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Development of Novel Robots with Modular Methodology

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Abstract— **Modules have been widely used in the development of re-configurable robots and snake-like robots. Modular methodology can also be applied in design of other robots. To build robots flexibly and quickly with low costs, we have developed two basic joint modules and several functional modules including grippers, suckers and wheels/feet as end-effectors. In this paper, we introduce the development of these modules, and present several novel robots built using them. Specifically, we show how to use them to set up a manipulator, a 6-DoF biped walking robot, a wheeled mobile robot, a biped tree-climbing robot, and a biped wall-climbing robot. It has been shown that a few modules can easily spawn a variety of novel robots with modular methodology.**

I. Introduction

In the development of robotic technique over 40 years, many robotic systems have been developed for various applications in industry, military, space, medicine, education, entertainment, home and social services. However, except for industrial applications and some successful applications in planetary exploration, social security and home service, robots are not used extensively. There are many factors limiting wide applications of robots (say, functionality, performance, reliability, intelligence, and so on), among which the complexity and high costs of building robotic systems are important factors.

Modularization is an effective methodology in system development. It may solve some problems caused using traditional method and bring the following benefits:

- **Versatility**: Using a few identical or different modules, various robots with different functionalities or locomotion modes can be built quickly for different purposes;
- **Reconfigurability**: The configuration (mechanical structure) of a robot may be modified by changing the connection or combination of modules automatically by the system or manually by human, so that the system has adaptive functions or locomotion modes depending on tasks and/or environments;
- **Scalability**: The degrees of freedom of a robot can be increased or decreased by simply adding joint modules to or removing joint modules from the system;
- **Low-costs**: Modules are usually identical and may be mass produced. The costs of design, manufacture, assembly and maintenance of built systems by them are lower than their counterparts by conventional design method;
- **Fault-tolerance and Self-repair**: If a module is detected to be malfunctioning, it may be detached automatically by the system and other normal modules are re-connected so that the system can continue work. A joint may be replaced by another one in trivial actions of disconnection and connection of them.

With so many advantages of modules as in part listed above, the methodology of modularization design is adopted more and more widely in the development of robotic systems. A variety of modules have been developed and a lot of reconfigurable robots have been constructed with them for security and inspection tasks (see, for example, [8], [20], [21]). These modules usually have two joints whose axes are parallel or perpendicular to each other. Most of them are autonomous, and hence the robots composed by them are usually self-reconfigurable. All snake-like robots consist of a number of modules [6], [19]. Since these modules are designed specially for reconfigurable robots or snake-like robots, the robots constructed by them lack of manipulation function though with a high mobility due to multiple locomotion modes.

Modularization design is also applied in the development of other types of robots. In a multi-fingered hand or a multi-legged robot, the fingers or legs are usually identical, and hence can be regarded as modules [7], [15]. Some mobile robots are equipped with special "modules" which may be fully functioned as arms, legs or wheels [13], and some consist of several identical sub-systems which are in fact tracked mobile robots and actually modules of the whole systems [9], [16]. Even some wall-climbing robots are composed of modules to fulfill transition between walls [18]. However, these modules are for special systems, not for general purpose.

For applications different from those of aforementioned robotics, Robotics Research Corporation in USA has developed a series of joint modules, by which space robots or manipulators can be constructed. Since the modules are originally oriented to applications in space, their prices are

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prohibitive to general users. AmTec (purchased by Schunk) in Germany has developed commercial 1-DoF (degree of freedom) joint modules whose rotation axes is collinear with the link axes. They cannot be connected directly, and with only one type of joint module, special connecting links are needed to build a robot with them, which limits to some extent its applications in robotic system development.

To construct robots flexibly and quickly with lower costs, we have developed two types of 1-DoF joint modules for general purpose, which are called I-typed and T-typed joint modules whose rotation axes are collinear with and perpendicular to the link axes, respectively. We are also developing several functional modules used as end-effectors, including grippers, suckers and wheels/feet. Using these joint and end-effector modules, various robots can be built straightforwardly. Imposing multiple locomotion modes to the robots is one of our targets in developing modular robots.

II. Modularization Methodology

All robots have the utmost basic function – motion. And the robotic motion is realized by various (electric, hydraulic, pneumatic, or biologic) motors through mechanisms called joints in appropriate structure. Besides the basic motion, many robots have the function of manipulation to perform tasks, which is usually implemented by the so-called end-effectors. Most joints of existing robots are revolute and driven by electric motors. According to the relationship between the axes of joints and links, it is well known that there are two basic types of joints, which we call I-type and T-type. In the I-typed joint, the (revolute) joint axis and link axis are collinear or parallel to each other; and in the T-typed joint, the axes of joints and links are perpendicular to one another. In other words, with these two basic 1-DoF joints, the main body of robots are built. If we make each joint as an independent module with unified or "standard" interfaces for connection, and make end-effectors or accessaries as functional modules with the same connection interface, then a variety of robotic systems may be built by combining these modules in appropriate configurations.

In design of joint and functional modules for robotic systems, the following features are to be obtained:

- **Independence**: Each module is a system whose mechanical and control (hardware and software) systems are independent of other devices;
- **Completeness**: Each module is a complete mechatronic system with function(s) of motion and/or torque control;
- **Opening**: The control system is open to users so that they may extend the functions of the modules;
- **Coordination**: Modules can be integrated and coordinated with a top controller. This is specially important to building multi-DoF robotic systems;
- **Compactness and light-weight**: The modules are to be used for building robotic systems with high mobility, it is required that they are compact and light with strong driving capacity.

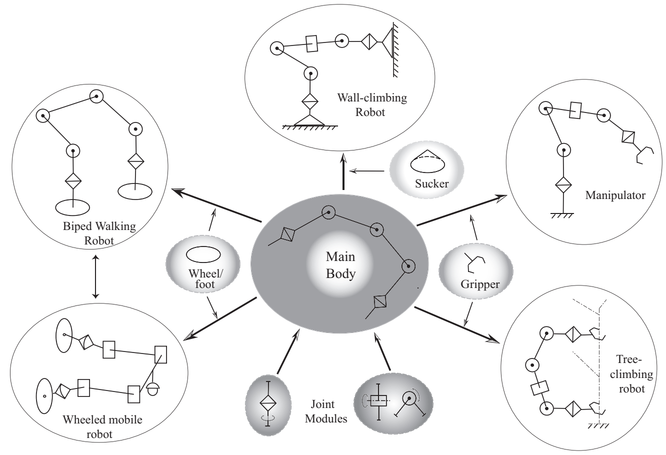


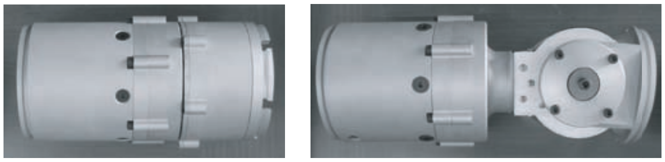
Fig. 1. The conception of modularization design of novel robots

We classify the I-typed and T-typed joint modules into basic modules, and the gripper, sucker and wheel/foot into functional modules. Combining and connecting them in appropriate configurations may give rise to a variety of robots. Fig.1 shows such conception and some examples of the robots built in this manner, among which are a manipulator, a biped tree-climbing robot, a biped wall-climbing robot, a 6-DoF biped walking robot and a two-wheeled robot with one caster. The main bodies of the robots are first constructed by connecting a few I-typed and T-typed joint modules in series in configurations like robotic arms, and then one or two ends of the main body are connected with functional modules to form different robotic systems for various tasks or missions. More complex robots may also be built by connecting more modules in both series and parallel modes using proper connecting parts. In the following sections, we will see how these modules and the novel robots are developed.

III. The Modules

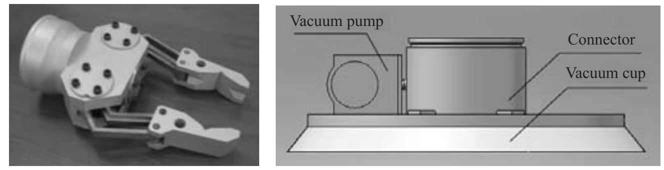
A. The Joint Modules

Each joint module is designed to be an independent and complete mechatronic system. One DC servo-motor, RE40 (Graphite Brushes, 150 Watt) by Maxon, is employed to drive the joint. An encoder, MR-L 1024 (three channels) also by Maxon, is mounted directly to the motor for position and velocity measurement and feedback control. The motor is connected to a harmonic speed reducer with a ratio of 150, and the latter is then connected to a pair of bevel gears (in the T-typed module) or internal gears (in the I-typed module). Finally, the gear drives the joint axis. Fig. 2 shows two pictures of the joint modules. In order to have the module compact and short in length, a pancake-type harmonic drive, rather than the commonly used cup-typed one is used. The gears at the end of the transmission chains are used to increase further the reduction ratio and to keep (for I-typed joint) or change (for T-typed joint) the direction of rotation. In the I-typed module, the central gear drives three idle gears distributed uniformly and the latter drive the inner gear. Axes of the



(a) I-typed joint module (b) T-typed joint module

Fig. 2. Two basic joint modules



(a) The gripper (b) The sucker

Fig. 3. Two functional modules

motor and the harmonic drive are arranged to be collinear, and to reduce both size and weight of the modules, costumed harmonic components rather than harmonic unit are employed.

The rotational range of the T-typed joint is up to $\pm 110°$, and that of the I-typed joint is $\pm 180°$ (no rotation limits for wheeled mobile robots). The diameters of the modules are 100 mm, the lengths of the T-typed and I-typed joint modules are about 230 mm and 170 mm, respectively. The main parts of the modules are made of aluminum alloy to reduce the module weight. The weights of our improved T-typed and I-typed modules are reduced to about 2.6 kg and 2.7 kg, respectively, and the output torques are larger than 100 Nm.

The control systems of the joint modules are in three-layered architecture. A PC (host computer) is used as the highest level (top) controller for task management, motion planning, man-machine interface (issuing control commands and show feedback message from the lower layers). At the bottom is the controlled unit, i.e., the servo-motor of the module. In the middle layer is the core of the control system, the motion controller and the driver. Compact, small and light controllers and amplifiers with high control performance are required in order to make the joint modules self-contained. We employ Accelnet Micro Module by Copley Control Corporation. This control module is a compact, powerful integration of both control and amplifying function, with the a number of good features including multiple control modes, two communication modes, multiple feedbacks, digital IO, and small size ($64 \times 41 \times 16$). The controller/amplifier uses up to three nested control loops - current, velocity, and position - to control a motor in three associated operating modes. An outer loop use all its inter loops. The loops of velocity and current use digital PI algorithm. For the details of the joint module development, refer to [4].

In the integration of multiple modules for robotic systems, the controllers of modules may communicate through serial mode or CAN bus. By the former, the first controller module connects to the host PC by serial port cable, and connects to other modules with CAN network cable in series one by one; and by the latter, a CAN interface card or a USB-t0-CAN converter is required, CANopen adds support for motion-control devices and command synchronization.

B. The Gripper

Grippers are widely used in many robots for grasp tasks. In general, the action (say, opening or closing of the two fingers) of a gripper is driven by one (electric, hydraulic or pneumatic) motor, so we can take the entire gripper as one functional module with appropriate mechanical interface.

The gripper, as shown in Fig.3(a), has two fingers which can form opening and closing action. Driven by one motor, the fingers can move linearly and simultaneously, through a transmission formed by a harmonic drive, a worm gear and two 4-bar linkage mechanisms. A flat DC motor and harmonic components are purchased and employed in order to reduce the size and weight of the gripper. The generated grip force may be up to 300 N.

For both climbing and manipulation functions, the gripper must be adaptive to different shapes and various sizes of objects. To this end, two V-shaped grooves perpendicular to each other are made on the finger face. With the V-shaped grooves, the gripper can grasp cylindric or prismatic trunks/branches, poles or trusses in climbing procedure. It can grasp spherical objects (e.g., apple or bulk) with eight contact points. With the flat faces of the two fingers, cubic objects can also be grasped. By combining the V-shaped grooves and the flat faces of the fingers, more objects may be grasped.

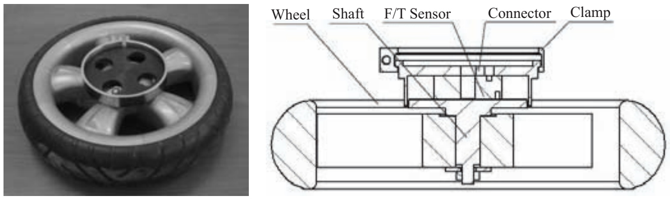
C. The Wheel/Foot

Wheels are widely used in mobile robots. Besides this usage, they are used as feet in our special biped walking robot. As will be seen shortly, our biped walking robot is unique and quite different from conventional biped ones, disk-like or torus-shaped feet are preferable, and wheels are ideal choice. When they are used as feet, they contact the ground with side surface and their axes are perpendicular to the ground.

We use and customize wheels of baby car as the driven wheels of our mobile robot and feet of our biped walking robot. The module consists of a wheel and a shaft for wheeled mobile robot, and one more F/T sensor and connector for biped walking robot. Fig.4(a) is a picture of the module and Fig.4(b) is a drawing of the module assembly.

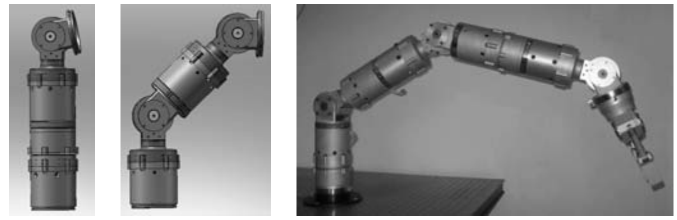
D. The Sucker

Among many attachment methods (e.g., magnetic, bio-inspired by cockroach or gecko, and propeller-generated) for wall-climbing robots, suction is the most commonly used to attach climbing robots to walls. For suction, vacuum of a cup or a chamber is generated by sucking the inside air out though a software pipe or by a vacuum pump or ejector. Several cups may be used for a wall-climbing robot.



(a) A picture (b) Assembly drawing

Fig. 4. The wheel/foot module



(a) (b) (c)

Fig. 5. A pan-tilt unit, a 2-DoF planar robot, and a 5-DoF arm

In our design for biped wall-climbing robot, the sucker module consists of a vacuum cup, two vacuum pumps, a valve and a pressure sensor. The vacuum cup, as the main and supporting part and of the module, is used to form vacuum chamber. The vacuum pumps are used to absorb the air inside the cup out to generate negative pressure, and the pressure sensor measures the negative pressure inside the cup. The vacuum needs to be eliminated to release the sucker, and a valve or pores is employed to this end. The valve closes when the sucker works, and it opens to air when the sucker is released. The valve is driven by electromagnetic mode or springs. These components are connected by soft pipe. The CAD model of the sucker is shown in Fig.3(b), where the valve and the pressure sensor are invisible since they are contained in the mechanical connector.

IV. Robotic Prototypes

The joint modules we are developing are basic joint units of regular sizes with one degree of freedom and for general purposes. With these basic modules and the functional modules as end-effectors, a variety of robotic systems may be constructed in various configurations. What needs to do is just to connect them in series in proper configurations. Each module is joined to its adjacent modules by quick-disconnect band clamps. Two adjacent modules can be decoupled in seconds facilitating maintenance or retrofit. Some of the robotic prototypes built in this manner are shown below.

A. Simple Mechatronic Systems

Pan-tilt units are commonly used in visual systems for adjusting orientation of cameras. A pan-tilt unit can be built trivially using one I-typed module and one T-typed module, as shown in Fig.5(a). Planar robots can be built using two or three T-typed modules connected with joint axes parallel, as shown in Fig.5(b). Based on this planar robots, a SCARA robot can be easily constructed by adding an I-typed module as the first joint, with all joint axes parallel and vertical.

B. A 5-DoF Manipulator

Manipulators may be set up using several joint modules. Fig.5(c) is a picture of a 5-DoF manipulator composed of three T-typed joint modules, two I-typed modules and one gripper. More robotic arms may be created in the same manner with different number of joint modules and in different connection between them (say, with parallel or perpendicular axes).

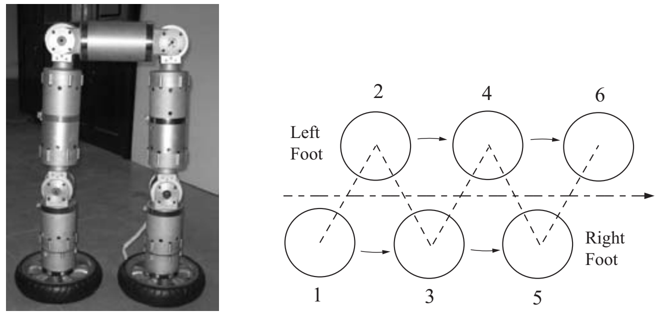
C. A Biped Walking Robot

Most of biped robots are active walking platforms, while another category of biped walking robots is passive or semi-passive where few actuators are equipped and the locomotive movement is fulfilled using potential energy along a slope [2], [12]. Almost all of nowadays biped walking robots carrying out locomotion in biped modes similar to human walking gaits.

Although active (full-activated) biped walking robots have strong locomotion ability, good adaption to environments and high robustness, they have in general a lot of degrees of freedom, usually up to 12 DoFs, and hence result in complex control and high energy consumption. On the other hand, passive or semi-passive walking robots require less DoFs and have high energy-efficiency, but their walking capability and robustness is poor. Is it possible to develop new biped robots that are capable of active walking with a few DoFs so that possess the advantages of active walking and passive walking but get rid of their drawbacks?

A 8-DoF biped robot with two disks as feet was presented in [14]. Here we propose a biped walking robot with only six DoFs. The robot consists of four T-typed joint modules with parallel joint axes assembled, two I-typed joint modules and two wheels as feet, as shown in Fig.6(a). The features of the biped walking robot include: 1) small number of active joints, 2) possible manipulation ability as long as end-effectors are mounted at the feet (since the main body is actually a robotic arm), and 3) special gaits of walking.

Due to its special structure different from those of conventional humanoid and biped legs, this robot may fulfill biped active walking in special gaits for locomotion. As illustrated in Fig.6(b), the steps of the turning-around gait are as follows: 1) the robot adjusts its CoM (Center of Mass, in quasi-static case) or ZMP (Zero-moment Point, in dynamic case) by the upper four T-typed joints so that it is supported by one foot; 2) The robot lifts the foot not in support by further rotating the upper four T-typed joints; 3) It then rotates the I-typed joint near the supporting foot (about the vertical axis), so that the swinging foot moves to a target place; 4) The robot puts the swinging foot down onto the ground by rotating the upper four T-typed joints; 5) It changes the foot roles (supporting or swinging), and repeats the preceding steps.



(a) A picture (b) The turning-around gait

Fig. 6. A 6-DoF biped walking robot and one of its gaits (overview)

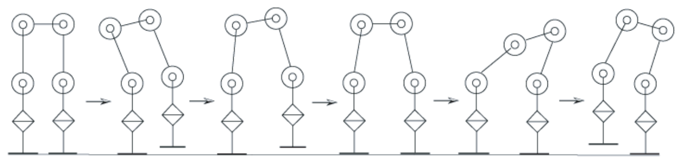


Fig. 7. Gait 2 of the walking robot (side view)

In the second gait, the locomotion is mainly performed out by actuating the four T-typed joints, no I-typed joints required (except for changing walking direction). The first two steps are the same as in Gait 1. In step 3), the robot moves the the swinging foot forward or backward still by rotating the four T-typed joints. After the robot puts the swinging leg onto the ground, as in step 4) of Gait 1, it swaps the roles of the two legs, moves the previous supporting foot forward or backward in the same manner. In this gait, the sequence of front and rear feet does not change. This gait is similar to human walk in the lateral plane step by step, with the procedure as shown in Fig.7. The third gait is similar to Gait 2. But after the swinging leg is lifted, it turns over, by rotating the four T-typed joints, around the T-typed joint of the supporting leg, so that the swinging leg moves forward or backward and the sequence of front and rear feet exchanges.

D. A Wheeled Mobile Robot

The aforementioned biped walking robot can be used as a wheeled mobile robot after being put down onto the ground and attached a caster at the middle link of the robot. To make the system simpler, one T-typed joint module may be removed so that the robot consists of five joint modules, two wheels and one caster, as shown in Fig.8.

Wheeled mobile robots have been intensively investigated in the past decades. Many systems have been developed and widely used in outdoor exploration and indoor services. The number of wheels in mobile robots varies from one to eight. The distances between wheel centers are constant, and except for the steering wheels, most wheels keep their orientation fixed with respect to the main body of the robot.

This novel mobile robot has unique characteristics that conventional wheeled mobile robots do not possess, that is, it can change: 1) the distance between the wheels, 2) the orientation of the wheels with respect the robot, and 3) the shape of the robot, by rotating its T-typed joints. With these features, the robot is flexible, dextrous, omni-directional, and hence very adaptive to environments. In straight moving, the two wheels should be parallel; and in turning their orientation should be adjusted like car steering through the associated T-typed joints. When the robot stretches out completely, it can roll down a slope without consumption of any energy. The motion planning and control of this type robot by coordinately controlling all joints to keep the nonholonomic motion constraints (pure rolling without slipping) is challenging.

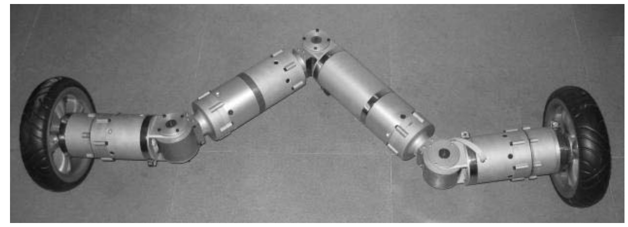


Fig. 8. One picture of the two-wheeled mobile robot

E. A Biped Tree-Climbing Robot

Inspired by climbing motion of inchworms, slothes, monkeys and chimpanzees, we have set up a robot that can climb poles, trees and trusses in biped mode using three or four T-typed modules, two I-typed modules and two grippers, as shown in Fig.9(a). Clearly the robot has strong functions of both climbing and manipulation.The robot climbs in a biped mode as follows: 1) Supported by one gripper firmly grasping an object (a pole, a tree or a truss), the robot moves the other end to a target position; 2) after the latter gripper grasps the target stably, the robot releases the former gripper and moves it to a new target position; 3) the robot repeats the above steps, the two grippers interchange their (supporting or swinging) roles. The mechanical design and basic analysis of grasp force the biped climbing robot can be found in [3].

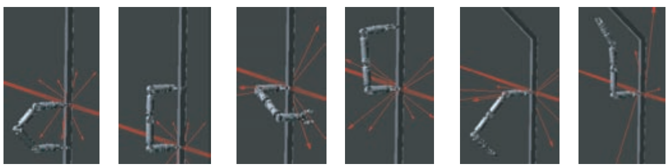
We present three climbing gaits similar to the preceding biped walking gaits, namely the inchworm gait, turning-around gait and turning-over gait. Fig.10 shows several snapshots of an animation of the robot climbing a pole with these gaits in turn (Fig.10(a) and (b) are of inchworm gait, (c) and (d) turning-around gait, (e), (f) and (g) turning-over gait). The details of the presented gaits are referred to [5].

F. A Biped Wall-Climbing Robot

Using two suckers to replace the two grippers in the above climbing robot gives rise to a new robot – biped wall-climbing robot, as shown in Fig.9(b). Owing to the main body in structure similar to an arm, the robot has the following important features which most of the existing walling climbing robots do not possess: 1) strong wall-transmitting ability: the robot can transit from different walls trivially; 2) strong obstacle-negotiating ability: it can step over obstacles on walls; 3) climbing in biped mode: the suckers at exchange their

(a) A tree-climbing robot (b) A wall-climbing robot

Fig. 9. Two kinds of biped climbing robots



(a) (b) (c) (d) (e) (f)

Fig. 10. Animation snapshots of the tree-climbing robot climbing a pole

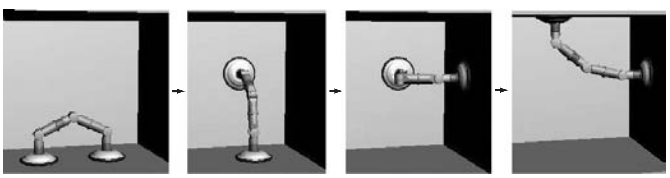


Fig. 11. The biped wall-climbing robot transmitting between walls

(sucking or releasing) roles in turn during climbing. To impose these functions or features to the systems has being been a goal in development of new wall-climbing robots which is admitted by many researchers and verified in miniature wall-climbing robots [1], [10], [11], [17], [18]. Our robot presents the solution by modular methodology using a few basic joint modules and two suckers of regular size. A virtual scenario of the robot transmitting between walls is illustrated in Fig.11.

V. Concluding Remarks

Modularization is an important trend and methodology in development of robotic systems. The benefits brought by modularization design include the versatility, reconfigurability, adaption, scalability, flexibility, lower-costs, and fault-tolerance of the systems. For these benefits and the needs of basic joint modules of regular sizes with low costs, we have developed two kinds of 1-DoF joint modules, which are I-typed and T-typed joint module. We have also developed several functional modules including grippers, wheels/feet and suckers. We have presented their design and basic functions.

With these modules, a variety of robotic systems can be built easily and flexibly. We have proposed several novel robotic systems built with modular methodology using these modules, among which are a 5-DoF manipulator, a 6-Dof biped walking robot, a two-wheeled mobile robot, a biped tree-climbing robot, and a biped wall-climbing robot. Built with the basic T-typed and I-typed joint modules, the main bodies of these robots are biped and actually arms, and hence the walking robot, the tree-climbing robot and the wall-climbing robot may have similar gaits. The features and benefits of these robots include simple structure, high mobility, wide adaption to environments, and potential manipulation function.

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