Wheeled Locomotion for Payload Carrying with Modular Robot

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

Abstract— **Carrying heavy payloads is a challenging task for the modular robot, because its composing modules are relatively tiny and less strong compared with conventional robots. To accomplish this task, we attached passive rollers to the modular robot, and designed a wheeled locomotion gait called tricycleBot. The gait is inspired by paddling motion, and is implemented on the modular robot called SuperBot. Features of this gait are systematically studied and verified through extensive experiments. It is shown that tricycleBot can carry payloads at least 530% of its own weight. It can also be steered remotely to move forward/backward, turn left/right. Capability of tricycleBot demonstrates that the versatility of modular robot can be further expanded to solve very specialized and challenging tasks by using heterogeneous devices.**

I. INTRODUCTION

COMPOSED of multiple modules, modular reconfigurable robots can form a variety of shapes for different tasks. For example, in the search and rescue scenario, the modular robot can walk over rubble piles in a spider configuration, and then penetrate the cracks in a snake-like configuration. Due to its versatility and adaptability, modular robot is potentially applicable in areas such as space exploration, battlefield reconnaissance, fire fighting etc.

At present, different kinds of locomotion patterns on the modular reconfigurable robots have been extensively studied and implemented[1-8], such as rolling track, H-walker, snake and spider movement etc. All these gaits are very efficient and have demonstrated the versatility of modular robots. However, few of them were focused on the problem of payload carrying. Payload carrying is clearly a very useful ability for the robots to perform various tasks. For example, for industrial application, robots with payloads can be used for palletizing, assembling parts etc. For space exploration, robots with scientific instruments can probe and exploit the space environments.

Currently, an only very small payload like a deployable camera has ever been carried by the modular robot of Polybot[1]. It is criticized that the modular robot can not carry heavy payload with satisfying speed due to three facts: 1.The building blocks of the robot, i.e. the modules, are tiny in size and weak in motor torque. When carrying payloads, it is not the total strength from all the modules but the weakest supporting point in the robot that has to be able to support the payload. So, modular robot is delicate in payload carrying. 2. Modules are not specifically designed for the task of payload transportation. It is challenging to design an energy effect gait to overcome forces added by the payload while still move in a satisfying speed. 3. The multiple degrees of freedom make the robot versatile in its potential capabilities, but also incurs a performance tradeoff and increases the mechanical and control complexities for the task of carrying heavy payload.

To expand the modular robot's versatility to accomplish this special task, here we proposed to use the special tool of wheels. Wheels enable lower resistance to motion, and thus are widely used for payload transportation. In this paper, we have designed a wheeled locomotion gait called tricycleBot. It is composed of three homogeneous SuperBot modules[4] assembled in a T-shape, with three rollers attached at the bottom. Locomotion pattern of tricycleBot is inspired from canoe paddling, and is systematically studied in the paper. Experiment result shows that tricycleBot can carry payloads with more than 5 times of its own weight, which is much greater than the module's maximum motor force. Besides, it can be steered remotely to move forward/ backward and turn left/right.

In the field of modular robotics, wheels have only been used in the gait of KateDemowithJoystick[9], while in the field of conventional robotics, wheeled robots have been widely studied. Some robots use active wheels such as Vuton[10], PatrolBot [11] , ATHLETE rover[12], etc, and others use passive wheels, like Roller-Walker[13], biped ice-skater robot [14],etc. Compared with these conventional wheeled robots tailored for the tasks of payload carrying or moving on smooth terrain, the wheeled modular robots may be inferior in the performance, but offer several advantages: 1. Versatility: Instead of only carrying out a single task in a static environment, the reconfiguration ability of modular robot allows it form different configurations to adapt to different tasks. For example, the wheeled modular robot can detach its wheels and reconfigure into a snake robot. Or they can attach with other special devices to climb a rope [15] 2. Robustness: Since robot modules are interchangeable, a faulty module can be replaced by another for self-repairing 3. Low cost: Instead of spending months to design a new mechanical wheeled robot from scratch, we can build the wheeled modular robot just by connecting several mass-produced modules and attaching the wheels through the module's uniform connecting interface, and control the robot using the uniform API (Application programming interface) built in all the modules. It is only days of work.

The rest of the paper is organized as follows: Section II discusses choosing the building parts for tricycleBot, and briefly reviews the design of our SuperBot module, while

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section III describes the configuration design and locomotion control of tricycleBot. Section IV shows how to use the wireless communications to remotely control tricycleBot. A series of experimental results is given in Section V. Finally, conclusion and future works are made in Section VI.

II. BUILDING PARTS

A. Building parts determination

The first thing to build tricycleBot is to choose its building blocks. Should the building modules be homogeneous or heterogeneous? Should we use chain-type robot modules or lattice-type modules? Also, should the added wheels be active wheels or passive wheels? This section discusses all these questions on choosing the building parts for tricycleBot.

Depending on the hardware design, modular robots are classified into two types: lattice-type such as 3D Fracta[16], Molecule[17], ICubes [18], ATRON[19] and Molecube[20], Catoms[21] etc, and chain-type such as PolyBot[1], Conro[2], M-TRAN[3], Superbot[4], CkBot[5], YaMoR[6] etc. 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. Hereby, for our task of payload carrying, we will use chain-type modules as the building block for TricycleBot. It has been demonstrated in [4] that SuperBot module combines advantages from many existing chain-type robot such as M-TRAN, ATRON and CONRO etc, and provides the most flexibility for different locomotion of multi-modules. Hereby, our SuperBot module is an appropriate choice as the building block of TricycleBot.

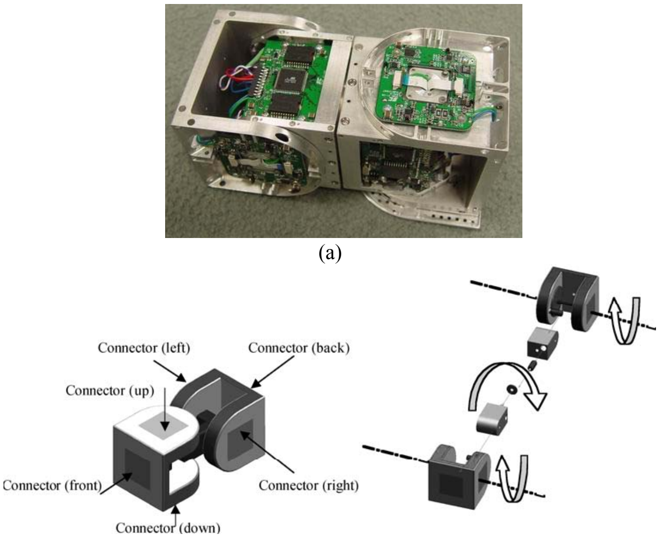
However, SuperBot is a general building block that is not customized for the wheeled locomotion. It is hard for a modular robot made up of homogeneous SuperBot modules to accomplish this special task of carrying payload in a wheeled locomotion. One way to solve this problem is to make tricycleBot a heterogeneous modular robot that contains other modules specialized for this function as well as SuperBot modules. This makes tricycleBot more flexible and functional, but it is expensive to build and maintain it. Individual hardware design and control software are needed for different functions in heterogeneous robot. On the contrary, modules in homogeneous robot are the same and can be mass produced. Controlling homogeneous robot is also simpler since the API is uniform for all the modules. So, to make tricycleBot has the flexibility of a heterogeneous modular robot, and also costless and easily maintainable like a homogeneous modular robot, here we proposed to add heterogeneous devices like wheels instead of heterogeneous robot modules. Heterogeneous devices expand the versatility of homogeneous robot for special tasks but at a low cost. They can be easily attached to the robot via the module's uniform connector, and does not need individual hardware design or software control.

After deciding to use the special tools of wheels in tricycleBot, the last question is what type of wheels to use. Active wheels are powerful and quick. However, installation of active wheels needs actuators, brake mechanism and steering mechanism. This equipment is so heavy that it's not practical solution for modular robot which has many degrees of freedom. So we use passive wheels in our TricycleBot.

B. SuperBot Module

Before describing the tricycleBot configuration, here we briefly review its building block, the SuperBot modules, in this section. 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-a, 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

The mechanical design of a Superbot module is shown in Fig. 1-b. Each SuperBot module has three joints. The two joints at the end can each rotate 0^{o}~180^{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}). The maximum torque of a module is 6.38 Nm. Also shown in Fig. 1, 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. Other heterogeneous devices or tools can also be docked to SuperBot by using the same connector.



(a)

(b)

Fig. 1 SuperBot module and its mechanical design

III. TRICYCLEBOT

A. Configuration and Locomotion

The locomotion 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 passive wheels to the robot, and use the paddling action to propel the robot.

Fig. 2 shows the heterogeneous devices to be assembled in tricycleBot, including the passive wheel and the elastic ball attached through pipe. Fig. 3 shows the front and back view of the tricycleBot configuration. It is in a tricycle-like “T” shape, composed of three modules, three wheels, and two elastic balls attached to the side modules through pipes. The three unidirectional wheels are fixed at the bottom to maintain balance and roll to move the robot, and also provide support for the payload. 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 middle module can be regarded as the canoe, and its rear part is the stern that is responsible for steering the robot.

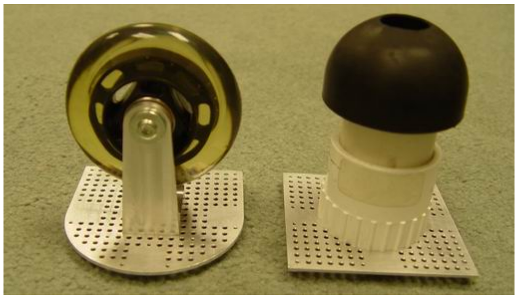


Fig. 2 Heterogeneous devices for tricycleBot

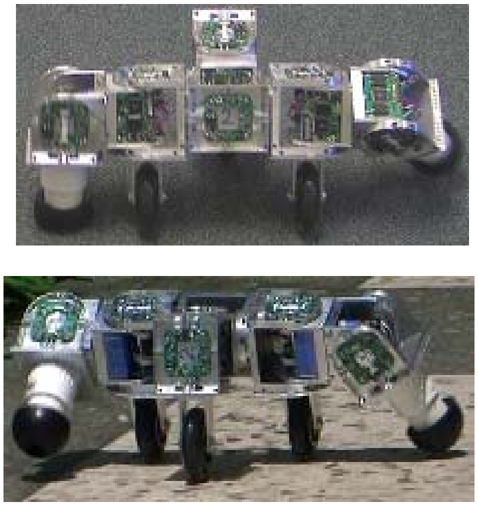
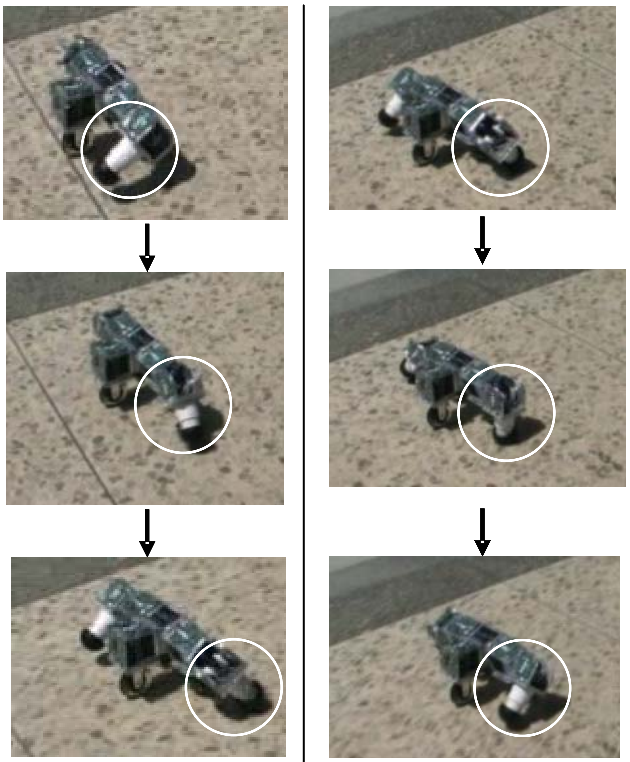


Fig. 3 Front view and back view of tricycleBot gait

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”. Fig. 4 shows the sequence of the paddling action. Unlike the Creep gait [22] 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.

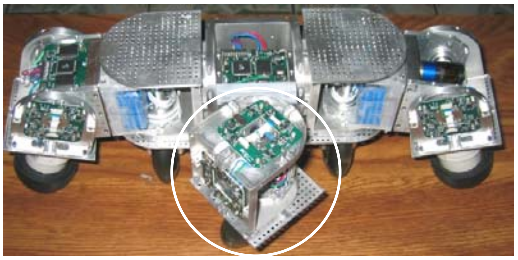


(a) “Paddle” is stretched out and drawn forward

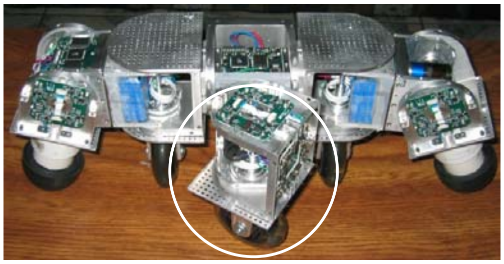
(b) “Paddle” is drawn backward against the ground

Fig. 4 Action sequence of paddling

The two arms modules can do the stroke motion either alternately or simultaneously. Both arms moving at the same time can produce the most thrust, but no propelling force is preserved when preparing for the next stroke. In contrast, 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.



Turn tricycleBot left



Turn tricycleBot right

Fig. 5 Turned real-wheel of tricycleBot

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. As shown in Fig. 5, when the rear wheel is turned, 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.

B. *Payload Carrying*

Usually, 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 coefficient of friction, F_N is the normal force exerted between the surfaces, and equals to the gravity when moving on the flat terrain. Hence, if the payloads are put on top of tricycleBot, the resistant friction is

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

, where μ_r is the rolling resistance coefficient between the wheels and the ground, *Mr* is the mass of the robot, *Mp* is the mass of the payloads, and $g = 9.8 m/s^2$. Usually, μ_r is very small, so the resistance force by the wheels is also small. It increases linearly with the added payloads at a very slow rate μ_r. So, transporting payloads with wheeled robot is efficient and energy saving.

Fig. 6 Payload carrying

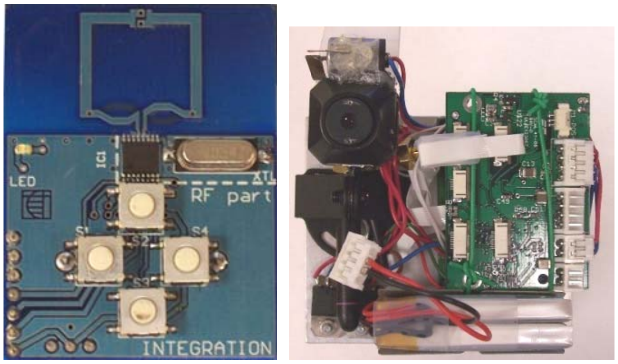
Fig. 6 shows how we use tricycleBot to carry payloads. The two cubes connected to the middle module are used to support the payload. Compared with KateDemowithJoystick [9], a similar gait that also uses wheels for the locomotion of modular robot, tricycleBot is more energy efficient in payload carrying. In the KateDemowithJoystick gait, the robot goes up and down besides moving horizontally. The direction of the motor motion is against the gravitational forces, which results 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 and moves the robot horizontally. The robot does not have any energy-wasting vertical movement to move against the payloads' gravitational forces. All the resistance to be overcome is the rolling friction in (2). So even though the weight of payloads is greater than the maximum motor force, the robot can still carry it and move.

C. *Locomotion Control and Synchronization*

Distributed locomotion control and synchronization was achieved using the digital hormone method [2]. 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 accordingly. 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 be programmed to turn its rear motor steering 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. Here, we use two different kinds of wireless communications to control tricycleBot.



(a) Wireless Transmitter (b) WiFi pod

Fig. 7 Wireless communication devices

The first one we used is the wireless radio frequency communication. 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. 7-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).

The following table 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 accumulatively, and $\theta = 90^{\circ}$ means turning the driving wheel back to center.

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	$\theta = 90^{\circ}$
	Up	Right	$\theta = \theta + \Delta$
	Down	Right	$\theta = \theta + \Delta$
	Left	Right	$\theta = 90^{\circ}$
	Right	Right	$\theta = \theta$

In addition to the radio communication devices, SuperBot has a dedicated WiFi pod (as shown in Fig. 7-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 Fig. 8.

V. EXPERIMENTAL RESULTS

We have conducted several experiments to evaluate the performance of tricycleBot. These experiments include choosing the balls on the "paddle blade", speed measurement on various terrains, energy consumption measurement, payload carrying performance, versatility verification etc.

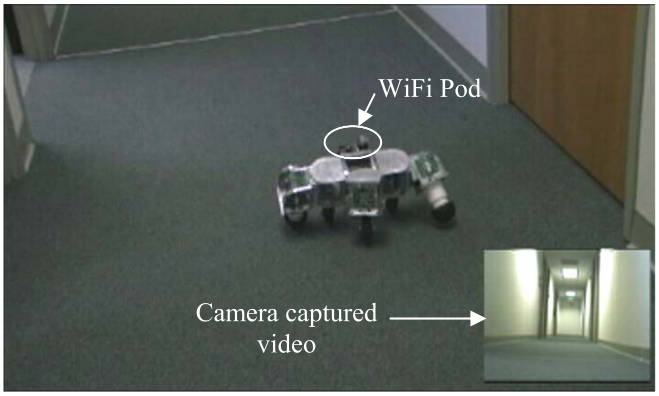


Fig. 8 Tele-operating the tricycleBot with WiFi Pod

As described in section III, the attached pipes with balls in tricycleBot play the role of paddle blades that swing against the ground to propel the robot. In our first experiment, we compared the performance of elastic rubber balls with stiff tennis balls to decide which one is better in propelling the passive wheels. We found that tricycleBot with rubber balls runs faster. Moreover, in the payload carrying experiment described later, the tricycleBot with rubber balls can carry more weight with satisfying speed. The reason that the rubber balls outperform is due to its deformable feature. During every cycle of paddling action, when the arms are lowered to touch the ground before swing backward, the stiff balls on the "paddling blade" will impede the movement a little bit. In contrast, the elastic ball can distort so as to not impede the movement. Also, in the situation of payload carrying, we can elongate the "paddle blades" a little bit to cause more deformation to the elastic balls, so as to generate more moving power. However, with the stiff balls, the generated moving power is unchangeable. Therefore, rubber elastic balls are attached to the arms modules in our configuration design of tricycleBot.

Next, we want to measure tricycleBot's speed without payload, and compare the speed when the tricycleBot's two arms paddle in different ways: alternate or simultaneous stroke. When running the tricycleBot on the carpet, we find that the speed under alternate stroke is 0.162m/s, while the speed under simultaneous stroke is 0.158m/s. When running on the marble surface, tricycleBot also runs a little bit faster under alternate stroke mode (0.311 m/s) than the simultaneous stroke mode (0.309m/s).

We made another series of experiments to show how the performance of these two locomotion modes change with added payloads, and compare the performance of running tricycleBot on different surfaces. As shown in Fig. 9, the moving speed on the marble surface is much greater than on the carpet as expected. Besides, when carrying the payload, the locomotion of simultaneous stroke always beats the alternate stroke. This is consistent with what we expected. The explanation is as follows. As we know, the overall moving force that the robot gets is

$$F=F_a-f \qquad (3)$$

where F_a is the thrust produced by the arms, and f is the friction. As shown in Fig. 10, 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. So the impulse (force × time) of the overall moving force, namely the shadow area bounded by the force lines in Fig. 10, are very close for these two locomotion mode. When payloads are added, according to equation (2), the kinetic friction f is increased proportionately and hence the overall moving force is reduced the same amount for both locomotion modes. So the moving force lines in Fig. 10 should be lowered the same amount of height for both simultaneous stroke mode and alternate stroke mode. Since the forces are more frequent in alternate stroke mode, its shadow area bounded by the force lines will decrease more. Namely, the impulse of moving force 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 in our Fig. 9, the speed decreasing rate under the alternate stroke mode is greater than that of the simultaneous stroke mode.

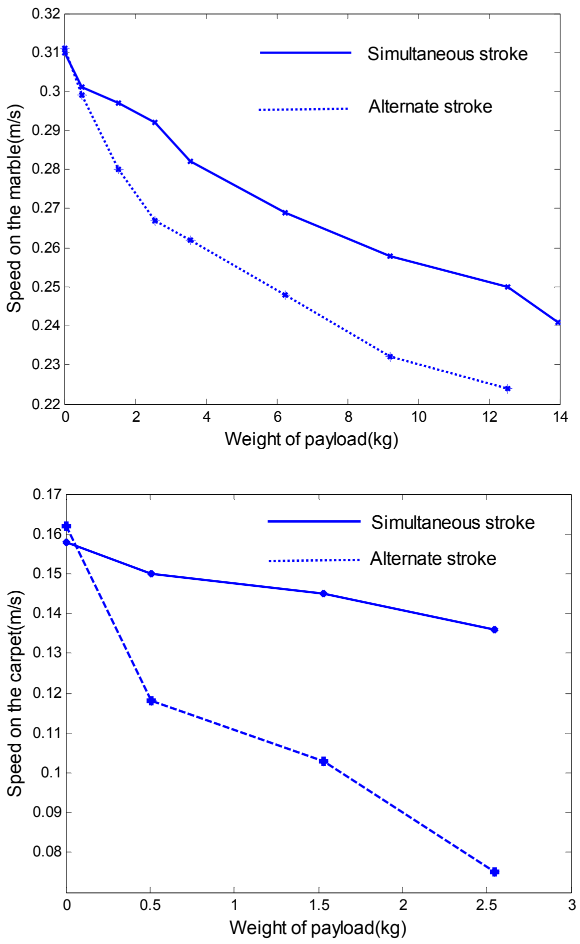


Fig. 9 Speed measurements versus weight of payload on marble and carpet

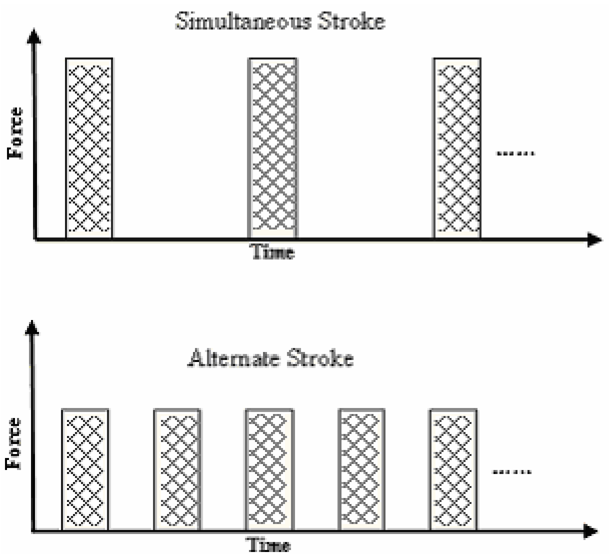


Fig.10. Moving force under the locomotion mode of simultaneous stroke and alternate stroke

The maximum payload we tried is 13.963 kg. With this amount of payloads, tricycleBot can run on the marble surface with 0.241m/s, and on the carpet with 0.083m/s under simultaneous stroke mode. We did not try more weight just in case some accidental damage to the modules due to too much weight on it. But from the speed measurements, we can see that for sure tricycleBot can carry more than 13.963 kg. Considering that tricycleBot weights only 2.636 kg by itself, the payload ratio, i.e. the mass of the payload divided by mass of the robot is

$$\text{Payload ratio} = 13.963/2.636 = 530\% \qquad (4)$$

Also, considering that each module's torque is only 6.38Nm, this result is very impressive for modular robots.

Every module runs on the battery with 7.2V, and the total energy required is 15.84W. The arm modules consume more energy than the middle module, and it is 5.76 W. Given the set of batteries we are using is 11.52 watt-hour, it is estimated that tricycleBot can run for 11.52/5.76=2 hours, From our previous speed measurement results, we can compute that tricycleBot can run up to 0.162*2*3600=1166.4 meter on the carpet in the office environment, and up to 0.311*2*3600=2239.2 meter on the marble surface without payloads. Of course, this result is only a rough estimation of the performance of tricycleBot, and in practical situation the battery may last less than 2 hours due to higher current draw.

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

Finally, to demonstrate the versatility, we have detached the devices of wheels and balls from tricycleBot and have the T-shape robot do a scorpion gait. Video of scorpion gait is at http://www.isi.edu/robots/superbot/movies/Scorpion.avi. Also, modules in tricycleBot can be reconfigured into more shapes, or connects with other SuperBot modules for more configurations. Please visit
http://www.isi.edu/robots/SuperBot.mov
for all kinds of locomotion with SuperBot. On thing to mention is that, at the time of writing this paper, the connectors in SuperBot are still primitive and require manual docking and de-docking. Thus all the configurations are assembled by hand.

VI. CONCLUSION AND FUTURE WORK

In this paper, a new wheeled locomotion gait called tricycleBot is presented for payload carrying, which is a challenging task for modular robots because the robot modules are small and weak in the motor force. Special tools of wheels are proposed to accomplish the task.

TricycleBot is made up of homogeneous SuperBot modules and adds-on devices like wheels and propelling balls. It can transport payloads weighting 530% of its own weight with satisfactory speed, and can be steered remotely to move forward/backward and turn left/right. On a fully charged set of batteries, it is estimated to be able to travel over 1 km in a carpeted office environment, or over 2 km on a smooth marble surface. TricycleBot gait demonstrates that the versatility of homogeneous modular robot can be expanded for special and challenging task by adding some special heterogeneous devices.

One of our future works is to test tricycleBot on some uneven terrain, and see how it performs in terms of payload carrying, speed and balancing etc. Also, some other configuration structure, like attaching the passive wheels to the "paddles", is to be designed and compared with tricycleBot. How different configurations and mechanisms contribute to the performance is to be further explored.

ACKNOWLEDGMENT

This research is supported by NASA Cooperative Agreement NNA05CS38A. We are grateful to all members in USC/ISI Polymorphic Robotics Lab for their support during the experiments.

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