Modular Robot Climbers

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***Abstract*— The goal of modular robots is to achieve versatility in the field, while satisfying any number of traditional robot tasks. We chose the task of traversing terrain by climbing, and present various methods of climbing with modular robots. In particular, we focus on the tasks of climbing across a horizontal rope, climbing up a vertical rope, and climbing up stairs using the Superbot modular robot. The horizontal rope climber has successfully traversed a 20 meter rope at various inclines, while the vertical rope climber has successfully climbed the height of a 6 story car park on a fully charged set of batteries in under an hour.**

I. INTRODUCTION

A modular robot can be defined as a robotic system constructed from a set of standard components known as modules. The motivation behind reconfigurable modular robotics is to design a robot capable of adapting its configuration or topology as well as its locomotion and manipulation based on the environment and the corresponding objectives. Systems such as Conro [1], Superbot [2], M-Tran [3] & Polybot [4] have successfully demonstrated the versatility of modular robots in accomplishing complex tasks in unstructured dynamic environments, yet locomotion and manipulation in certain terrains still remains a challenge.

Locomotion is an interesting challenge in modular robotics as it involves the interconnection of several modules to overcome limitations of a single module such as power, size, torque and actuation precision. Wheels, tracks, paddles, legs and arms can be formed with modular robots enabling a large number of gaits for traversing diverse terrain. Wheels can be attached to each module and are best suited for traveling fast over smooth surfaces as demonstrated by ACM-R3 [5]. Tracks formed by closing a chain of modules enables tackling slightly rugged terrain as demonstrated by Polybot G2 [6]. Paddles can be used in aquatic terrains and also in conjunction with wheels as demonstrated by Superbot [7]. Legs and arms [8] cover the most complex repertoire of gaits geared towards tackling a variety of problems ranging from traversing jagged terrain to reaching higher ground.

In typical modular robotics applications such as reconnaissance, inspections of hazardous environments, exploration and search & rescue [9], dynamic three dimensional environments almost always present obstacles such as hills, dunes, plateaus, walls and landings. Sloped surfaces, stairs, ropes and cables can be utilized in such scenarios to traverse the terrain. It is immediately apparent that the task of climbing is challenging for any robot, as it involves overcoming strong gravitational forces by possibly exploiting friction or suction with its actuators. In contrast to a custom-built robot, a modular robot has some advantages which could aid in this task, while there are some disadvantages which need to be mitigated to ensure success.

The scalability of size by altering the number of modules and the dynamic reconfiguration of the shape of the system are great strengths of a modular robot that would yield an appropriate design for almost every situation. For example if the robot was to climb a rope the configuration could contain long arms, while longer legs would be preferable for stair climbing and these could be scaled based on the thickness of the rope or the dimensions of each step. The addition of modules could result in increasing the degrees of freedom, which is quintessential for transferring the center of mass of the robot to the desired location. For example in a multi-legged walker the center of mass needs to be shifted to compensate for lifting a leg which is in contact with the surface. However, modularity comes at the cost of each module being restricted by its weight, fixed dimensions and maximum torque. The torque generated must be able to carry more than the weight of the module to be useful in most climbing tasks, while the height determines the leverage and the surface area & texture determine the frictional forces. In most cases these problems can be circumvented by the use of an appropriate number of modules in a suitable configuration, such as connecting modules in parallel to increase the actuated torque. The greatest advantage of a modular system would be its ability to autonomously transform or self-reconfigure so as to adapt to the environment, yet we will exclude this research from this paper as it is outside the scope of the immediate task of climbing.

This paper presents two gaits for rope climbing demonstrated on the Superbot modular reconfigurable robot and one gait for climbing stairs demonstrated with the Superbot simulator built using the Open Dynamics Engine [10]. In addition to this research, modular climbing robots such as the Polybot have successfully demonstrated climbing a wire fence as a caterpillar (Fig. 1 i) and climbing stairs as a rolling track [11] (Fig. 1 iv), while M-Tran II demonstrated climbing with the aid of helper modules (Fig. 1 ii) and Superbot demonstrated climbing a sand dune [12] (Fig. 1 iii).

The rest of the paper is organized as follows: Section II reviews the overall design of a rope climber, and in particular subsection *A* describes a gait known as the “horizontal rope climber” for climbing a rope which is tied horizontally, while subsection *B* describes a gait for climbing a rope tied vertically called the “vertical rope

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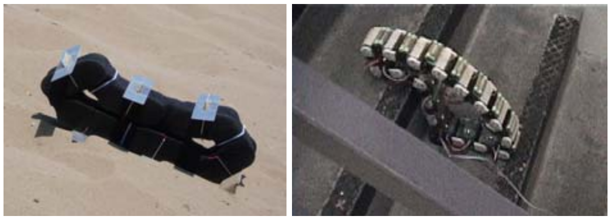
(i) PolyBot fence climber (ii) M-TRAN II Climbing up



(iii) Superbot sand climber (iv) PolyBot rolling up stairs

Fig. 1 Several modular climbers

climber”. Section III describes a versatile modular robot configuration named the “stepclimber” and a gait for climbing stairs known as the “stairclimber”. Finally, the conclusion and future work are discussed in Section IV.

II. Rope Climbing

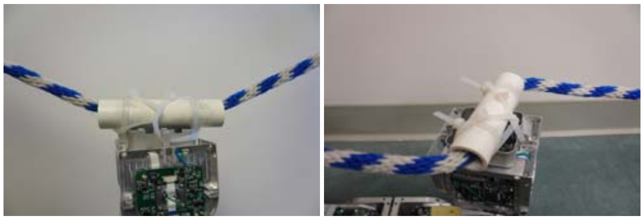
The rope climbing tasks have not been implemented in the field of modular robotics, but some project demonstrations can be found online [13]. We have implemented a gait and method for traversal of a rope in the horizontal and vertical cases, referred to as the horizontal rope climber and the vertical rope climber respectively. The gait in both cases is essentially the same general movement, an inchworm type movement, but using a different number of modules and different methods of gripping the rope in each case. The primary considerations in a rope-climbing action are the gripping attachments used to traverse the rope and how to deal with changes in rope tension.

The inchworm gait essentially works by alternating gripping between each connector and sliding the other end along the rope in the desired direction. Much of the attention in developing the rope climbing action was on getting the attachments to grip and release at the appropriate times and consistently.

A. Horizontal Rope Climbing

In the horizontal climb, we use a 3 module configuration as seen in Fig. 2 i. At each end of the worm configuration, a PVC pipe is fitted with the rope fed through it as seen in Fig. 2 iii & iv. The 3 modules are needed to perform a twisting action at each end. The gripping action is accomplished by twisting the desired pipe attachment to increase the friction with the rope and thus put it into a fixed contact.

(i) Configuration (ii) Rope distortions create a valley



(iii) PVC pipe connector (iv) Twisted connector

(v) Climbing a 20 meter rope tied around pillars at the top of a structure

Fig. 2 Horizontal rope climber

Most of the difficulty associated with horizontal rope climbing is the varying tensions in the rope. Since the rope is strung up horizontally, there is a valley towards the middle in Fig. 2 ii. If the robot is added to the rope, the valley is further distorted. The tension and forces experienced by the robot change depending on where the robot is located on the rope.

Towards the center of the valley, this is the closest to ideal conditions since the tension on the rope is lowest and the forces experienced are near vertical and in equilibrium. As the robot climbs up the valley, the tension on the rope increases and the rope reaction force is no longer perpendicular to the robot length since the robot is now starting to climb upwards.

In addition, the twisting of one pipe to create friction further distorts the rope locally and creates unwanted friction on the other pipe that is supposed to be loose. The twisting action changes the direction of the rope locally with respect to the robot orientation so the “loose” pipe is fighting against this. Because of these difficulties and the choice of gripper attachment, the horizontal rope climber is only successful while in the middle of the valley. When the

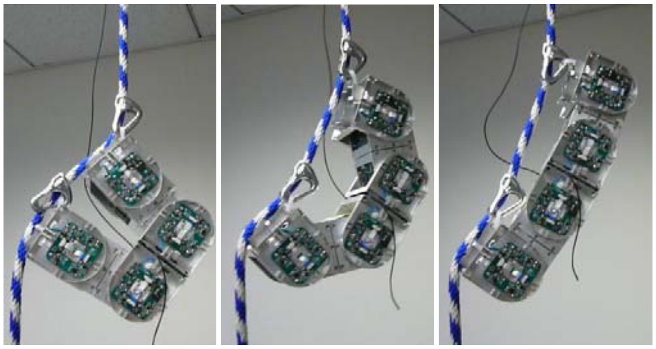


Fig. 3 Vertical rope climbing sequence

Fig. 4 (i) Climbing ascender (ii) Attached to Superbot

robot is on the sides of the valley, it either fails in making progress or slides toward the middle. The horizontal rope climber has been tested by crossing a 20 meter wide gap using a rope at various inclines (Fig. 1 v).

B. *Vertical Rope Climbing*

For the vertical rope case, a different attachment is required since the PVC pipes in the previous gait cannot create the friction required to hold the entire weight of the robot vertically. Consequently, only 2 modules are necessary since we no longer require the twisting action. This climbing sequence is shown in Fig. 3.

The gripper attachments in this case are two standard utility ascenders which are typically used in rock climbing activities. The particular device we use is the Tibloc ascender from Petzl. The Tibloc is a single steel piece seen in Fig. 4 i, with a loop for a carabiner and spikes to grip the rope when pinched. The ascender has two functional states, the grip and the lift. In the grip, a carabiner is pulled down on the loop and thus pinches the rope against the spikes which will hold the rope in place and allows a great deal of weight to be placed on the ascender without slipping or tearing. In the lift, the carabiner is pulled up in the loop, releasing the pinch on the rope and pulling the ascender in the opposite direction of the spikes, sliding the ascender up the rope. For our application, in place of a carabiner, we use a zip-tie fit through a metal pipe with the same diameter as a carabiner as seen in Fig. 4 ii. The zip-ties are required to be loose so that they can slide up and down in the ascender to alternate between the lift and grip states.

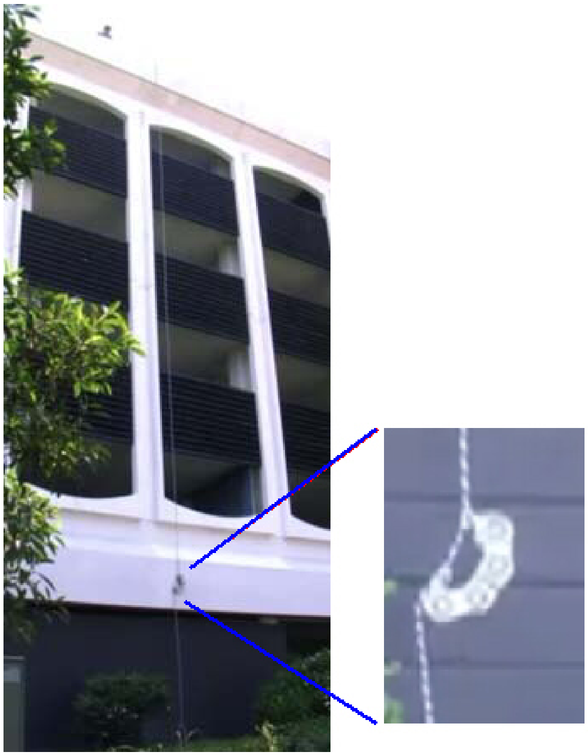


Fig. 5 Climbing 6 floors on a rope

The tension of the rope also varies in this climbing method and is a function of the location of the robot along the length of the rope. If the robot is low on the rope, the tension it experiences is low, but if the robot is high on the rope, the tension is higher because the entire weight of the rope below it is exerting a force. Further, the weight of the robot adds tension as well. If the top attachment is gripping the rope, the bottom attachment will not experience the tension created by the robot weight. However, if the bottom attachment is gripping the rope, the top attachment will still experience the tension caused by the robot weight.

These changes in tension cause difficulties. For one, if the tension is not high enough, the gripper has difficulty releasing the rope as well as catching the rope early once the robot pulls the ascender downward. Also, if the tension is too high, the ascenders will not release the rope at all and the robot will make no progress. For this latter problem, the high tension can be mitigated by increasing the torque on the motors, but the problem will eventually return for sufficiently long ropes. The problems caused by low tension at the bottom of the rope can be mitigated by adding a light weight to the rope bottom or starting the robot a little higher up on the rope.

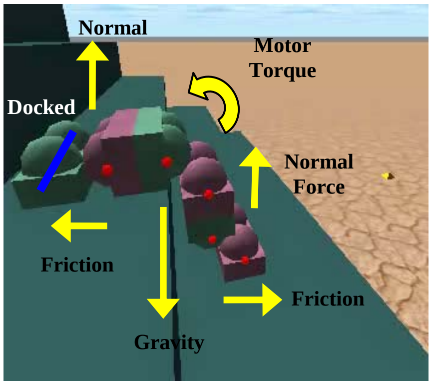


Fig. 6 Forces acting on the modular step climber

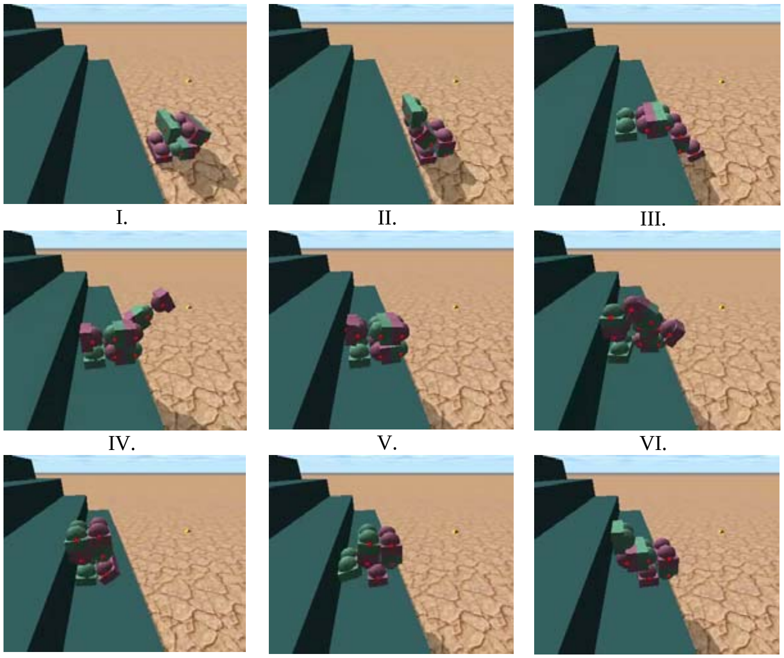
The robot's orientation on the rope is a function of which gripper is attached to the rope. The robot hangs at an angle to balance out the torques in each case as seen in Fig. 5. The simple inchworm action is sufficient to progress the robot up the rope as long as the motor torque is strong enough to overcome the stiffness from the rope tension. This configuration may also work in the horizontal case and solve the previously mentioned problems, but still needs to be tested. The vertical rope climber was able to climb from the bottom to the top of a rope attached to the side of a 6 story car park (Fig. 5) in 51 minutes on a fully charged set of batteries.

III. STAIR CLIMBING

Stairs consist of steps, which are quite common in most urban structures, but can even be found in archeological sites. In comparison to rugged terrain this provides a more systematic environment which could be traversed by a dynamic or static gait. There are several stair climbing designs that could be assembled with a modular robot. Custom-built climbing robots typically take the form of large legged walkers or track-based. The limitations in the torque and dimensions of each module generally rule out the possibility of mimicking a successful custom-built climbing robot. Looking at the problem from the modular robotics perspective requires a comprehensive understanding of the physics of the environment and the capabilities of the modules.

Consider the dominant forces in the system highlighted in Fig. 6. For the climb to be successful the motors within the modules must generate a sufficient force in the direction of the normal forces to overcome gravity, while ensuring that the frictional forces remain balanced. This is true even if the modules form long legs or a track. The ratio of the dimensions of each module against each step is an important consideration as it determines the number of modules that can be resting on the surface of each step, directly affecting the contact friction and also the run distance of the gait. The contact friction must be maximized to prevent the robot from sliding down the stairs under the influence of gravity.

TABLE 1 STAIR CLIMBING SEQUENCE


I. II. III.
IV. V. VI.
VII. VIII. IX.

The length of each module and the number of modules would determine the height that the robot could reach known as the rise, yet this would affect the weight of the robot thereby requiring the actuators to generate larger forces to overcome the increased gravitational force.

The configuration in Fig. 6 contains 6 Superbot modules with two 3 module caterpillars docked at the top most adjacent faces (hinged) and is referred to as the "stepclimber" configuration. This is a compact yet versatile configuration capable of utilizing at least four gaits for locomotion, namely caterpillar, double rolling track, biped walker and the stairclimber gait. On a modular robot it is possible to determine the number of modules a single module could translate while doing work directly against gravity, this would serve as a limit to its reach.

Table 1 shows a sequence of phases required to move the robot up to the next step. The first phase is to stand all the modules vertically (Table 1 II), which can be accomplished as stated in paper on free climbing snake robots [14]. The next phase is to drop the hinged side onto the step (Table 1 III). At this point if the bottom half is raised the entire robot would slide down the steps as the rotational torque would cause loss of contact between the top half of the robot and the higher step (i.e. negate the normal and frictional forces on top). To avoid this each leg must be retracted one at a time (Table 1 IV). Repeatability of gait is of paramount importance for climbing. Towards this, it is visible that the hinge must be moved to the top of the folded structure, which means it needs to be flipped. With automatic docking and undocking, this is a straightforward process. However, if this is unavailable, it can be still be achieved by vertically standing each leg one at a time as shown in (Table 1 VI), then twisting the modules at the bottom to realign with the step so as to increase the stability of standing by pushing away from the wall (Table 1 VII), and finally, simply raising the hinged side as before (Table 1 VIII). Several steps can be parallelized to exploit the momentum of the system and subsequently increase its efficiency such as moving one leg prior to the completion of the movement of the other.

It is important to note that this gait was tested in simulation using real world physics due to time and resource constraints. The length of a Superbot module is approximately 17 cm, while the height and width of a typical step in our laboratory are 18 cm and 24 cm respectively. Several experiments were conducted by varying the height of each step and the gait performed well for heights between 16 cm to 20 cm. However, it is suspected that there is both a lower bound (not less than 12 cm due to hindrance caused by restricting the motion of each module) and upper bound (not more than 24 cm due to loss of contact) to the rise based on the height of each module, but these limits are yet to be determined experimentally. The run size has been varied from 22 cm to 28 cm and seems to be bounded such that at least 1.5 modules must rest on each step for the repeatability of the gait.

The payload can be increased by extending the configuration sideways by attaching more caterpillars. Experimentally this has resulted in an increase in stability as the motors in parallel increase the overall torque in the system. The energy efficiency can be improved by transferring momentum between legs through improved timing as well as commanding the motors to more appropriate angles, rather than driving them to joint limits resulting in the PID controller generating maximum torque. The velocity of the climb is governed by the speed of the motors and the tradeoff made for generating sufficient torque for lifting connected modules.

In comparison to a long legged walker or a rolling track, the stepclimber configuration and its stairclimber gait is compact and more stable against falling sideways on a step, with the ability to switch between several gaits [15] when necessary.

IV. CONCLUSION & FUTURE WORK

This paper presents three gaits demonstrated on the Superbot modular robot to accomplish the task of climbing across or reaching higher ground in dynamic three dimensional environments. The horizontal rope climber gait uses two cylindrical appendages with the rope going through it attached at the ends of a caterpillar configuration consisting of at least 3 Superbot modules. The gait works by alternately twisting one cylinder and grabbing the rope while sliding the other end forward along the rope. In contrast, the vertical rope climber gait uses special appendages called ascenders with the rope going through it attached at the ends of a caterpillar configuration comprised of at least 2 Superbot modules. The vertical climber gait does not utilize a twisting action to lock the ascenders, instead it inchworms its way up the rope. The stairclimber gait is designed for a configuration called the stepclimber, which is comprised of 2 caterpillars each made up of 3 modules that are docked or hinged at one end. This gait climbs one step at a time by standing up, falling onto the higher step and subsequently retracting its legs one at a time. Since automatic docking is currently unavailable the gait requires an additional sequence of steps to flip it self to ensure the hinge moves to the top for repetitive operation.

In future we intend to conduct several experiments to optimize the performance of the gaits. These include testing the use of ascenders in horizontal rope climbing, measuring the performance of the gaits by increasing the number of modules and its payload, and in the case of the stairclimber to establish metrics on the physical Superbot hardware along with the possibility of using automatic docking & undocking.

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