AUTONOMOUS RECONFIGURABLE MOBILE ROBOTS FOR UNEVEN TERRAIN

PROJECT REPORT
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ABSTRACT

A unit-modular robot is a robot that is composed of modules that are all identical. In this project we study the design and control of unit-modular dynamically reconfigurable robots. This is based upon the design and construction of a robot. We further choose statically stable locomotion as the task domain to evaluate the design and control strategy. The result is the creation of a number of unique locomotion modes.

The exciting aspect about a modular robot is that it does not only describe one robot, but also presents the building blocks from which many different types of robots can be formed. Dynamic reconfigurability adds a new dimension to the capabilities of the robot.

To gain insight into these capabilities in the domain of locomotion, we first build a general, functional taxonomy of locomotion modes. We show that my Robot is capable of generating all classes of statically stable locomotion, a feature unique to this robot. Next, we propose methods to evaluate vehicles under different operating conditions such as different terrain conditions. We then evaluate and compare each mode of locomotion on this robot within each class. This study leads to interesting insights into the general characteristics of the corresponding classes of locomotion.

Finally, since more modules are expected to increase robot capability, it is important to examine the limit to the number of modules that can be put together in a useful form. We answer this question by investigating the issues of structural stability, actuator strength, computation and control requirements.

ACKNOWLEDGEMENTS

The success and outcome of the project requires a lot of guidance and assistance and I am extremely privileged to have got this all along the duration of the project. All that I have done is only due to such supervision and assistance and I would not forget to thank them.

I respect and thank Prof. B. K. Rout, for providing me a golden opportunity to do the project work under his guidance. I owe my deep gratitude to him for taking keen interest in this project work and guiding me all along, by providing all the necessary information and suggestions during this project work.

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CHAPTER 1: INTRODUCTION

1. PROBLEM STATEMENT

Reconfigurable robots consist of many modules which are able to change the way they are connected. As a result, these robots have the capability of adopting different configurations to match various tasks and suit complex environments. For mobile robots, the reconfiguration is a very powerful ability in some tasks which are difficult for a fixed-shape robot and during which robots have to confront unstructured environments e.g. navigation in rugged terrain. The basic requirement for this kind of robotic system is the extraordinary motion capabilities. In recent years considerable progress has been made in the field of reconfigurable modular robotic systems, which usually comprise three or more rigid segments that are connected by special joints. One group of the reconfigurable robots featuring in interconnected joint modules realizes the locomotion by virtue of the structure transform performed by the cooperative movements and docking/undocking actions of the modules. Because the modules in these robots are not able to move independently and the possible structures of the robot are limited, these kinds of robots are not suitable for the field tasks. The other kind of reconfigurable robots being composed of independently movable modules is more suitable for the field environment.

However, in complex field terrain, the fact that the existing reconfigurable mobile robots can only assume limited configurations due to relatively simple posture-adjusting is a ubiquitous deficiency. The project presented here aims at developing a reconfigurable mobile multi-robot platform made highly flexible and robust by its three-DOF posture-adjusting ability. The key object of the project is to develop a new posture-adjusting mechanism featuring in compact structure, large workspace and powerful driving ability. As a secondary object, the project has developed an effective connecting mechanism aligned to flat terrain and synthesized it with the posture-adjusting mechanism. The locomotion abilities of the system are expected to be as follows:

1. The single robots in the system have an independent omni-directional locomotion ability equivalent to that of a normal outdoor mobile robot.
2. Due to the posture-adjusting mechanism, which enables the robots to drive very well and to operate in a large workspace, the robots can adjust the posture of their partners.
3. The connecting mechanism tolerating large posture deviation in flat terrain can link two robots in a locked connection and transit large forces and torques between them.
4. Compared with a single robot, the connected robots are able to perform more demanding locomotion activities, such as stepping over high obstacles, crossing wide grooves, passing through narrow barriers and self-recovering from invalid postures and other actions which are impossible for a single robot.

In the past decade, there has been some work on modularity in robotics the goal of making more versatile, easily adaptable manipulator arms. More recently there has been some work on adding reconfigurability to modular robotic systems. Again, the goal was to make even more versatile autonomous robot systems.

In this project, I wish to explore the versatility of reconfigurable modular robotic systems, the initial goal being to determine how versatile such a system can be. To make the problem manageable, the application domain was restricted to statically stable locomotion.

To study versatility in a chosen domain, we must examine that domain in general. While there has been work on specific means of statically stable locomotion, a generalized study of locomotion has had little attention.

The end result of this report is the creation of a taxonomy of the different kinds locomotion possible, and the design, construction and analysis of a robot that can achieve them.

To reach the above targets, a novel reconfigurable mobile robot system based on a serial and parallel active spherical mechanism and a conic self-aligning connecting mechanism has been developed. This system is composed of three robot modules which are able to not only move independently, but also to connect to form a chain-structured group capable of reconfiguration. On flat terrain, each module can corporate with each other by exchanging information to keep up its high efficiency; while on rugged terrain, the modules can actively adopt a reconfigurable chain structure to cope with the cragged landforms which will be a nightmare for a single. In this project, after giving an overview, the discussion focuses on some special locomotion capabilities of it. Then the related kinematics analysis of the serial and parallel mechanism is discussed thoroughly as well as the theory of the connecting mechanism. Based on the discussion, the mechanical is introduced in detail.

2. LOCOMOTION

Robot locomotion has been studied quite extensively, though each study was typically designed for one type of robot that locomotes in one particular way in one particular type of environment. For example, many three-wheeled synchro-drive (all wheels are driven synchronously and turned synchronously) robots such as those built by Nomadic Technologies, Real World Interface, and Denning Robotics have been used to study path planning and obstacle avoidance in an indoor setting. The CMU Ambler is a very different, large six-legged robot built to traverse Martian like terrain. While the three-wheeled robots cannot traverse over a one cubic foot boulder, the Ambler cannot traverse through a standard 10-foot-wide building hallway. Size is just one factor in determining the suitability of a form of locomotion for a given terrain. Different areas of terrain may pose different constraints to locomotion.

A reconfigurable robot would be able to reconfigure itself to use different modes of locomotion to adapt to different terrains. This adaptability can be very important. A Mars exploration mission is one example. If a robot sent to Mars is not well suited to the type of terrain in which it lands, the mission could be an expensive failure.

To illustrate the potential difficulties, consider Dante II, an eight-legged robot that uses statically stable locomotion. Dante made news history in August 1994 by descending to the bottom of Mt. Spur, an active volcano in Alaska, something that had never been done. One of the missions' secondary goals was as a preparation for a possible Mars or moon exploration mission. There are many interesting locomotive issues in this event. The terrain was extremely difficult including steep slopes, large boulders, falling boulders, soft soil, and harsh temperatures. As the robot returned from the bottom, it fell over onto its back helpless. This occurred despite being teleoperated and having the aid of a support tether. This mission followed Dante I, another eight-legged robot which was to descend into Mt. Erebus, a volcano in the Antarctic. Dante I broke down after descending 21 feet past the rim in January 1993.

Our study of locomotion comes in two parts, a generalized study of statically stable locomotion by the creation of a taxonomy of locomotion, and an analysis of some of the parameters that are used to evaluate the suitability of locomotion modes for different locomotion tasks. There has been a great deal of study on animal locomotion. The text by J. Gray [Gray 1968] has served as a guide for many researchers on this subject. The main purpose here, as with other texts on locomotion, was to study each type of locomotion separately, and not to generalize. In these animal locomotion texts, the implicit classification is based on animal type, i.e. invertebrates, vertebrates, mammals etc. In our taxonomy we will use a more mechanistic view since we wish to include mechanisms as well as animals. For vehicle locomotion an analogous book to Gray's text has been written by Bekkar [Bekkar 1969]. There has been a significant amount of work in studying wheeled and tracked locomotion on rough terrain as there are over 900 references in Bekkar's book. In this sense his book also serves as a survey of the state of the art in mechanical locomotion in 1969. Bekkar also briefly covers legged locomotion and screw locomotion although he makes little attempt at generalization.

3. REVIEW OF MODULARITY AND RECONFIGURABILITY

Very often the terms modular and reconfigurable are meant to describe different things. Here we make our meaning clear. Modularity: Modularity is defined as the characteristic of being constructed of a set of standardized components which usually can be interchanged. We wish to examine unit-modularity. Unit-modular describes a system which is composed of a single type of repeated component. As implied, systems may have varying degrees of unit-modularity. Single type modular systems would be at one end of the scale (true unit-modular), systems with two types less unit-modular, etc.

For an autonomous robot, a system with at most one of each type of module should contain all the components needed to be autonomous; this minimum set could be an autonomous robot in itself. Reconfigurability: Reconfigurability is a nebulous term which has often been used to mean different things in robotics. The three most common definitions are as follows:

- the ability to attain the same end-effector positions in manipulators with grossly different joint positions, for example, elbow-up and elbow-down configurations in articulated arms
- the ability to rearrange a robot's physical components
- the ability of the robot to rearrange its own physical components.

We will be using the last definition. Dynamically reconfigurable in this sense means the robot may reconfigure itself on-the- own. Its opposite is manually reconfigurable which means another agent (human or robot) must reconfigure the robot.

4. CHARACTERISTICS OF RECONFIGURABLE MODULAR ROBOTS

There are many advantages to having a system built up of unit-modules. These include:

- **Manufacturability:** Reducing the number of operations for individual parts simplifies manufacturing, making them easier and cheaper to build. Repeating modules reduces the number of operations for a mechanism of comparable complexity. Economies of scale come into play and making many modules becomes feasible.
- **Redundancy:** Unit-modularity usually implies highly redundant systems since many modules are available due to the ease of manufacture.
- **Repairability:** If a module fails, it is easy to replace the module since there are many of the same kind. Reconfigurability adds the characteristic that the system can be self-repairing.
- **Robustness:** Redundancy and repairability combine to add to the robustness of the system. Redundancy alone does not necessarily increase robustness as adding redundant components adds more components that can fail. There are two properties which mitigate against this. First, modules can each be made very simple which usually results in a higher robustness per module. Second, typically each module in a system has a limited effect on the overall performance; thus the failure of one module is not catastrophic. The result is a gradation of failure instead of a catastrophic one in non-redundant systems.
- **Ease of design:** Modularity has always been useful as a way of breaking down complex systems into simpler modules to help in both design and analysis (which are tightly coupled).

Another property of highly redundant modular robots is that each module usually has a relatively limited workspace. This is often a result of the small size of each module relative to the overall robot. For revolute joints, the range of motion is typically on the order of 20 degrees and usually less than 45 degrees (which is the range of the robot segments). These robots rely on the serial chaining of modules to attain much larger workspaces.

CHAPTER 2: DESIGN

Unlike the modular reconfigurable manipulator systems previously described, a unit-modular robot must have all major components on one module. That is link structure, actuator, interconnection mechanism, computation and power must all be on every module. This is the first requirement of the design, full functionality. In the case of robot, we separate out the power requirement. We have one module called a segment which contains all components except a power supply and a second module called a node which holds the power supply. Any robot or electro-mechanical system can be broken down into three parts: the electrical hardware, the mechanical hardware, and the software. Software is easily changeable and great improvements can be achieved with better software; however, the best that can be achieved by software is always limited by the hardware. Thus, the first design philosophy of this robot was to build hardware that was the least limiting in the types of tasks that it could achieve.

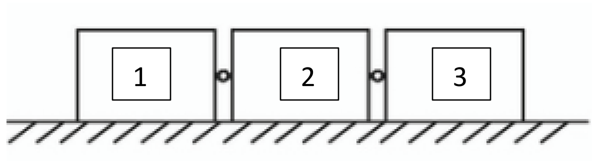
Two items that partially define the suitability of a robot to specific tasks are the degrees of freedom of the robot and the size of the robot. The size has two conflicting roles: 1. the robot must have a large enough workspace to reach all points necessary, 2. the robot must be small enough to be contained within the boundaries of the environment and easily avoid obstacles.

Since this robot is modular, to achieve large workspaces we may add as many modules as needed (assuming we have a very many of them). However, to be useful in constrained environments, we need these modules to be as small as possible. Considerable effort was put into making the modules small while still cost effective. The result is modules that are less than 10 cubic inches (2.5in. on a side) that cost less than $100.00 each. For mass produced modules, the cost and possibly size could be reduced dramatically. The design goals for the robot modules are summarized below:

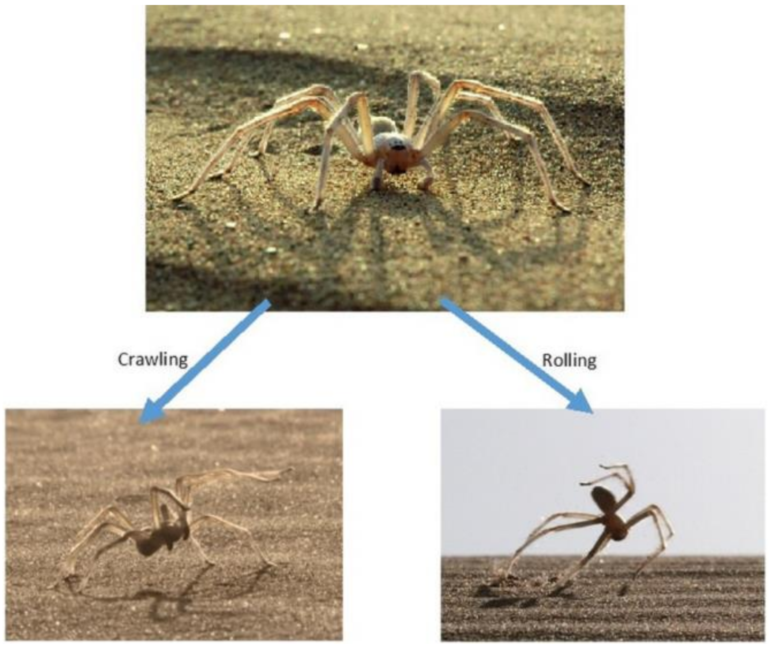
1. Full functionality in one module.
2. Minimum size.
3. Manufacturability (to make many modules feasible and cost effective)
4. Minimum cost (limited available funds)
5. Although stiffness of the structure, and strength and speed of the actuator is not critical for statically stable locomotion, these were also desirable.

Is it possible to be too small? While a small size is one of the overriding goals, we are limited by the available tools and parts. For example, there exist very small motors and transmissions, on the sub-centimeter scale. However, their cost is prohibitive. Micro-structures and actuators (on the micrometer scale) using silicon wafer technologies are an interesting possibility for the future. But at present, integrating them into a fully functional module is not feasible. The two types of modules of the robot, segments and nodes, are shown in Figure 2.1. The next two sections describe the segment and the node, respectively. They are followed by sections on the interconnection system and manufacturability.

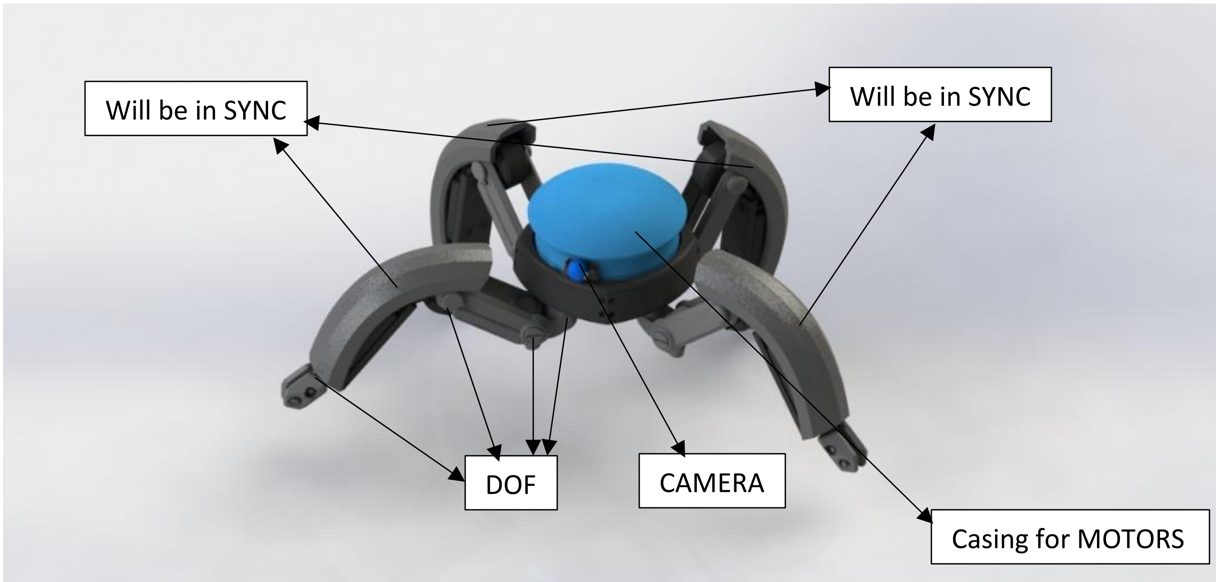
I. SYSTEM DESCRIPTION



PART 1 & 3:



The design of Spider robot is based on the real huntsman spider introduced above, which is capable of crawling and rolling. The huntsman spider has eight legs, but we simplify the design to four legs which are sufficient to perform crawling and rolling. It is observed that the Spider robot consists of four legs (tibia), four servo covers and joints (femur), four main joints (coxa), and a body. The processor, controller, and sensors are placed inside the body.

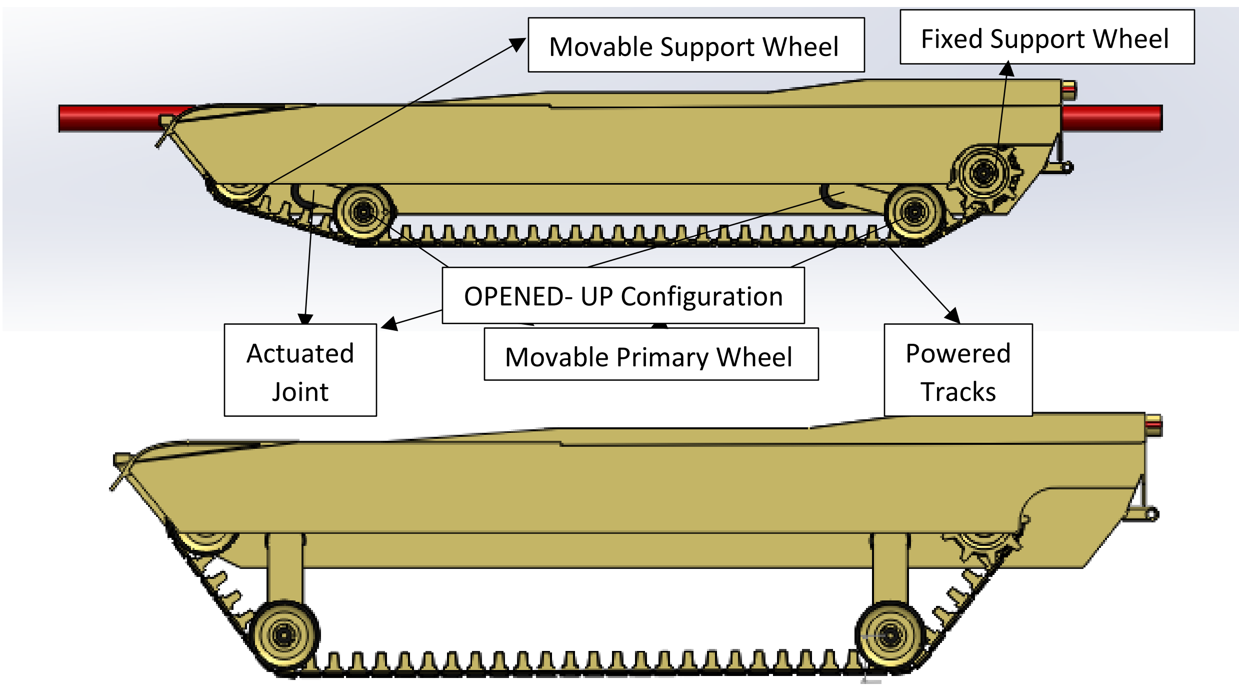


We have 1 camera and 4 legs, with diagonally 2 legs in SYNC. Hence, we have 8 DOF per module. Also, we have a groove for the camera which enables the camera to rotate 360^{o} which gives more accuracy and precision for the movement. 8 servo motors are used in this Spider robot to generate locomotion. Each leg is mounted with 4 servos, so it has 8 degrees of freedom. These legs are able to rotate and transform from crawling to rolling gaits.

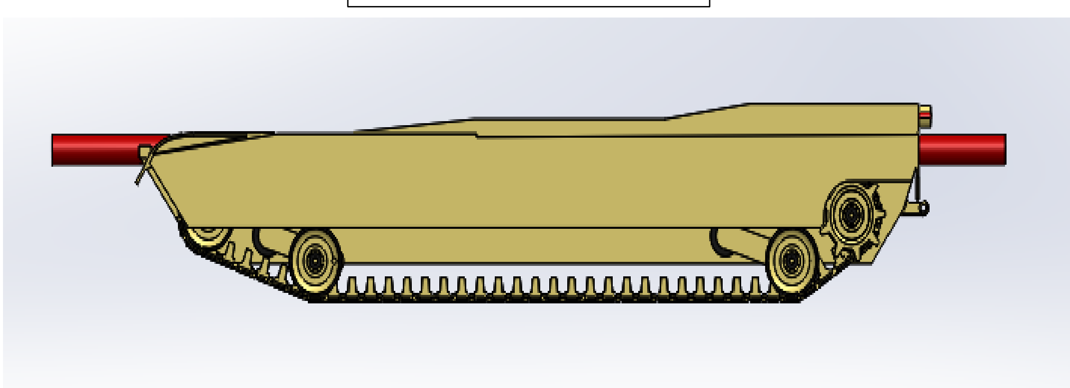
For crawling motion, the Spider robot opens up its four legs. The crawling involves 3 degrees of freedom. Due to twist degree of freedom just below the body, the robot is able to move sideways. Transformation from crawling pose to cylindrical exoskeleton for rolling requires a motion of 4 degrees of freedom. The Spider robot uses its legs to push from the ground and shift the center of gravity to achieve the rolling motion with 1 degree of freedom. The rolling speed of the Spider robot doubles the rate of crawling speed.

PART 2:

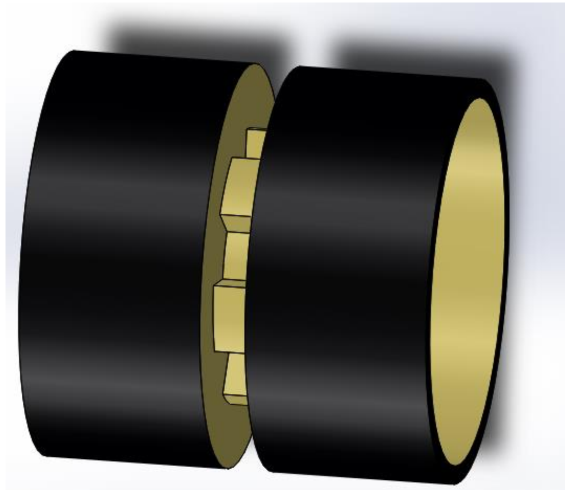
The mechanical structure of the module which has two powered tracks, a serial mechanism, a parallel mechanism. Two DC motors drive the tracks providing skid-steering ability in order to realize the flexible omni-directional movement.

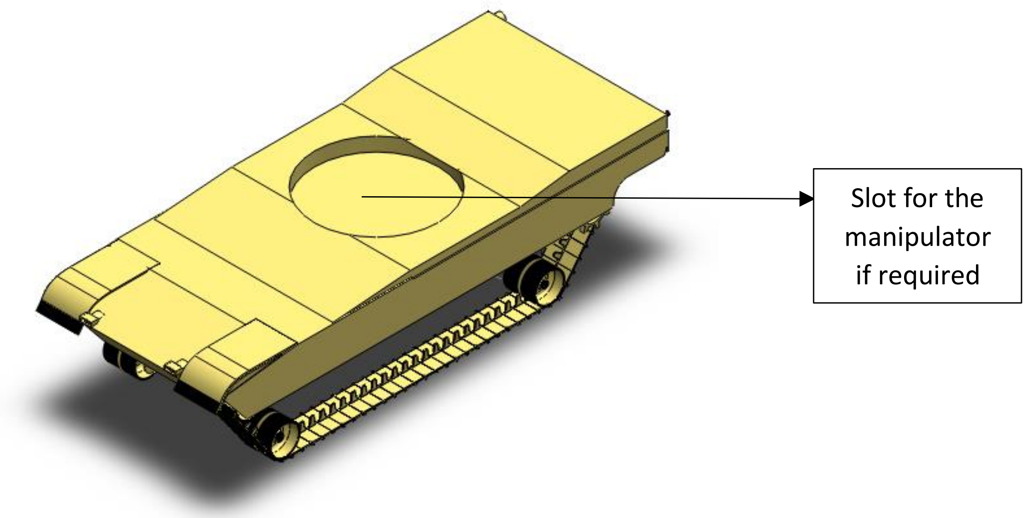


RETRACTED Configuration



Wheel CAD Image





All the movable primary wheels and movable support wheel of one side move in coordination and are governed by a single actuator. Whenever we want it to climb a higher obstacle, the actuated joint will open up and make the movable wheel vertical. But to accommodate this change only, we have to keep the length of the powered track variable. Hence, to remove this constraint, the movable support wheels will

move towards fixed support wheel in such a way that the length of the powered tracks will remain constant.

II. ACTUATORS

The type of actuator chosen to drive the four-bar linkage is decided by two factors, size and cost. Pneumatic and hydraulic actuators are out of the question if the robot is to be autonomous, since carrying around a large compressor would not be feasible. Furthermore, there is too much loss in valves and actuators to use pressurized cartridges. In addition, the connectors required for reconfigurability would be costly and large.

Shape Memory Alloy (SMA) actuators are an interesting new actuator. However, control and range of motion make them difficult to use. They also require precise temperature control which is difficult in uncontrolled environments.

Piezo-electric motors are another promising new actuator technology, but cost and availability precluded its use.

Electrical motors are by far the most prevalent in the size range of interest. And of these, DC brush motors are the smallest and cheapest. So, we choose these actuators.

CHAPTER 3:
DESIGN FOR MANUFACTURABILITY

One advantage of unit-modular systems over standard modular systems is the ease of manufacturing due to repeated parts. The design of all the structures within each module as well, was done with this in mind.

The segment is made up of sixteen machined parts, the node is made of eighteen. Of these thirty-four machined parts only five are unique. To achieve this small number, symmetries in the structure were exploited. For example, the node is a cube with six identical faces, one part can be repeated six times. Each piece was designed to be machined on a three-axis CNC machine. Multiple copies of each piece could be made with one or two simple fixturing.

The design of the segments as a ten-bar linkage is also easily modified to be made out of sheet metal or by an injection molding process to make very low cost large scale manufacturing feasible.

CHAPTER 4:
FUTURE WORK

In this design proposal, a lot of work is remaining. Stress analysis is required to support the design. Also, the dimensions need to be calculated. Bill of Materials (BOM) need to be calculated. Also, we need to find different materials for the different parts of the body to handle the various stresses.

Cost analysis need to be done, i.e., how much it will cost to manufacture the prototype and products. Also, we need to calculate how small modifications in such design can help us to use it inn different terrain. Also, the feasibility of reconfiguring the legs of spider robot into wheels needs to be verified.