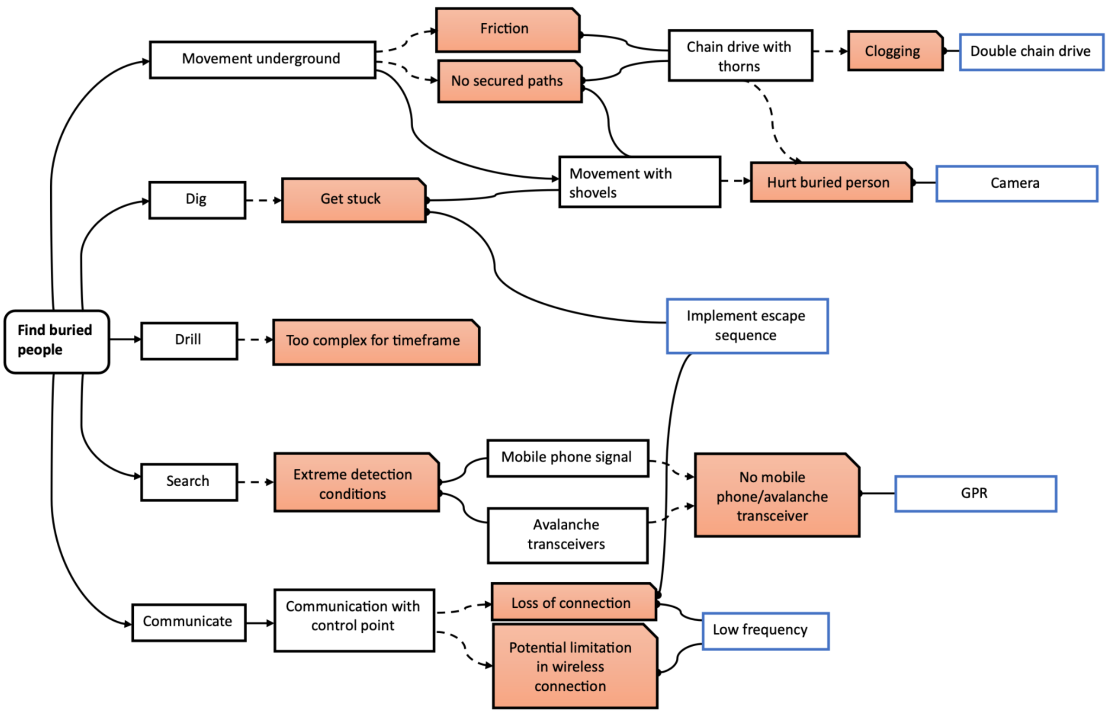
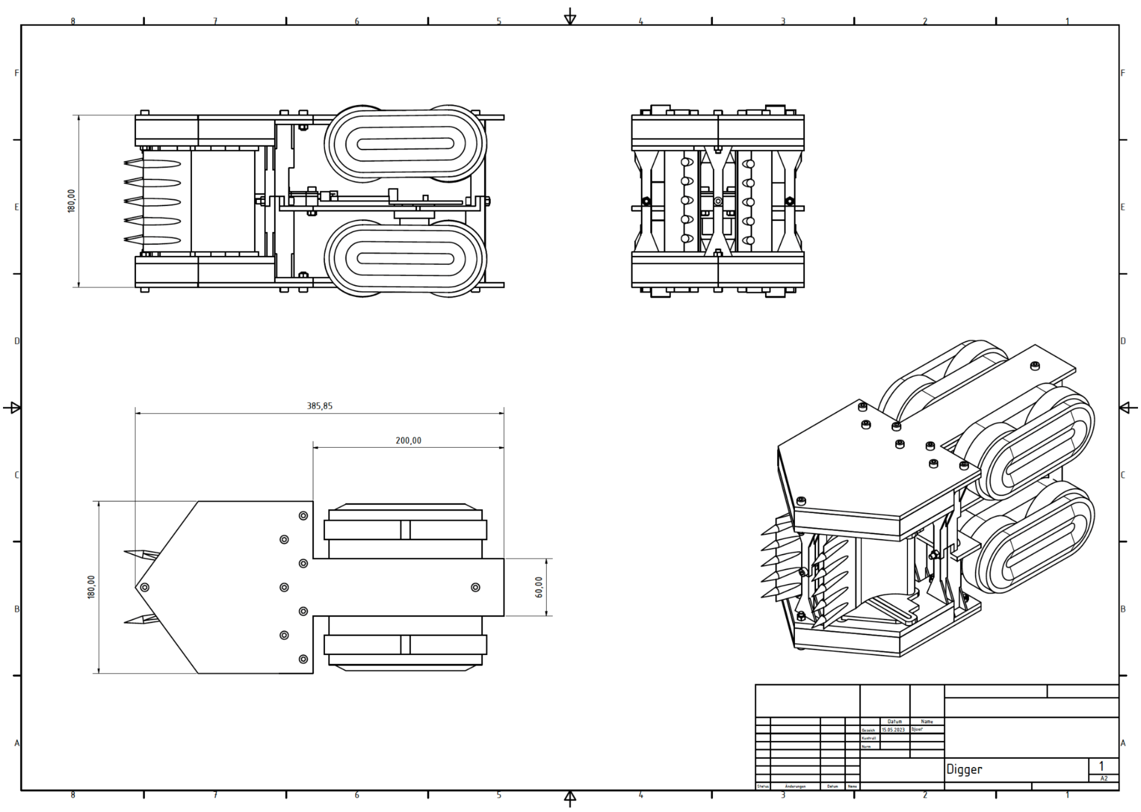
Appendix



Appendix 1: Function Diagram to Problem of Finding Buried People



Appendix 2: Dimensions of Prototype