# Multifunctional SuperBot with Rolling Track Configuration

Harris C. H. Chiu, Mike Rubenstein, Wei-Min Shen

*Abstract*— **SuperBot is a modular, multifunctional and reconfigurable robotic system built for NASA applications. This paper reports the design of the 20 SuperBot modules and experimental results for multifunctional behaviors of a rolling track configuration, including a long-distance (1km) running and a steep sand dune climbing. These behaviors of a single rolling track demonstrate the multifunctional capability and endurance of the SuperBot system and also its ability to work in a rough environment condition.**

## I. INTRODUCTION

ALTHOUGH self-reconfigurable robots are conceptually versatile, fault-tolerant, and efficient for space applications, building, controlling, and deploying such robots in the real world is a very challenging problem. The SuperBot project [1] is a bold attempt at this task. Supported by NASA, the Polymorphic Robotics Lab at the University of Southern California has designed and built 20 deployable modules and conducted many experiments to demonstrate the diversity and multifunction of these modules both indoors and outdoors. These experiments include crawling, slithering, sidewinding, walking, moving in sand, climbing ropes between buildings, and climbing vertical rope from the ground to the sixth floor [6][7]. Although there are only 20 modules in total, the reconfiguration of these modules and the ease of programming with the help of concurrent task management [3] have demonstrated so many different behaviors in a short time. The demonstrations have created sufficient evidences that reconfigurable robotic system can indeed provide multifunction that would require many different special-purpose robots to accomplish.

Transition from a controlled environment to a real-world situation, however, introduces many new challenges to the field of self-reconfigurable robotics [2]. These challenges include efficient performance of locomotion, manipulation, and self-reconfiguration tasks in the presence of obstacles, power management issues, modules mechanical and electronic endurance and reliability in spite of being in contact with a rough environment, dealing with dust, moisture, and strong light sources, designing reliable and strong connectors, sensing and meaningful interactions with the environment, and efficient human-robot interactions and controls.

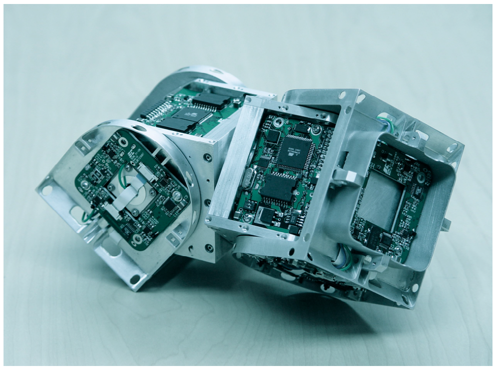

Fig. 1 SuperBot Module Design and Three Degrees of Freedom.

To show the efficient locomotion and the endurance of SuperBot, Superbot is made into a rolling track to have long-distance travel by running 1km in a single charge of battery. The reason of using a rolling track is not only because of its energy efficiency and speed, but also its multifunction with different gaits can be performed with a single configuration. Previous work [4] has shown that the rolling track can roll dynamically for efficient travel by dynamically shape changing and its practicality and efficiency in dynamic rolling [5] suggests a high chance of SuperBot to demonstrate the efficient travel in a long period of time.

In tackling a rough and steep environment, SuperBot is programmed to travel up a sand dune with rolling track configuration. Previously, with a legged configuration of 4 modules, SuperBot is capable of climbing slopes up to 45 degree on hard surfaces. Such experiments have been conducted on carpet boards in office environment and on riverbanks with concrete surface [6]. In [4], it shows the low-deck rolling track is able to climb up a steep hard surface in simulation. However, climbing sand dune is very challenging for legged robots because the sand on a steep slope is so loose that it is difficult to firmly anchor the legs without sliding down.

In this paper, we present a novel deployable and multi-functional self-reconfigurable robotic system called SuperBot. SuperBot is being designed for NASA space exploration programs and addresses the multiple challenges existed in self-reconfigurable robot. To demonstrate the practicality of multifunctional Superbot in a real-world environment, two experiments have been performed to show the efficient performance and endurance of locomotion and the reliability to work in a rough and steep environment. This paper is organized as follows: Section 2 describes the

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Fig. 2. Modules Configured into Different Shapes.

mechanical design of SuperBot modules. Section 3 describes the 1km rolling experiment with SuperBot modules, and the climbing experiments on a large sand dune. Section 4 concludes the paper with discussions and future research directions.

## II. MECHANICAL DESIGN OF SUPERBOT MODULE

SuperBot is intended to operate in a harsh and rough environment, perform locomotion, manipulation and self-reconfiguration tasks in the presence of obstacles in an uncontrolled environment. Therefore, it is essential for the modules to have enough dexterity in order to maneuver around obstacles to perform the task in hand and at the same time conserve energy by minimizing the number of required movements.

To meet these needs, the overall body of a SuperBot module is in the form of two linked cubes with 3DOF as shown in Figure 1. Each cube is of 84 millimeters (mm) in length and therefore each module is 168 mm long. The current prototypes are made up of a hard aluminum alloy and weigh about 800 grams including the electronics and batteries. Each module consists of three main parts: Two end effectors and a rotating central part. This allows a module to have three degrees of freedom in the form of 180° yaw, 180° pitch, and 270° roll. This design gives the SuperBot module the most flexible movements that we know in the literature, and will allow a single module to bend and twist into many different shapes and provide the needed flexibility for multimode locomotion.

There are six (currently manual) connectors on each SuperBot module; one on each side of the end effectors. Any of the six connectors of a module can connect to any connectors of another module in all 90° interval orientations. It is through connectors that SuperBot modules are reconfigured into different shapes in the experiments. Figure 2 shows the 20 modules configured into different configurations.

The drive train of each degree of freedom of a module consists of a MicroMo® DC electric motor, a planetary gearbox, and an external gearbox. The DC motor outputs between 5.0 to 21.18 milli-Newton-meter torque. The gear ratio of the planetary gearbox is 1:86 and its efficiency is 70%. The gear ratio of the external gearbox is 1:5. These result in a maximum of 6.38 Nm torque so that each module can lift two neighboring modules. This has been confirmed by experiments.

Fig. 3 A 6-Module SuperBot Rolling Track and the Changes of its Shape while traveling.

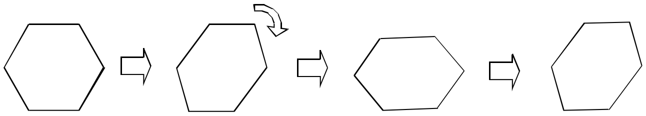

Fig. 4 Traveling forward by deforming its shape.

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Loop:
    1. Get accelerometer readings;
    2. Check sensor value if it falls in one of the six
    ranges
    and determine the state;
    3. Motor angles are assigned according to the state
    detected.
LoopEnd
```

Fig. 5 Distributed Control Algorithm for Rolling Track

## III. EXPERIMENTS WITH ROLLING TRACK

### A. *1-kilometer Run*

To demonstrate the efficiency and endurance of SuperBot, an experiment is designed to enable the rolling track to run long distance (1 kilometer) by going around the building of Information Sciences Institute (ISI) at the corridor of 9th floor in a single battery charge. Each lap is 107m, so it takes the robot 9.34 laps to achieve the 1-kilometer run.

Shown in Figure 3, six SuperBot modules are connected in a closed chain for the rolling track. Adopting the idea of shape changing from [4] and [5], it rolls forward by changing its shape as shown in Figure 4. The chain was initially a hexagon shape. To move forward, the robot changes to a squeezed hexagon shape (a.k.a. American football shape in [5]). With the center of gravity moved forward, the robot rolls. In the meantime when the rolling

TABLE I
AVERAGE REMAINING BATTERY VOLTAGE (V) [A]

| Module | 1st Run (970m) | 2nd Run (1142m) |
|---|---|---|
| Module 1 | 3.63 | 3.48 |
| Module 2 | 7.41 | 5.19 |
| Module 3 | 7.45 | 3.63 |
| Module 4 | 7.43 | 7.23 |
| Module 5 | 7.43 | 6.70 |
| Module 6 | 7.44 | 7.63 |

[a] A fully charged battery has a voltage of 8.2V

track has traveled the length of one module, it changes the shape again to keep the center of gravity in the front to keep the rolling track imbalance so that it can continue to roll forward.

The control of shape changing is implemented in a distributed fashion with sensor feedback. All modules are running the same algorithm shown in Figure 5. Each module first gets sensor values from its accelerometers. The values are divided into 6 different ranges representing 6 different orientations of module with the rolling track in a position shown in the 1st step in Figure 5. Sensors values obtained are then checked to determine the state of orientation of the robot is in. The motors of a module act accordingly to the state the module is in. The gait is synchronized by the proper arrangement of accelerometer ranges and thus the modules do not need to communicate to their neighbors for synchronized actions.

Two runs have been carried out in the office environment with a fully charged battery and running the algorithm described in each module. The turning at the office corridor for going around is done manually. In both runs, the average time elapsed for each lap is about 4-7 minutes. In the first run, the robot ran 9 laps plus 7 meters (about 970 m) in 45 minutes. A power shutdown was observed in a module at the first lap. After resetting the module with the same battery, the experiment continued with no problems occurred for the rest of the run until some of the voltage of batteries run low. Table 1 shows the average battery voltage in individual modules after the rolling track completely exhausted its batteries in one of its modules. Batteries in the other five modules are still in good condition at the end of the run.

In the second run, the rolling track traveled 1142.5 meters in 54 minutes before some batteries became exhausted. In the first 6 laps, the rolling track experienced power shutdown 5-6 times but the experiment continued after resetting the module with the same battery. The exact cause of power shutdown is not completely determined but we suspect that they are due to a high current surge caused by the mechanical motions conflicts between modules in the closed kinematics chain.

From the result, the rolling track is capable of running a 1km within an hour in a single charge of batteries. The performance can be further improved with higher stability and robustness of the gaits with better software parameters. Video clips of the experiments can be found at the following website:
http://www.isi.edu/robots/superbot/movies/rolling1km.avi

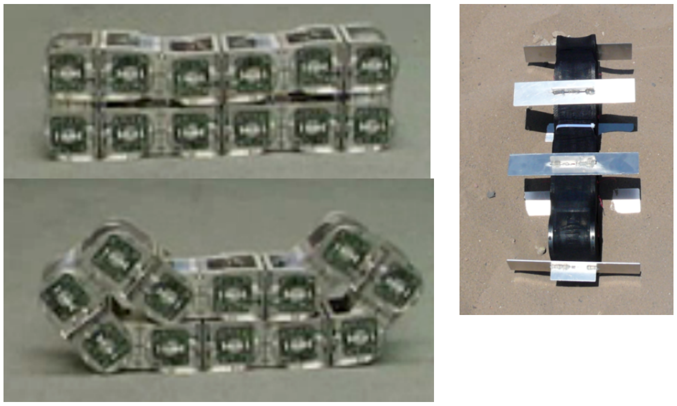

Fig. 6 The Two Shapes of the Climbing Rolling Track

### B. *Sand dune Climbing*

Another experiment is to show the ability of SuperBot to work in rough and steep environment. An experiment of climbing up a sand dune is performed. The sand dune for SuperBot to climb is located at the Sand Dune Park in Manhattan Beach, California (33°53'55.75"N 118°24'45.11"W). The dune is made up of dry, fine sand, with an average slope of 20 to 25 degrees from the horizontal. The surface was bumpy with many footprints. A straight path was marked on the dune, directly up the dune, 90 meters long.

The rolling track is again made of 6 SuperBot modules, connected in a loop configuration, which is the same as the one shown in the previous experiment as shown in Figure 6. Each module had its roll and pitch axis aligned and parallel to each other. To overcome the anchoring problem on loose sand, the rolling track was collapsed to keep its center of mass as low as possible. There are 2 shapes for this rolling track, a "U" shape and a Square shape, which are shown in Figure 6. Using communication between modules, the modules will synchronize their actions and move between these shapes in synchrony. For every cycle of these two shapes, the rolling track will move a half a module forward (1 cube). Each module will have a "state", which represents where they are in the rolling track, and what configuration the track is in (U or Square shape). Using its state, a module will know what angle its motors should be at, based on a pre-determined table. One module is chosen arbitrarily and loaded with the "leader" program, and the other 5 modules are loaded with the "follower" program. The leader program will start at state zero, and increment its state every second by 1, modulus 24. It will then send current, (state+4) mod 24, to the module connected to its front dock. The module on the front dock of the leader will update its state to be the value it received, and then continue passing the message forward, by sending (state+4) mod 24 to the module connected on its front dock. The incrementing message is passed in this fashion down the entire rolling track. This messaging scheme will synchronize all 6 modules, and each module will be at a state four ahead (mod24) of its front neighbor. After 24 state changes, the modules will have

Fig. 7 The Overview of the Sand Dune and the Climbing Rolling Track with Sand Protection.

returned to their original position in the rolling track, and the track will have moved 1 meter forward. One full rotation of the rolling track is accomplished in about 24 seconds.

The sand-climbing rolling track was covered in a plastic bag to seal out the sand, and then covered in black nylon to protect and hold the plastic. Six aluminum cleats were secured to the outside of the rolling track, at evenly spaced intervals (see Figure 6). The cleats served two purposes, first to widen the footprint of the rolling track to prevent it from tipping over, second to dig into the sand and adding traction. Without this traction, the rolling track would just roll in the loose sand without reliably making forward movement.

The robot climbed the entire sand dune without any stopping up the full length of the course in approximately 42 minutes. Figure 7 shows the overview of the sand dune and some snapshots of the climbing process. The only human intervention was to occasionally steer the robot, because the robot was not capable of turning in this configuration autonomously. The video clip of this experiment can be found at the website: http://www.isi.edu/robots/superbot/movies/duneclimber.avi

## IV. CONCLUSION

This paper described the SuperBot robotic system designed and constructed for deployable, multifunctional self-reconfigurable robotic missions. We discussed architecture of the SuperBot modules and experimental results for a dynamic rolling track running with speed of about 1km/hour in an office environment and climbing a large sand dune. This has demonstrated the multifunction of SuperBot with just a single configuration, the long traveling endurance of SuperBot and the ability of working in rough environment. Future research directions include fine-tuning the software parameters for multifunctional behaviors, designing and performing more functions in a single configuration, and completing the self-reconfigurable connectors. In addition, we will also complete power-sharing mechanism among modules so that SuperBot can be more robust in terms of power endurance

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