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WALS-Robot: A Compact and Transformable Wheel-Arm-Leg-Sucker Hybrid Robot

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Abstract: Based on the integrated design concept of using the robot's mechanical arm for both locomotion and manipulation, we proposed a compact and transformable robot, i.e. the WALS-Robot, which utilizes combination and switch among four components: wheels, arms, legs and suckers. The WALS-Robot could transform among five locomotion modes to fulfill locomotion requirements in indoor unstructured environments, and have dexterous manipulation, and low power consumption. To reduce the redundancy of mechanical structure and the moving payload for the robot, the mobile platform and the mechanical arm could work as a unity, i.e. the mechanical arm can switch into a leg of the robot to reduce payload during moving modes. Experimental results validated key performance of the robot, including locomotion accuracy and efficiency, compact volume and low power consumption. The integrated design concept illustrated the adaptability in diverse unstructured indoor environments, enlarging the manipulation workspace, and enhancing the energy efficiency.

I. Introduction

In order to automate tasks in the areas of home/hospital indoor service, and for rescuing/surveillance tasks, robots using locomotion and manipulation have been investigated for a long time to perform these tasks rapidly and dexterously. Several technical challenges need to be solved including locomotion in unstructured and narrow environments, dexterous manipulation, low power consumption etc. Mobile manipulator could be a favorable choice to fulfill these goals, because it integrates the advantages of a mobile platform and a dexterous mechanical arm [1-3].

Manipulation or grasping operation for a mobile manipulator in unstructured environments is challenging, because the payload capability is quite limited, and the onboard manipulator has to be relatively light-weighted to avoid tipping over. Carrying an onboard manipulator through an irregular terrain itself may become a burden for the mobile robot [4]. In this way, the mechanical arm with robotic hands may become useless payload when the robot moves forward, and thus limits the velocity of the robot. What's more, the mechanical structure of mobile manipulator is not compact, which may hinder the robot's flexibility of moving through a narrow space.

Therefore, it is necessary to find a new design to turn the mechanical arm to be work as part of the mobile platform, and guarantee that the robot could realize diverse locomotion and perform complex manipulation tasks.

A. Related Works

In related research on mobile manipulation, a mobile robot "Mobipulator" manipulated objects on a desktop, which combined locomotion and manipulation elegantly with the wheels [5]. It showed the basic idea of integrated design. "Uni-Rover" could move around on the ground with high mobility and could be converted into the "manipulation mode", where the arm acted as a manipulator with a gripper. That is to say, it could change between the locomotion mode and the manipulation mode by changing its arm's motion. Inspired by "Uni-Rover", Arm-wheel hybrid robot "Souki-II" was proposed [6]. It is capable of moving across irregular terrain and is able to perform dexterous manipulation.

A tracked mobile manipulator was designed [7], using the manipulator for either locomotion or manipulation. A self-reconfigurable tracked mobile robot "RLMA" was designed and proved that the manipulation may typically take three different modes in terms of box-pushing, cylinder moving and lateral hitting modes [8]. With the multi-terrain adaptability, the robot "RLMA" was capable of crossing barriers and suitable for unstructured environments.

The robots mentioned above are typical examples of locomotion and manipulation integrated design robot. "Mobipulator" can only move by wheels. "Uni-Rover" and the advanced arm-wheel hybrid robot "Souki-II" utilized the idea of integrated design, but they are not stable enough when their manipulator begins to grasp objects. Furthermore, they cannot switch between different modes and adapt to different environments. In comparison, "RLMA" can cross more barriers with the track, but it has very limited manipulation.

Therefore, we decided to design a new locomotion and manipulation integrated robot, which can maintain the advantage of lightweight and compact volume for unstructured indoor environment as well as low power consumption and high energy efficiency.

II. System Overview

In this paper, a Wheel-Arm-Leg-Sucker hybrid robot (WALS-Robot) is designed. The robot has a 5 DoFs (Degree-of-Freedom) mechanical arm and a 5-DoFs humanoid hand, which aims to enhance both the locomotion and manipulation capability. Compared to previous hybrid robots that were equipped with the hybrid mobile mechanisms such as the track-leg mechanism, the

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track-wheel-leg mechanism [9], the combination of wheel, sucker and arm and the combination of wheel, sucker and leg enable the robot to transform and become compact and portable, and become suitable for indoor environment, and is capable to complete difficult tasks.

A. Features of the proposed robot

To meet the requirement of indoor anti-terrorism tasks, the proposed robot has these following features:

- **Locomotion Capability in Multiple Terrains: W**e combined suckers, active and passive wheels with the robot's legs or arm, to form an integrated wheel-arm-leg-sucker system, which enable the robot to have powerful deformability. The design concept enables the robot to move with wheels like a car, to walk with sucker-foot, to stand with a pad-foot like a human, to climb and crawl like a reptile, or to slide like a scooter to adapt different environments.

- **Dexterous Manipulation**: It is necessary for indoor anti-terrorism robot to be equipped with multi-DoFs mechanical arm to complete complex operations. Therefore, the robot needs to have a dexterous mechanical arm with humanoid mechanical hand. A five-finger hand was mounted at the end of the robot's wrist to help perform difficult tasks, which is more superior to traditional manipulator with a gripper.

- **Lightweight and Compact Volume for Unstructured Environment**: As the robot is going to be applied in indoor environment and can be portable, its volume and weight should be limited. The robot can transform to a suitable configuration to have a compact structure and maintain a small volume for fitting through tight spaces. The weight of the robot is approximately 3kg, which make the robot become portable.

- **High Energy Efficiency:** We come up with the idea of integrating the manipulator and mobile platform by eliminating the difference of role between legs and arm. That is to say, the mechanical arm of robot can be used to manipulate objects in complex environments, but when it moves, the mechanical arm can turn to be one of the robot's legs as part of the moving device or can be known as a tail sliding on the ground. This design concept may improve power efficiency by reducing useless payload contributed by mechanical arm and hand when the robot moves forward.

B. Concept design of the robot

As shown in Fig. 1, the mechanical arm and the mechanical hand has 5 active DoFs respectively. Steering engines were used as the actuators for the arm's joints.

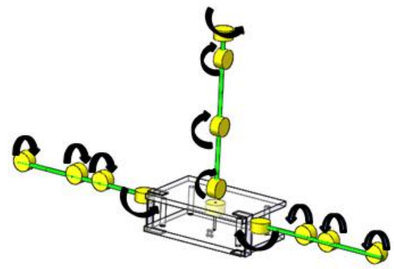

Figure 1. Kinematic sketch of the WASL-Robot

We introduce the idea of arm-leg integrated design in this WASL-Robot. As shown in Fig. 2, a passive wheel was fixed on the robot's wrist, so as to allow the robot's arm to contact the ground like a tail or a supporting cane, and can be regarded as one of the robot's leg, which is expected to help reduce energy consumption. A sucker was installed on the other side of the wrist, and could be part of the sucker foot when the robot moves forward.

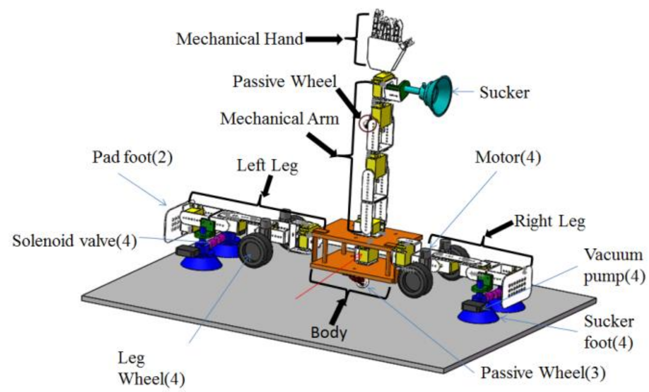

Figure 2. Overview of the main components in WASL-Robot

There are two symmetrical drive systems on both sides of the robot's body. Each has 4 active revolution joints (Fig. 1), which are driven by steering engines. Two pairs of wheels driven by motors are independently assembled on the robot's two thighs, and two pairs of suckers are independently assembled on the robot's two calves, which are operated by vacuum pumps and solenoid valves (Fig. 2).

The body of the robot is a container, which is designed to store electronic components and the control system. The mechanical arm and legs are fixed on the body (Fig. 2).

III. Five Locomotion Modes

A. Overview of five locomotion modes

In this part, we briefly introduce the multiple locomotion modes for the WASL-Robot. The transformation relationship and the 3D virtual prototypes corresponding to the five locomotion modes are illustrated in Fig. 3.

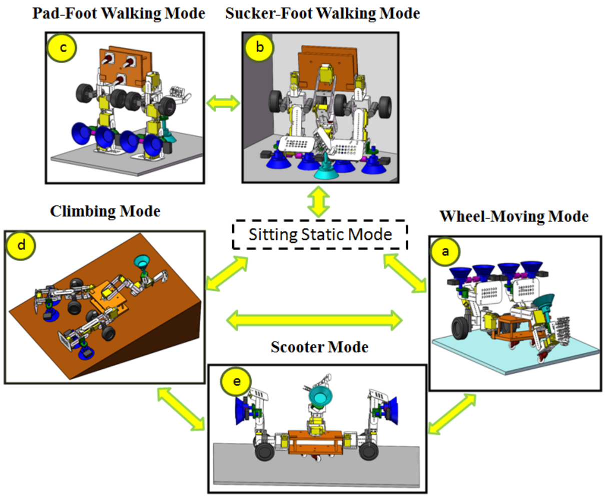

Figure 3. The virtual prototypes of the five locomotion modes and the transformation relationship between the five locomotion modes: (a)Wheel-Moving Mode, (b)Sucker-Foot Walking Mode, (c) Pad-Foot Walking Mode, (d)Climbing Mode, (e)Scooter Mode. The Sitting Static Mode is an intermediate mode in the transformation process.

B. *Wheel-Moving Mode*

Generally, a wheel mechanism has the advantages of having simple structure, strong flexibility and high stability, which is suitable for the regular indoor environment. But the disadvantage is that the ability to overcome obstacles is relatively low [10, 11].

As shown in Fig. 4, when the WASL-Robot moves in the wheel-moving mode, it can be regarded as a mobile robot with a 5-DoFs mechanical arm and a mobile platform with four active wheels. But different from the traditional type, the mechanical arm is able to attach to the ground through a passive wheel like a tail towed by the body passively, which can reduce energy for the platform to support the mechanical arm. The $C_i (i = 1, \cdots, 6)$ represent the contact points between the four wheels and the flat ground. mg represents the total weight of the whole robot. v_m means the maximum velocity in wheel-moving mode, and a means the maximum acceleration in wheel-moving mode. These two parameter can be calculated by the radius of the wheels, rotation rate for motor n_m and the power for motor P_m .According to our test, v_m can be approximately 1.5m/s.

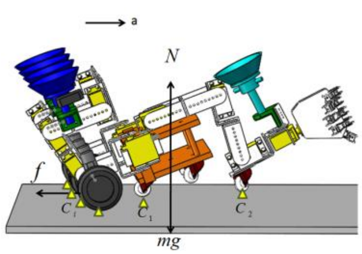

Figure 4. The mechanics model of wheel-moving mode

C. *Climbing Mode*

To enable the abilities of climbing to the robot, we apply a pneumatic system on the calves of the robot. The pneumatic system contains a triple valve connected with a sucker, a mini vacuum and a solenoid valve. We call this system simply as sucker in this paper. With the suckers, the robot can be adsorbed onto a slope or even a vertical wall by virtue of the pressure difference. The diameter D should be larger than $D_{\min}$, which can be calculated in Eq. (1). It is depended on vacuum degree (p), safety parameter (k), the number of suckers (n), and force of payload (mg). k means the safety factor, and it is set as different values under different condition.

$$\frac{1}{4} nk\pi D_{\min}{}^{2} p = mg \tag{1}$$

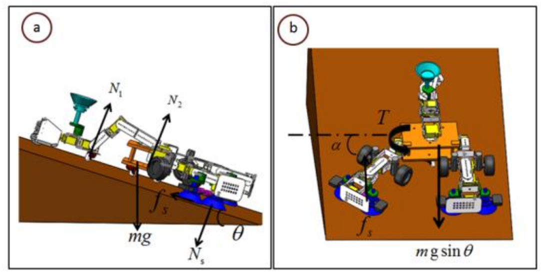

Figure 5. The mechanics model of climbing mode:(a) the mechanics analysis in the normal direction of the slope surface, (b) the mechanics analysis in the tangential direction of the slope surface

As shown in Fig. 5(a), the force components in the normal direction of the slope surface can be computed as

$$\begin{cases} N_s + m g \cos\theta - N_1 - N_2 = 0 \\ f_s - m g \sin\theta = 0 \end{cases} \tag{2}$$

where N_s represents the force created by the pressure difference between the air and the internal volume of the sucker, f_s means the friction force created by the sucker stuck to the slope. θ represents the obliquity of the slope where the robot is climbing, and α means the swing angle of the robot's one leg when it tries to move forward in one step. N_1 , N_2 are the supporting force.

As shown in Fig. 5(b), the force components in the tangential direction of the slope surface can be computed as

$$mg \sin\theta (L\cos\alpha + W_b / 2) - T = 0 \tag{3}$$

where W_b refers to the width of the robot's body.

The motion sequence of climbing process are shown in Fig. 6, in which step A (Fig. 6 (b)) and step B(Fig. 6 (c)) are executed repeatedly. Through this method, the robot could move forward in the way of crawling like a reptile.

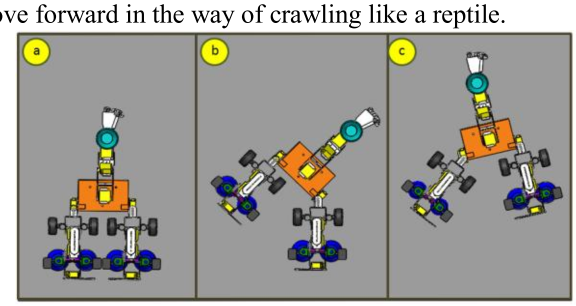

Figure 6. The sequential motions of slope climbing: (a) the initial position, (b) step A,(c) step B

D. Pad-Foot Walking Mode

It is well-known that humanoid robots have the advantage of striding over obstacles and high terrain adaptive ability. However the stability is not very good, especially the change of its center of mass may reduce its stability. To improve the stability of the WASL-Robot and reduce the payload for the driving system, the mechanical arm of WASL-Robot could attach to the ground like a cane. As shown in Fig. 7, the supporting surface is enlarged when the mechanical arm serves as one of the legs for the robot. The stability of the robot could be improved and the energy cost of raising the robot's arm could be eliminated during the walking process.

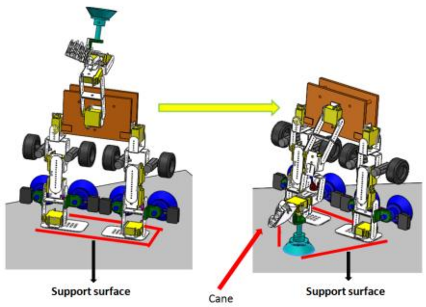

Figure 7. The illustration of the advantage of enlarging the supporting surface

E. Sucker-Foot Walking Mode

As shown in Fig. 8, when the robot stands in the Sucker-Foot walking mode, we can make good use of the pressure difference (p_d), and improve the robot's stability when it walks. Compared to the pad-foot walking mode, the sucker-foot walking mode requires the ground to be relatively flat. We can see that when the robot uses the sucker-foot to walk, the workspace of the manipulator is expanded, and the hand can reach a higher place to operate or grasp objects. N means the supporting force generated by the ground.

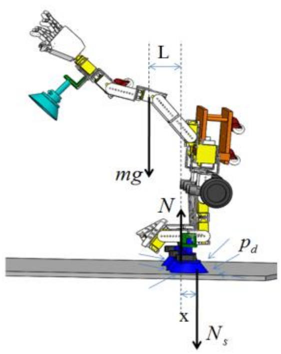

Figure 8. The mechanics model of sucker-foot walking mode

F. Scooter Mode

As shown in Fig. 9, when the robot needs to go down a slope, it can transform to be a scooter with three passive wheels attached to the slope, and thus roll down quickly. The benefit of this mode is obvious. It can save energy, because the motors do not need to work like the wheel-moving mode.

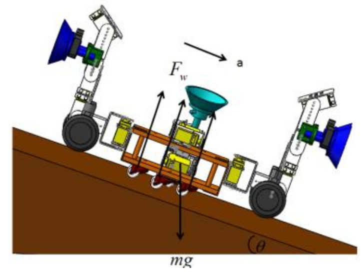

Figure 9. The mechanics model of the scooter mode

IV. Performance Analysis of the Virtual Prototype

A. Locomotion Capability in Multiple Terrains

As shown in Fig. 10, the robot could move in five locomotion modes. It could reach the highest place in 835mm height, go through a narrow entrance of 200mm in width and 750mm in height, and go beneath a low space about 170mm in height and 600mm in width.

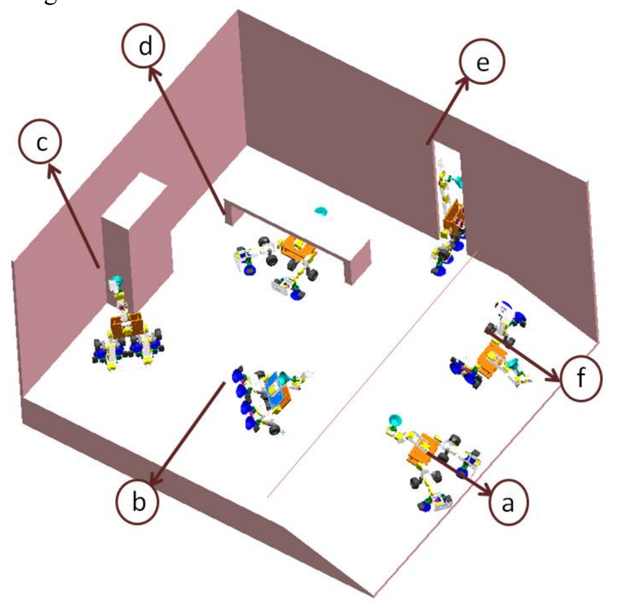

Figure 10. The virtual models to show environmental adaptation capability. (a) climb the slope in climbing-mode, (b) move forward in wheel-moving mode, (c) raise the hand and enlarge the workplace in pad-foot walking mode, (d) crawl beneath the bench in climbing move, (e) go through a narrow crack in sucker-foot walking mode, (f) go down the slope in the scooter mode

B. Volume of the robot under each locomotion mode

From Fig. 11, we can clearly see that the robot can transform to be compact and become portable.

According to our design, the robot could be put into a container which has a volume of 424mm in length, 300mm in width and 330mm in depth.

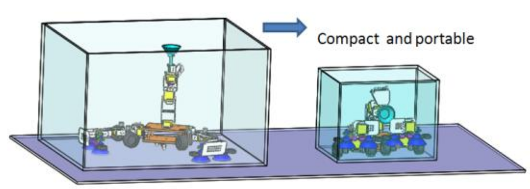

Figure 11. Transform from a large volume configuration to a compact structure

C. Reduce energy consumption

As illustrated in Fig. 12, the WASL-Robot has the advantage of saving energy in either the wheel-moving mode or the climbing mode. When the robot moves, the mechanical arm attaches to the ground through the passive wheel, and the friction is very small when it moves forward. Therefore, the robot consumes less energy than the mobile manipulator of the same size and weight.

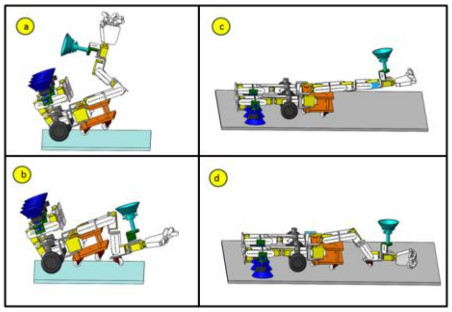

Figure 12. Comparison between the traditional method and the new method we applied to the WASL-Robot: (a) traditional method for wheel-moving mode,(b) new method for wheel-moving mode, (c) traditional method for climbing mode, (d) new method for climbing mode

V. Experiments of the Physical Prototype

A. Prototype WALS-I

A first generation prototype of the robot named WALS-I was fabricated and some preliminary tests were performed for validating the feasibility of the design. The specifications of the prototype are shown in Table I.

TABLE I. SPECIFICATION OF THE WALS-I ROBOT

Total Weight	3.08kg	Weight of leg	0.92kg
Length of body	240mm	Weight of manipulator	0.96kg
Width of body	115 mm	Length of manipulator	425mm
Thickness of body	55 mm	Length of leg	290mm

The movement of the robot was tele-operated by a human operator using wireless control system. The control system of the robot was composed of controllers on the robot and a remote control station. As shown in Fig. 13, a remote control system based on visual feedback was realized for controlling the robot by an operator. One webcam was equipped on the robot and the video was sent back through a wireless video transmission system.

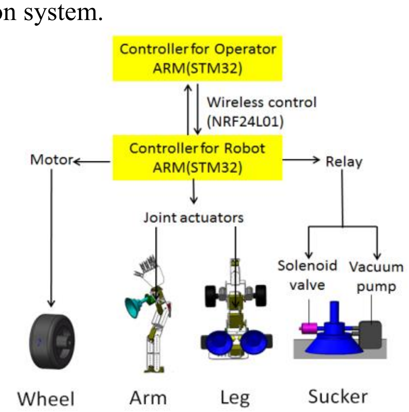

Figure 13. Scheme of the robot's remote control system

B. Locomotion performance test

1) Illustration of locomotion mode switching

The accuracy of angle for the joints is very important to fulfill the locomotion requirement, as small deviations for some critical joints of the robot may cause the robot fail to change into the expected locomotion mode. We performed repeated experiments to qualitatively analyze the accuracy of shape transformation. In each test, we measure the deviation of angles for some critical joints to validate the accuracy of locomotion mode switch. As shown in Fig. 14, the robot fulfilled all the five locomotion modes. The results show that the transformations are accurate, and the error of all joints' angles was always less than one degree.

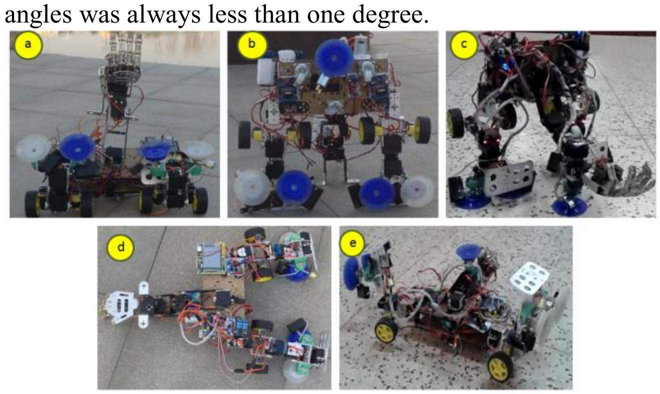

Figure 14. Five locomotion modes of prototype WALS-I robot: (a)wheel-moving mode,(b)pad-foot walking mode,(c)sucker-foot walking mode,(d)climbing mode,(e)scooter mode

2) Speed of locomotion mode switching

Fig. 15 showed the sequential motions of transforming tasks, and we can clearly see that the robot can transform to the locomotion mode as we designed.

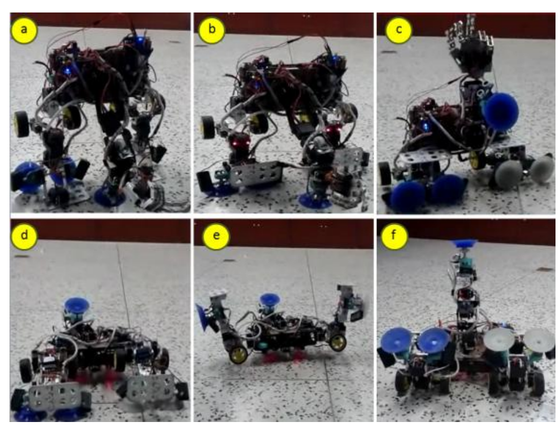

Figure 15. The sequential motions of transforming tasks: (a) pad-foot walking, (b) sucker-foot walking mode,(c)sitting static mode, (d)climbing mode,(e)scooter mode,(f) mode wheel-moving mode

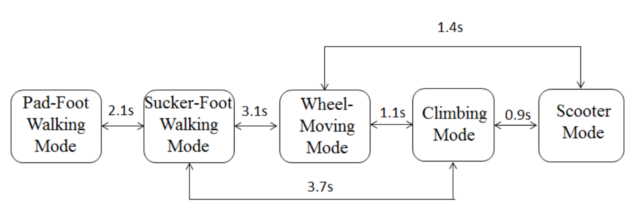

Figure 16. The result of the speed of locomotion mode switching

The speed of locomotion mode switching is important, as the robot needs to switch quickly to adapt to the environment. We used the stopwatch to test the time cost by transforming between the five modes. The test was performed repeatedly for 10 times. The average time cost is provided in Fig. 16.

C. *Power Consumption Test*

In the experiments, WALS-I was powered by Li-poly battery. We used battery monitor cellmeter-7 to externally measure the power consumption and combined the battery monitor system with buzzer at the same time. We started a stopwatch when the robot begun to move, and pressed the stopwatch when the buzzer rang. Each time, we charged the battery to reach the maximum voltage (12.6V). And we set the buzzer to ring when the voltage goes down to 11.1V. For either the wheel-moving mode or the climbing mode, we measured the continuous operating time while the robot was moving for ten runs.

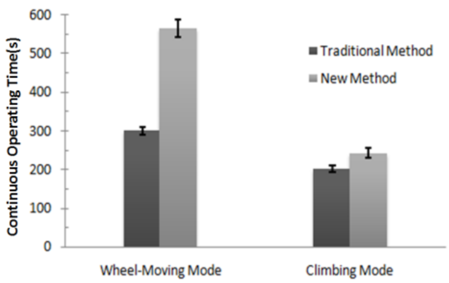

Figure 17. Result of the continuous operating time in the power consumption test .These results are briefly compared with traditional method for designing mobile platforms and the new method

The average and standard deviation of the continuous operating time are shown in Fig. 17. The measured continuous operating time in each run was a little different, because the time might be influenced by many unmodeled factors, such as varying friction conditions and the instable current output.

For the wheel-moving mode, the average continuous operating time for the traditional way was 300s, while the new way was 566s. For the climbing mode, the average continuous operating time for the traditional way was 203s, while our new way was 244s. According to T-test, the data of the traditional method and the new method are significantly different both for the wheel-moving mode ($t(9)=34.3$, $p<7.4e-18$) and the climbing mode ($t(9)=8.0$, $p<2.6e-7$).

VI. Conclusions and Future Work

In this paper, we design a compact and transformable Wheel-Arm-Leg-Sucker hybrid robot. Experimental results show that the prototype of the robot (WALS-I robot) could transform quickly and accurately among the five locomotion modes, and the integrated design concept could effectively meet the requirements of adapting to multiple terrains, performing dexterous manipulation tasks, having compact structure, and saving energy.

In the future, we plan to design a new generation of WALS robot by optimizing its parameters to improve its performance, such as payload capacity, the obstacle surpassing capabilities etc. Furthermore, we plan to perform further rigorous experiments in various field locomotion scenarios.

Acknowledgment

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