

BIOINSPIRED DESIGN: A CASE STUDY OF RECONFIGURABLE CRAWLING-ROLLING ROBOT

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Abstract

Mobile robots capable of traversing rough terrains are highly desired for numerous applications including search, reconnaissance and surveillance missions. To this end, nature offers numerous highly effective, efficient and optimal biological precedence as a result of evolution process. Developing a bio-inspired robot poses numerous challenges and requires systematic design process to mimic biological counterparts. This paper presents our efforts in developing a bio-inspired self reconfigurable miniature robot capable of producing crawling and rolling locomotion gaits to traverse in highly complex terrains. Also, the article provides a descriptive account on the use of Problem-Based Biological Design (PB-BID) process in solving a robotics problem and summarizes our key observations. Furthermore, the paper details experimental validation of the developed robotic prototype that mimics Cebrennus Rechenberg, a class of huntsman spider.

Keywords: Bio-inspired design and biomimetics, Robotics, Reconfigurable Robots

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1 INTRODUCTION

The functioning of nature is always inspiring and provides abundant solutions to enhance technology. Moreover, nature uses far less energy than we do- It is at least four times more efficient than current technology. Human beings have always been curious, interested or excited about the biomechanics of the animals that walk, climb manipulate and roll and have tried to understand, enjoy or imitate them for solving complex human problems. The locomotion of walking animals / creatures has gathered a special attention because they have potential applications in the field of military, inspection of nuclear power points, land, submarine and planetary exploration, forest and agriculture tasks, construction, civil projects, help for disabled people. This results in the proliferating growth in the development of legged / walking machines by classified them as bio-inspired or bio-mimicking robots Hui-Ti Lin et.al (2011), that are designed by taking inspiration from natural systems such as insects, birds, mammals and reptiles. This offers a truly interdisciplinary systems research challenge that encompasses biology, materials, mechanical design, controls, sensors and actuators, power, electronics, and computer science among the other topics. Emulating the performance of live creatures is extremely difficult to accomplish and the process of implementation involves great complexity.

Motivated by the ongoing research in the field of walking, climbing and rolling robots, the aim of the research is focused in the development of a miniature robot that synthesizes rolling, crawling and climbing, that is capable of performing two or more kinds of locomotion with one and same structure with that at faster pace and higher efficiency, depending on the terrain and providing useful information to the during the surveillance and rescue time by following the bio-inspired design methodologies. In this case authors looked at hundreds of papers for suitable organism. The advantage of increasing the different modes of locomotion, robot adaptability is increased because it may select the locomotion method suited for a particular environment. For example legged locomotion is excellent for rough and unstructured terrain, but it is slow and demands energy. Rolling is apt for higher speed and is more energy-efficient but requires smooth structured environments and greater accessibility to difficult spaces. The proposed research is complex and has many steps to be organized for everything to come together.

Figure 1, presents the idea with a block diagram where a single robot performs three different means of locomotion. We begin this paper by explaining the general design methodology of problem-driven low-complexity design procedure adapted from the Emily Obert (2011). The contribution in this paper is step by step implementation of bio-V design methodology which includes the steps of defining the problems searching for the solutions, data extraction, modelling, design and fabrications in detail which is really applicable for our research problem.

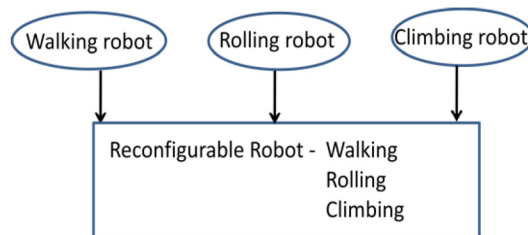


Figure 1. Block diagram representation of reconfigurable robot

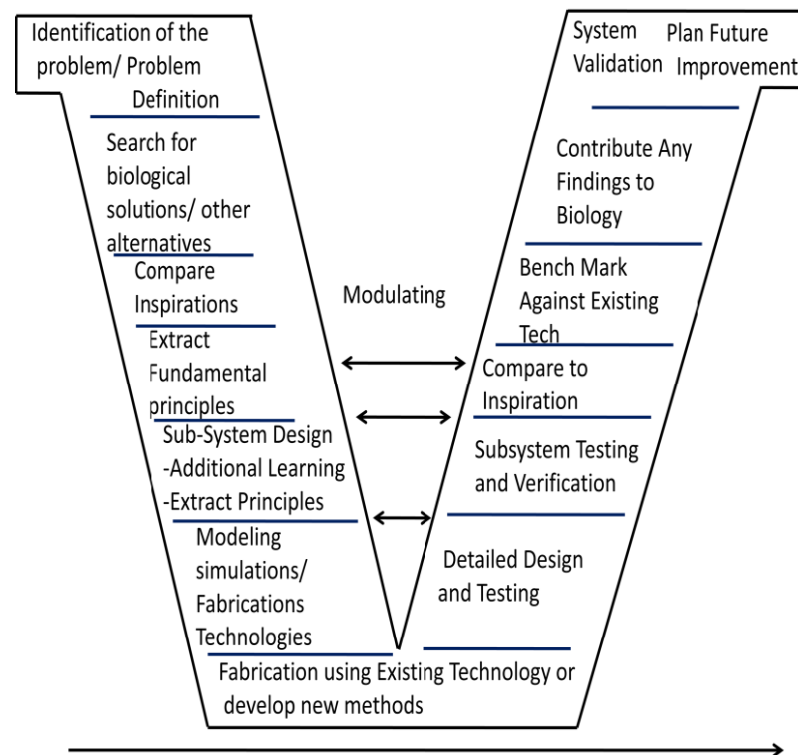
It is known that direct implementation of biological features and morphology often becomes ineffective and misleads engineers due to various reasons. Firstly, engineers investigate animals to achieve a few particular functions whereas features of animals may serve multiple functions or often remain unknown. Secondly, the difference between engineering manufacturing process and biological synthesis arouses the difficulties in direct replication. Moreover, this kind of work needs a formation of bridge between the biological domain and engineering domain. In order to overcome these problems, a need for a systematic bio-inspired design (BID) process was realized in early 2000s and since then, considerable research on the BID methodology has been progressed and ongoing M Haberland (2015). For instance, researchers at Georgia Tech did a study where they observed an undergraduate class of students. From their study two six-step processes for biologically inspired design were proposed, one is Problem-Based BID (PB-BID) and other is Solution-Based BID (SB-BID) Swaroop S.Vattam et.al (2010). It is known that in PB-BID procedure starts with an engineering

problem in engineering domain, whereas SB-BID begins with a biological system in biology domain(2011).The main limitation of their study is that did not emphasize on the fabrication and making prototypes. BioTRIZ was developed by Dr.Vincent of the University at Bath to move from the problem straight principles extracted from biological phenomena, so BioTRIZ is a very indirect form bio inspired design(Julian F.V Vincet 2006). Bio-Inspired conceptual Design (BICD) process which explains the design steps of hybrid bio inspired robots is also developed A hybrid bio inspired robot includes diverse functions, structures, and behaviours which are provided by multiple biological systems(2011). Nagel et al (2011) developed steps to perform functional models of biological systems. Vincent & Man (2002), for example describe their imitation of the design of pinecones to design clothing that can help regulate body temperature. Other examples include design of micro robots that can walk on water mimicking the locomotion of the basilisk lizard.

In this research work, we are starting with an engineering problem that is to develop miniature autonomous robot that uses one mechanism for generating multiple locomotion gaits for security and surveillance applications as mentioned above in detail. Section 2 introduces the Design process in this paper built upon the prior work. Section 3 illustrates the application of problem-driven low - complexity design procedure and it application in constructing reconfigurable robot Scorpio. Finally, problem-driven low-complexity design procedure and the case study are summarized and discussed in Section 4&5.

2 PROBLEM- DRIVEN BIOLOGICALLY INSPIRED DESIGN PROCESS (PB-BID).

Figure 2, shows the design process which is implemented for developing the reconfigurable bio-inspired robot "Scorpio". The bio-V has two sides, the explore-and-design side on the left and the test-and reflect side on the right. In the centre sit fabrication and iteration.



Direction of process: however feel free to iterate and repeat any parts as many times as necessary Emily Obert et.al (2011)

Figure 2. shows the design process which is implemented for developing the reconfigurable robot Scorpio bio-inspired robot

Firstly, it should be noted that the research started with a problem and authors sought inspiration from biology after doing through literature survey on other available sources. In this problem driven

approach, first a problem is discovered, but the design process does not really start until designer decides to pursue a bio inspired design solution in the next step. This is the only step more undefined than principle extraction. In this case the reader will notice V-shaped processes adapted from Emily Obert et.al(2011). The system V splits up the design step into setting system specifications, extraction of fundamental principles, subsystem design and detailed design. In the proposed research multiple people are involved. Different designers work on control algorithms, hardware to execute the desired locomotion, energy consumption, sensors design and more. Each of these pieces must be tested individually before they combine with the complementary components that form a subsystem. Each of these subsystems should be tested independently, before they are combined in to a whole. If one of the pieces does not meet its specifications, it must be redesigned; that iterative process is represented by the arrow in the centre of the diagram.

The counter part of comparing natural systems on the right side of the V is to benchmark the final result against other engineering solutions or even other natural systems that were not chosen. As previously mentioned, contributing any relevant findings to the field of biology is part of being good member of the bio inspired community. The result must be validated to make sure it meets specifications and any improvements can be planned with the information from the benchmarking and the validation. If a component or the final results fails the testing, it is redesigned and rebuilt. The above mentioned procedures are implemented step by step in our research and elucidated in the next sections.

3 IMPLEMENTATION OF PROBLEM-BASED BIOLOGICALLY INSPIRED DESIGN PROCESS

This Section provides a descriptive account on the use of Problem-Based Biological Design (PB-BID) process in solving an important robotics problem and summarizes our key observations.

3.1 Need for the Design / Defining the problem statement

The overall concept of the design is to create a robot with the ability to adapt itself to rolling, without requiring additional resources beyond those required for climbing and walking. The application of these kind of robots for example in cosmopolitan cities, such as Singapore there are numerous skyscraper continuously habitable building of many floors, usually designed for office, commercial and residential use. In the event of security threat or disaster, it is highly impossible to conduct search, surveillance, or reconnaissance missions due to safety considerations. During these operations it should be noted that the robot should move at faster pace and higher efficiency.

3.2 Studying the existing methods and available techniques

In this step, the design team found different available resources to do search, surveillance, or reconnaissance mission, one is by using flying robots. The limitations with the unmanned aerial vehicles are that they are prone to turbulence and controlling them is an arduous task. Moreover, they are not much energy efficient, and can be detected easily during the spying operations. Cost is a farther concern. The authors eliminated the idea of using flying robots. The advantages of robots that can walk are greater mobility, better ability of overcoming obstacles, greater energy efficiency. The one limitation with the walking/climbing rolling robot is the achievable speed and the control algorithms.

The variety of robots that are able to walk or to roll is enormous. Robots that have wheels mounted to their legs are categorically excluded from the research because this would mean having an additional structure, which is contradictory to the aim of performing research into two very different kinds of locomotion with one and the same structure. Literature survey is carried only for hybrid locomotion robots. The most common combination of walking and rolling found in the research i literature are leg-wheel designs A leg wheel design is characterized by a legged robot with wheels on either the distal leg link (the foot) or wheels attached somewhere on the body of the robot. Numerous attempts have been made previously towards realizing reconfigurable legged platforms that are capable of locomotion gaits beyond crawling with special design. Nansai et al. proposed a reconfigurable leg based on the Theo Jansen mechanism (2013) by changing the length of the links with motors, the leg can generate different gaits with only one driving motor. Chen et al. proposed a leg-wheel transformable mobile robot. Some miniature jumping robot with leg-hop had been proposed in (2008, 2010). N. Chadil et al.(2011) presented a reconfigurable spherical robot that can be reconfigured into

a form of two interconnected hemispheres with three legs equipped with Omni-directional wheels. Chen et al (2014) presented a quadruped robot based on modularized electrical paddle modules which could achieve both legged and wheeled locomotion.

However, most of these works on reconfigurable robotics tend to add new mechanisms to realize additional locomotion gaits and often fail to cover autonomy while mimicking the behaviour of their biological counterparts. Such an approach would result in redundant mechanisms so as to result in increased size, high level of computational complexity, and numerous controllability hurdles.

3.3 Searching for the Biological Solutions

So after reading the research papers at this point authors decided to go for biological solution search to find animals/creatures that has different locomotion gaits . It is known that in the animal kingdom, in the terrestrial environments propulsion is typically accomplished with jointed legs which can negotiate uneven terrains. Our aim is to identify the biological species that performs crawling and rolling locomotion.

After using searching tools like "engineering-to-biology thesaurus" (Jacquelyn K.S Nagel et.al 2010) by using the keyword like creatures "response to environment task or threat " authors found creatures like spiders, caterpillar and more are suitable for this kind of applications. The other tool that authors used during our search is a tool developed by the Biomimetics for Innovation and Design laboratory at the University of Toronto, is used. The search tool has been incorporated into Word Net, which is an electroniclexical database (Glier MW.et.al 2011). The third tools used is AskNature.org for searching biological solutions which sorts organisms by engineering function (Anette "Peko" Hosoi(2013). In this way, the authors carried out the search for the solutions. The authors also referred answer to the questions that were made by Emily Obert et. al(2011). For example, on a flat inter-tidal zone a stomatopod *Nannosquilla decempisnosa* prefers to flip its body across the wet sand when there is no water to swim Caldwell(1979). These shrimp-like creatures have legs specialized for swimming but not walking. Using the defined problem definition, the design team investigated the seven alternative biological sources of inspiration. Figure.3 shows the different biological species that performs crawling and rolling locomotion's in different scenarios and in environmental conditions.



Figure 3. Different biological species that performs crawling and rolling locomotion's picture credit (Ask nature.org)

Through exhaustive literature search, a list of species are identified. While doing the biological solution search, two kinds of rolling locomotion can be observed from the nature and can be classified as active rolling and passive rolling. In passive rolling, organisms are driven by external forces such as wind or gravity for their movement, whereas in active the organism rolling expends its own energy in achieving the rolling and thus controls its rolling such that it is able to move in a specific direction. Rhodri H. Armour et al.(2006) elucidated in detail about rolling motions of different organisms. Web toed salamander, wheel spider, tumbleweed plant, woodlouse come under the category of passive rolling. While on other hand mother-of-pearl moth caterpillar, stomatopod shrimp, Cebrennus Rechenberg comes in the category of active rolling. Rolling is a secondary form of movement for all know passive roller except the tumbleweed,since animals have legs for normal movement such as searching food. Rolling motion is only adapted as an escape during attacks from predators since it

allows much higher speed for these animals. By studying Rhodri H. Armour et.al.(2006) for developing a autonomous rolling robot that uses active rolling. The interesting part is that using this sort of movement robots are able to choose on which direction to travel.

Cebrennus Rechenberg is identified given that it is the only candidate capable of actively generating efficient rolling and crawling locomotion while traversing in highly complex rugged terrains. The unique characteristics of the Cebrennus Rechenberg are that it is the size of a human palm- approximately 100 mm, can run with a speed of up to 1 ms^{-1} . When switching the locomotion to rolling speed doubles to 2 ms^{-1} . Hence the spider's first benefit is- faster pace which is one main focus of the research. In other experiments of Rechenberg it is found that the walking gait allows the spider to go as far as five to six meters. Then it takes a metabolic break of approximately three seconds before it is capable of running another five to six meters. while using rolling locomotion it travels twice the distance, within the same period of time. This makes it more efficient. Hence the selected biological inspirations is more efficient in terms of time and distance hence its speeds.

3.4 Extracting the fundamental principles from the biological search

In this Section, we will extract the fundamental principles from the selected biological species that is, cebrennus Rechenberg. Rolling motion of the huntsman spider was discovered by Ingo Rechenberg from TU Berlin. Generally, most spider crawl using eight legs. The most interesting part of this spider is that when it is provoked or threatened by an external stimulus, it performs locomotion independently from the surroundings conditions, which means that it does not need a slope to initiate the rolling process by using gravity force. Figure 4, displays crawling and rolling locomotion of the cebrennus Rechenberg.

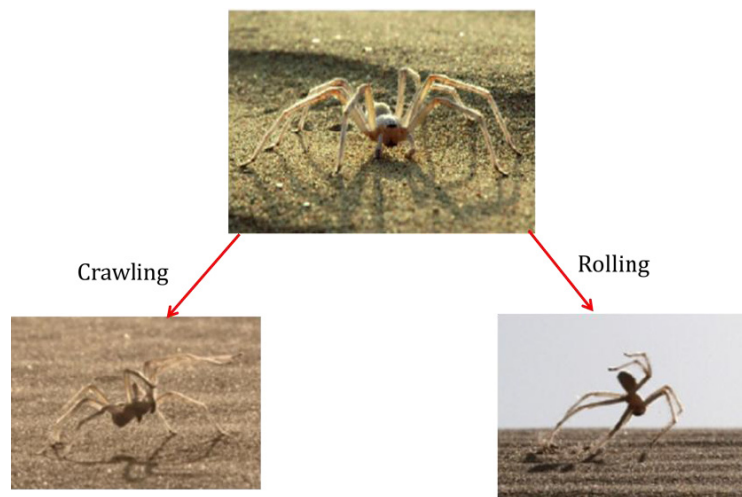


Figure 4. *Cebrennus Rechenberg*, also known as the Moroccan flic-flac spider, is a species of huntsman spider indigenous to Morocco Credit Prof.Rechenberg.

Additionally, the spider does not need to walk first or perform a start-up gesture to trigger the rolling locomotion. It can roll instantly from the point where it stands. Authors also learnt from interview of Rechenberg (2010) and Jager that it not easy to keep the spider in the artificial conditions. From the biological point of view the Cebrennus Rechenberg still needs to be investigated more thoroughly.

3.4.1 Locomotion Analysis

The implementation of the spider movement into robot model requires a thorough look into the role played by the individual pairs of legs locomotion. Rechenberg recorded the sequences of the spider doing somersaults. Since authors don't have the specimen to examine by reading the R.S King (2013) BiLBiQ the locomotion of the spider was understood. After thorough reading, authors got information that spider is forming an abstract wheel with its legs, a wheel that is neither mounted on, nor spinning around a fixed axle. Hence the whole body structure is rotating during the rolling locomotion. Rechenberg attempted to develop bio-mimetic robot based on the rolling spider locomotion. The design process initially involved at least four generations, with the fourth using six legs in three pairs. Rechenberg named the working machine model Tabbot. The model, which is approximately 25 cm in

length, can both walk in the sand and turn somersaults to move. It should be worth noting that Rechenberg's (2013) research focused solely on constructing an equivalent design through iteration with no consideration for autonomy and did not emphasize much on any kinematic, dynamic or control issues. Later, Ralf Simon King (2013) analysed the leg movement of the rolling spider in great detail with the help of video footage.

3.4.2 Additional Learning

The aim of the section focuses on transformation and extraction of biological applicable level. Finally, the design procedure needs to be applied on to a physical approach. Only after these steps can the physical performance of the robot be estimated. Therefore a final decision needs to be made with respect to the parameters to be obeyed, and which hard ware components can used. The two main parameters that are considered are - Hardware configuration and leg design, to examine and the implement the whole system. Some attributes can be easily assigned to technical samples by thinking about the real spider. For instance, spider has a metabolism to run its system. It needs to eat and digest, where as the robot consumes electrical energy that is provided by an accumulator or an external energy source. A classification table that contains exchangeable attributes and non-exchangeable attributes. Table 1, shows the exchangeable and the non-exchangeable attributes.

Table 1. Exchangeable and Non-exchangeable attributes.

Exchangeable attributes	Non exchangeable attributes
Power source	Design
Sensors	Number of legs
Actuators	Degrees of freedom



Figure 5. Cebrennus Rechenberg forming two imaginary abstract circles each subdivided in to parts representing the according the legs Credit RS King(2013) .

A spider has eyes, hair and other mechanism to recognize the environment. This can be achieved to certain degree using various of kinds of sensors, such as the distance measurement sensor and light recognition sensor. We classified these parameters into subsystems. The main system are design, kinematics, dynamics and control. While taking inspiration from complex creature much attention be given to mechanical body design and in choosing the legs. In this work we decided not to exactly copy the spider and construct an octopod into which the locomotion could be implemented both easily and successfully. Figure 5, shows the visualization of the Cebrennus Rechenberg forming two imaginary abstract circles each subdivided in two parts representing the according the legs.

Rather than that, a design is sought to fulfil the set of parameters, and by disregarding unnecessary additional structure-especially additional actuators. The huntsman spider has eight legs, but based on observation of the video of huntsman spider, it is known that only four legs are required to form the abstract circles. We simplify the design to be quadruped which are sufficient to perform crawling and rolling. Each leg is designed to be hollow to lighten the weight and save materials. The added weight for such devices is counterproductive and can prevent climbing capability. On the other hand, circular exoskeletons can increase certain robot dimensions ,such as link height ,and limit access to confined environment. The huntsman spider has eight legs, based on observation of the video of huntsman spider. Hence, in this work, we simplify the design to be quadruped which is sufficient to perform crawling and rolling.

4 DEVELOPMENT OF MECHANICAL DESIGN

Now we are in the bottom of V-shaped bio-design procedure that is development of mechanical design and fabrication. After extracting the fundamental principles from the huntsman spider motion in this section we present the mechanical design and different prototypes by using 3D printing with

PLA plastic. By doing several iterations by varying the size, weight, control strategy three prototypes have been developed and they are presented below in detail. Figure 6, shows the CAD model and prototype of Scorpio.

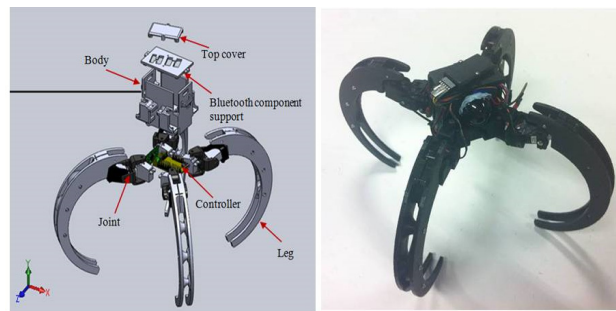


Figure 6. CAD Model and Prototype of Scorpio

In all the prototypes the robots have four links connected by three joints to form a planar linkage. The cross-sectional area of the robot is divided symmetrically among the links. To establish a symmetrical rolling, the mass of the robot is balanced among the other four links so that in closed position, the center of gravity of the robot is very close to the center of cylindrical shape. Every leg is designed with the protruded structure, and the width of the leg is designed to be appropriate for standing and fitting the size. Each leg is mounted with 3 servo motors, so it has 3 degrees of freedom. These legs are able to rotate and transform from crawling to rolling gaits.

4.1.1 Prototype-I

The design of Scorpio robot is based on the real huntsman spider as described above, which is capable of crawling and rolling. The first generation of Scorpio family as Scorpio 1.x., where the robot's diameter was 300mm capable of rolling and crawling locomotion. Figure 7, presents Scorpio 1.2 and its transformation phases. Scorpio 1.2 is the second iterative prototype of the Scorpio 1.x family which weighs about 1.2kg fitting into 300 mm diameter. This platform is equipped with a camera and CM50 controller that controls the gait generation and transformation.



Figure 7. Scorpio 1.2 and its transformation phase

4.1.2 Prototype-II

To achieve platform miniaturization, we studied a number of parameters including optimizing the specific design using CAD tools and simulations, fabrication process and materials, choice of actuators and controllers. Table 2, shows the specifications of the mechanical property of Scorpio 3.x. Figure 7, shows the Scorpio CAD models in crawling and rolling configurations. Systematic tuning of the above parameters in itself resulted in scaling down the platform from 200mm to 165mm measured diameter in the rolling form. Figure 8, presents the optimized CAD models for the third generation of scorpio 3.x family of robots with 165mm diameter in crawling and rolling gestures.

Table 2. Specifications of the mechanical property of Scorpio 3.x

Full body material	PLA (Poly lactic Acid or Polylactide)
Diameter (while rolling) in mm	168
LxWxH (while walking) in mm	230 × 230 × 175
Weight (Full weight) in grams	430

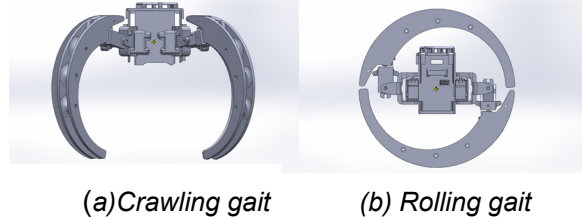


Figure 8. Scorpio CAD models in crawling and rolling configurations

5 REAL TIME TESTING AND EVALUATION OF RESULTS

Based on the mechanical design and architecture of the control system, scorpio has sufficient DOF (Degrees-Of-Freedom) to complete a series of motions. The robot can crawl and roll by legs through transformation of configuration, which is realized by controlling the rotations of servo motors. Figure 8, shows the transformation phases between crawling and rolling. The platform is also capable of recovering from a fall which is highly desired for any security robotic platform expected to traverse in highly complex terrains.

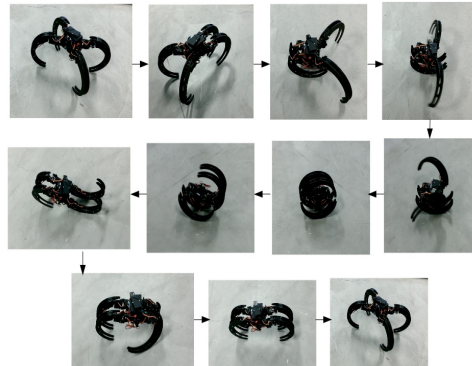


Figure 9. Transformation phases between crawling and rolling

6 CONCLUSION AND FUTURE WORK

In this paper, we have adopted a problem driven bio inspired design process and implemented step by step successfully to develop a self reconfigurable miniature robot. It is capable of producing crawling and rolling locomotion gaits to traverse in highly complex terrains. The V-shaped bio design process is effective in implementing because it has smaller steps and explicitly states to test and refine each piece. Initially two prototypes were developed and final Scorpio 3.x robot is able to crawl and roll with a speed of 0.3 ms⁻¹ while rolling and 0.03ms⁻¹ during walking. Experimental results presented in this paper clearly validate the ability of the developed Scorpio robotic platform in mimicking the rolling, and crawling locomotion gaits of Cebrennus Rechenberg. Future work will be mainly targeted towards achieving terrain perception and self reconfiguration wherein the robotic platform would be able to autonomously choose optimal morphology and locomotion gaits in response to terrain, or task handled.

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