Remotely-Controlled Autonomous TricycleBot Locomotion via SuperBot

Feili Hou, Nadeesha Ranasinghe, Behnam Salemi, Wei-Min Shen

Abstract— **This paper presents a new gait called tricycleBot, which is implemented on a reconfigurable modular robot called SuperBot. In this paper, the design of SuperBot is first reviewed, and then the configuration design and locomotion control of tricycleBot is described. Two different wireless controllers are used to remotely control tricycleBot. Experiment results show that tricycleBot is capable of carrying payloads more than 5 times of its own weight with satisfactory speed. It can also be steered remotely to move forward/backward, turn left/right, and travel over 1 km on a fully charged set of batteries in a carpeted office environment, or over 2 km on a smooth marble surface.**

I. INTRODUCTION

COMPOSED of many modules, a self-reconfigurable robot can change its shape and size to be adaptable to different tasks in an unknown environment. Due to its modularity and versatility, it has potential in many application areas such as fire fighting, battlefield reconnaissance, deep-sea mining.

Depending on the hardware design, self-reconfigurable robots are classified into two types: lattice-type [1-7] and chain-type [7-13]. Compared with the lattice-type robot that moves by a series of reconfiguration, the chain-type robot moves using the joint motors in the modules, which is more efficient in speed and flexibility. Locomotion on a chain-type robot has been studied extensively [14-18], such as the gait of legged-walking, tracked rolling, caterpillar-sliding, etc. These gaits are efficient either in speed or in its ability to carry a payload, but not for both. For example, tracked rolling outperforms others in the speed, but it is difficult to carry a payload. Legged-walking can carry a payload, but the weight of payload will decrease the speed greatly since the motors have to overcome the extra force added by the payload.

In this paper, a locomotion gait called tricycleBot is proposed using SuperBot12]. It can move forward/backward and turn left/right, and can carry a payload with 5 times of its own weight with a satisfying speed. It can also be remotely steered, which is clearly a useful ability for tasks such as environment exploration, or search-and-rescue etc.

The rest of the paper is organized as follows: Section II briefly reviews the design of the SuperBot module, while section III describes the configuration design and locomotion control of tricycleBot. Section IV shows how to use the wireless controller to remotely control tricycleBot. Experiment results are given in Section V. Finally, conclusion and future works are made in Section VI.

II. SUPERBOT MODULE

Each SuperBot module is a complete robotic system and has a power supply, micro-controllers, communication, sensors, three degrees of freedom, and six connecting faces (front, back, left, right, up and down) to dynamically connect to other modules. As shown in Fig. 1, it is in the form of two linked cubes. The dimension of each cube is $84 \times 84 \times 84$ millimeter and hereby the dimension of each module is $168 \times 84 \times 84$ millimeter. The current prototype is made up of hard aluminum alloy, and each module weighs about 878 grams including the electronics and batteries.

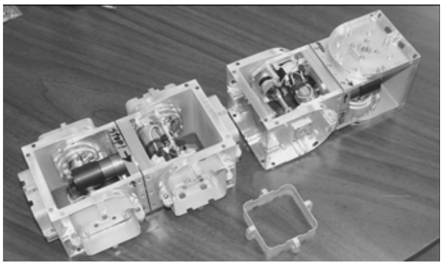

Fig. 1 SuperBot module and connectors

The mechanical design of a SuperBot module is shown in Fig. 2. Each SuperBot module has three joints. The two joints at the end can each rotate 0^{o}~90^{o}, respectively, and the middle joint can mechanically rotate continuously in both directions (currently it is limited by the electronic wires going through the joint and can only rotate 0^{o}~270^{o}). Also shown in Fig. 1 and Fig. 2, each module has six genderless connectors on the six surfaces of the two linked cubes, so that any connector in one module can connect to any connector of the other module in 4 different 90^{o} rotations. Also, any specialized devices or tools can be docked on SuperBot with the same connector.

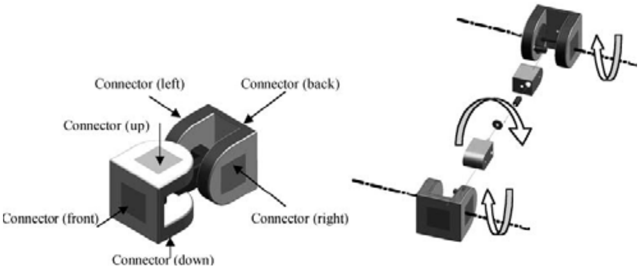

Fig. 2 The mechanical design of a SuperBot module

This design gives the SuperBot module the combined features of many existing reconfigurable robots such as M-TRAN[11], ATRON[13] and CONRO[10], and provides

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the most flexibility for different locomotion and reconfiguration of multi-modules.

III. TRICYCLEBOT LOCOMOTION

A. *Configuration Design*

The locomotion design of tricycleBot was inspired from the canoe paddling. The canoe is propelled on the surface of water through the action of paddling. Similarly, we can attach wheels to the robot, and use the paddling action to propel the robot. The wheeled mode of locomotion is preferred as it provides advantages of energy efficiency and high speed.

Fig. 3 shows the front and back view of the tricycleBot configuration. It is in a "T" shape, composed of three modules, three wheels, and two plastic balls attached to the side modules through pipes. The three unidirectional wheels are fixed at the bottom to maintain balance, and also comply by rolling to move the robot. The two modules on the sides act as two arms, and the attached pipes with balls play the role of paddle blades that swing against the ground to propel the robot. The plastic balls attached to them are elastic, so the stroke of the two "paddle blades" will produce moving power instead of impeding the movement. The middle module can be regarded as the canoe, and its rear part is the stern that is responsible for steering the robot.

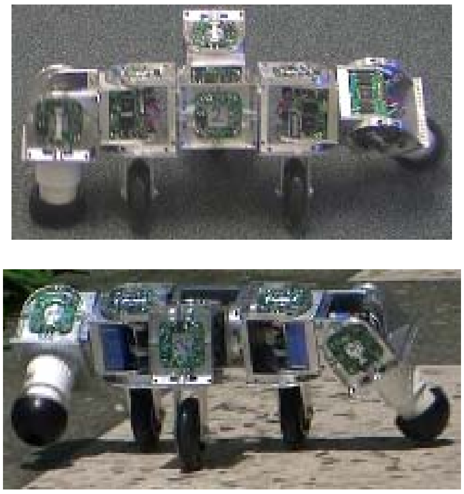
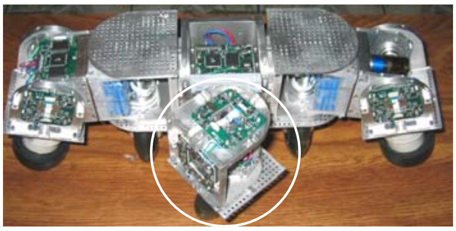


Fig. 3 Front view and back view of tricycleBot gait

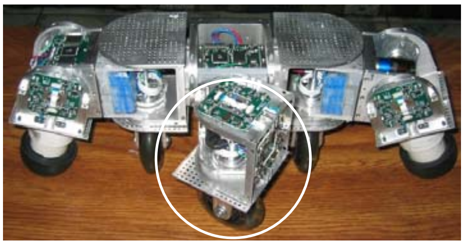
Like the back muscle rotation is the engine to complete the paddling action, the middle joints of the two side modules are rotated to produce the thrust. When moving forward, the "paddle blade" is stretched out and drawn forward, lowered to touch the ground, and brought backward along the side of the "canoe". Unlike the Creep gait [19] that rotates the end joints of the two arm modules' closer-to-center part, here we rotate their middle joints, by which the "paddles" are drawn straight back rather than following the "gunwale's" curvature. Therefore, all the moving thrust is in the same direction as the wheels to propel the robot.

The two "arms" can do the stroke motion either alternately or at the same time. Both arms moving simultaneous can produce the most thrust, but no propelling force is preserved when preparing for the next stroke. In contrast, the two arms moving alternately can propel the robot continuously, since at any time one arm can produce the moving force while the other is preparing for the next stroke. However, the propelling power is lower. Comparison of the performance of these two moving methods is given in Section V.

To make the robot go backward, the two arms have essentially the same movement as going forward, but done in reverse. To make the robot turn left or right, the end joint of the middle module's rear part is turned to steer the direction. When the rear wheel is turned (shown in Fig. 4), the moving force on it can be decomposed into two portions, one in the direction parallel to the front wheels and the other in the direction normal to it. The second portion of the force can make the robot turn left or right.



Rear wheel is rotated to turn tricycleBot left



Rear wheel is rotated to turn tricycleBot right

Fig. 4 Turning of tricycleBot

B. *Payload Carrying*

Usually, there are two ways for the robot to carry the payload: put the payload on the ground and drag it, or put the payload on top of the robot. As we know, when an object moves, the kinetic friction that slows it down equals to

$$f = \mu \bullet F_N \tag{1}$$

, where f is the resistant force, μ is the s the coefficient of friction, and F_N is the normal force exerted between the surfaces. When moving on the flat terrain, F_N equals to the gravity.

Hence, when dragging the payload with tricycleBot, the friction is

$$f = \mu_r \bullet Mr \bullet g + \mu_s \bullet Mp \bullet g \tag{2}$$

, while if putting the payload on top of the robot, the friction is

$$f = \mu_r \bullet Mr \bullet g + \mu_r \bullet Mp \bullet g \tag{3}$$

In (2) and (3), μ_r is the rolling resistance coefficient, μ_s is the coefficient of sliding friction between the payload the and the ground, Mr is the mass of the robot, Mp is the mass of the payload, and $g = 9.8m/s^2$

Usually, $\mu_r << \mu_s$, so it is clear to see that the resistance force in (2) is much smaller than that in (3). Hereby, putting the payload on top of the wheeled robot is more efficient and energy saving.

Fig. 5 Payload carrying

Fig. 5 shows how we use tricycleBot to carry payloads. The two cubes connected to the middle module are used to support the payload. Compared with the KateDemowithJoystick[20], a similar gait that uses wheels for the locomotion of reconfiguration robot, tricycleBot is more energy efficient. In the KateDemowithJoystick gait, the robot goes up and down besides moving horizontally. The direction of the motor motion is against the gravitational forces resulting in energy being wasted. Besides, due to the limit of the motor torque, as long as the weight of payload overtakes the maximum motor force, the robot cannot carry it. In comparison, the paddling action in tricycleBot only produces the forward thrust to move the robot horizontally, without the unnecessary vertical movement against the payloads.

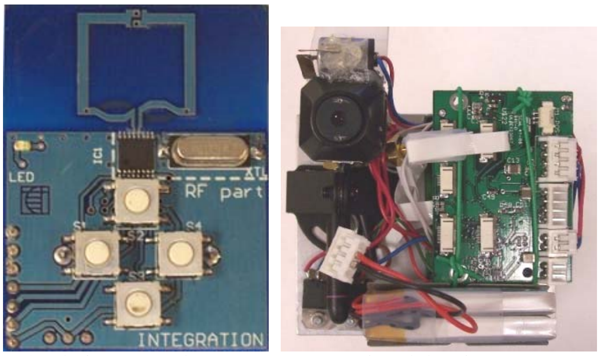
C. Locomotion Control and Synchronization

Distributed locomotion control and synchronization was achieved using the digital hormone method [10]. The middle module acts as the leader and is responsible for sending hormone messages to the other two modules and synchronizing their coordinated actions. Based on their local topology and the received hormone messages, the two arm modules will decide whether to swing the "paddle blade" back or to stretch it out and draw it back to prepare for the next stroke, and move the motor joints to the corresponding positions. By changing the order of the hormones to be sent out, the two arms can be synchronized to move forward or backward, do the stroke simultaneously or alternately. The middle module can also turn the motor in its rear end joint to steer the moving direction.

IV. HUMAN-ROBOT INTERFACE VIA HIGH FREQUENCY WIRELESS COMMUNICATIONS

For the effective use of TricycleBot, the wireless remote controller is designed so as to enable a human operator to alter the robot's motion in real-time. Robot remote control has many potential applications, such as remote production monitoring, remote exploration and manipulation in dangerous environments, etc.

Each SuperBot module has a built in wireless receiver providing outputs to the power circuit and two input pins of the microcontroller. Hence, two four-button handheld wireless transmitters (shown in Fig. 6-a) operating at 315 MHz have been programmed to control power and behavior commands respectively. The power controller allows a user to turn all SuperBot modules on or off simultaneously using two buttons, and while powered, allows toggling power to the motors with the other two buttons. The behavior controller allows the transmission of four uniquely addressable states which is memorized by the receiver each time a button is pressed. Hence, by combining this with the history of button presses, it is possible to transmit several distinguished commands to all SuperBot modules simultaneously. TricycleBot is programmed to listen to the above inputs and respond accordingly (i.e. commanding the gait to turn or move forward by changing the sequence of digital hormones).



(a) Wireless Transmitter (b) WiFi pod

Fig. 6 Wireless communication devices

TABLE I COMMAND TRANSMITTED VIA RADIO COMMUNICATION

Controller	*Previous Button Pressed*	*Current Button Pressed*	*Action*
Power	-	Up	System On
	-	Down	System Off
	-	Left	Motor Off
	-	Right	Motor On
Behavior	-	Up	Move forward
	-	Down	Move backward
	Up	Left	$\theta=\theta-\Delta$
	Down	Left	$\theta=\theta-\Delta$
	Left	Left	$\theta=\theta$
	Right	Left	$\theta=90^o$
	Up	Right	$\theta=\theta+\Delta$
	Down	Right	$\theta=\theta+\Delta$
	Left	Right	$\theta=\theta$
	Right	Right	$\theta=90^o$

Table I details the commands transmitted via radio communication during TricycleBot experiments. In Table I, θ is the motor angle of middle module's rear end joint. $\theta=\theta-\Delta$ ($\theta=\theta+\Delta$) means spinning the driving wheel left (right) a little bit, and $\theta=90^o$ means turning the driving wheel back to center.

In addition to the radio communication devices, SuperBot has a dedicated WiFi pod (as shown in Fig. 6-b) that enables 802.11g bi-directional wireless (2.4 GHz) communications between any SuperBot configuration and an external computer. With our genderless connector, the pod can be docked to any module. It communicates with that module via infrared, using the same inter-module communication protocol used for communications between adjacent SuperBot modules. The pod is also equipped with a color wireless camera with a controllable shutter that continuously streams live video at 2.4 GHz. This video stream can be decoded and fed into a computer which could subsequently perform image analysis. Data gathered via the WiFi and image analysis could then be used to generate a set of actions which are relayed back to the modules via a WiFi router. In our tricycleBot, the WiFi pod is docked to the center module and is used for tele-operation as seen in the picture below.

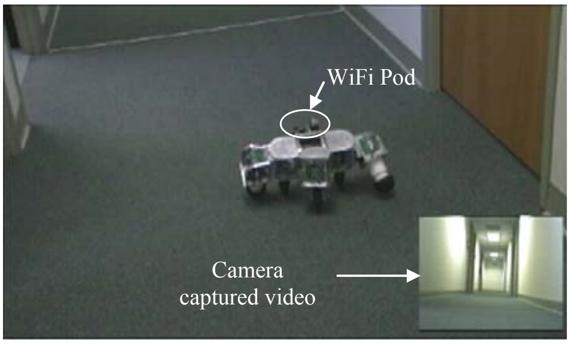


Fig. 7 Tele-operating tricycleBot

V. EXPERIMENTAL RESULTS

We have conducted several experiments to evaluate the performance of tricycleBot. These experiments include the speed measurement on various terrains, energy consumption, payload carrying performance, etc.

In the first series of experiments, we want to compare the speed when tricycleBot's two arms paddle in different ways: alternate or simultaneous stroke. We run tricycleBot on the carpet, and find that the speed under alternate stroke is 0.162m/s, while the speed under simultaneous stroke is 0.158m/s. On the marble, tricycleBot can run 0.311 m/s under alternate stroke, while 0.309m/s under simultaneous stroke.

We made another series of experiments designed to show how the performance of these two locomotion changes with added payloads. As shown in Fig.8, the moving speed on the marble surface is much greater than on the carpet. Also, we can see that when carrying the payload, the locomotion of simultaneous stroke beats the alternate stroke. This is consistent with what we have expected. The explanation is as follows. As we know, the overall moving force that the robot gets is

$$F = F_a - f \tag{4}$$

where F is the overall moving force, F_a is the thrust produced by the arms, and f is the friction. As shown in Fig. 9, when there is no payload, the moving force under simultaneous stroke is greater than that under alternate stroke. However, the time interval to prepare for the next stroke is long. In contrast, the moving force under alternate stroke is less strong but more frequent, since when one arm is preparing the next stroke, the other arm can produce the power to move. When the payload is added, according to equation (3), the kinetic friction f is increased proportionately and hence the overall moving force is reduced the same amount under both locomotion modes. So the moving force in Fig. 9 should be lowered the same amount of height. Since the forces come out more frequently in alternate stroke mode, the area bounded by the force line will decrease more. Namely, the impulse (Force×Time) of moving force. i.e. the shadow area will decrease more for the alternate mode than the simultaneous mode. The impulse of force is equal to the change in the robot's momentum. Hereby, we can see that the speed decreasing rate under the alternate stroke mode is greater than that of the simultaneous stroke mode.

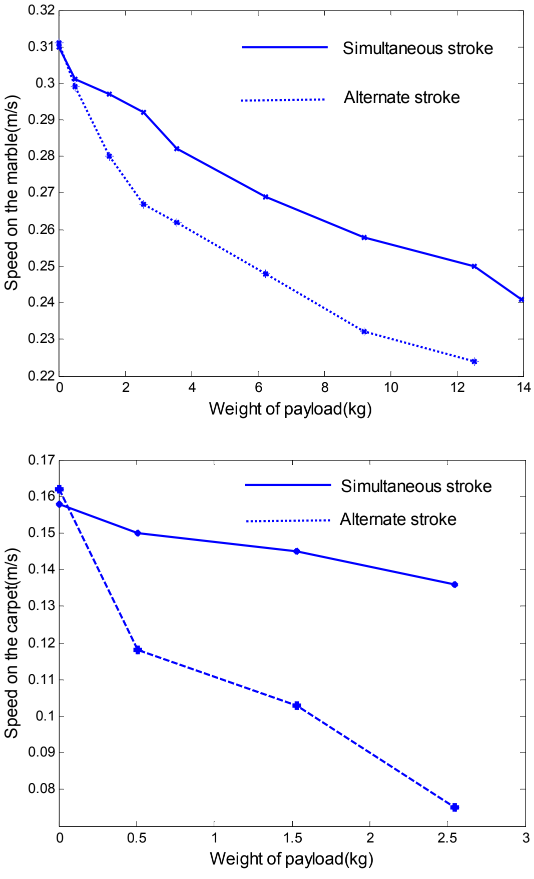


Fig. 8 Speed measurements versus weight of payload

Considering that tricycleBot weights only 2.636 kg by itself, the payload it can carry is impressive. The maximum payload we tried is 13.963 kg, 530% of its own weight. With these payloads, it can run on the marble surface with 0.241m/s, and on the carpet with 0.083m/s. We did not try more weight so as to prevent any accidental damage to the modules. However, from the speed measurement, we can see that for sure tricycleBot can carry much more than 13.963 kg.

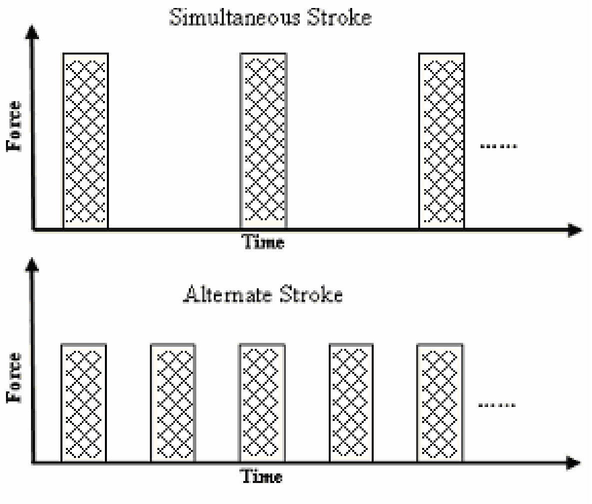


Fig.9 Moving forces under the mode of simultaneous stroke and alternate stroke

Every module runs on the battery with 7.2V, and the total energy required is 15.84W, thus 5.28 W per module in average. The arm modules consume more energy than the middle module, and it is 5.76 W. Therefore, tricycleBot can run for 2 hours, given the battery we are using is 11.52 watt-hour. From the measured speed, we can compute that it can run up to 1166.4 meter on the carpet in the office environment, and up to 2239.2 meter on the marble surface.

For videos of these behaviors, please visit:
Running on the carpet:
http://isi.edu/robots/superbot/movies/Hallway.avi
Running on the marble:
http://isi.edu/robots/superbot/movies/Marble.avi
Carrying the payload:
http://isi.edu/robots/superbot/movies/Payload.avi

We also docked the WiFi pod onto tricycleBot and tele-operated it via a WiFi router in the office. TricycleBot is remotely controlled based on the video stream returned from the camera. It is navigated to go out of an office, turn right and then left to get into another office door on the opposite side at the right, and then back off and make turns to go back into the previous door. For video of this indoor exploration, please visit
http://www.isi.edu/robots/superbot/movies/IndoorExploration.avi

VI. CONCLUSION AND FUTURE WORK

In this paper, a new gait called tricycleBot is presented. It is capable of carrying payloads with satisfactory speed, and can be steered remotely to move forward/backward and turn left/right. Our future work is to connect two tricycleBots head-to-tail to see how it performs. It is like canoe paddling by more people, and is expected to move at a higher speed, however turning would require further experimentation.

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