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## Climbing Robots

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### 1. Introduction

Today, due to technological advances of robotic applications in human life, it is necessary to overcome natural and virtual obstacles such as stairs which are the most known obstacles to the motion of such robots. Several research have been conducted toward the design of stair climbing and obstacle traversing robots during the past decade. A number of robots have been built for climbing stairs and traversing obstacles, such as quadruped and hexapod robots. Although these robots can climb stairs and traverse obstacles, they do not have smooth motion on flat surfaces, which is due to the motion of their legs. Buehler built a hexapod robot (RHex) that could ascend and descend stairs dynamically. He has also built a quadruped robot (SCOUT) which could climb just one stair (M. Buehler, (2002), U. Saranli, (2001), Martin Buehler, (2002) C. Steeves<sup>1</sup>, (2002)). Furthermore, a few wheeled and leg-wheel robots have been proposed that either can climb only one stair or can not climb stairs individually and need to be supported by a person; Therefore, they are not good enough to be practical. Koyanagi proposed a six wheeled robot that could climb a stair (Eiji KOYANAGI). Kumar offered a wheelchair with legs for people with disabilities which could climb a stair (Parris Wellman, (1995), Venkat Krovi, (1995)). Halme offered a robot with movement by simultaneous wheel and leg propulsion (Aarne Halme (2001)). Quinn built Leg-Wheel (quadruped and hexapod) robots (Mini-Whegs) that could ascend, descend and jump stairs (Roland Siegwart, (1998), Nakayama R (1998)). Kmen invented a wheelchair with wheels (iBOT 3000) that could climb stairs by human support (A. Crespi). Also NASA designed Urban Robot which was a Tracked robot. It could climb stairs and curbs using a tracked design instead of wheels. The Urban Robot (Urbie) led to the PackBot platform of iRobot. Besides, Dalvand designed a wheeled mobile robot that has the capability of climbing stairs, traversing obstacles, and is adaptable to uphill, downhill and slope surfaces (Dalvand and Moghaddam (2003)).

Parallel platforms present many advantages that make them especially suitable to be used as climbing robots, in contrast with other types of climbing robots with legs. The availability of a great number of redundant degrees of freedom of the climbing robots with legs does not necessarily increase the ability of the machine to progress in a complex workspace. Climbing robots with legs use their legs to hold and move the robot body (H.R. Choi, (2000)). The legs mechanisms have a sequential configuration that originates a limitation in the robot movement and great torques in the actuators placed on the legs base. Architecture of serial legs also implies a limit on load capability. This is a typical effect on serial articulated mechanisms influenced by force and torque effects present on joints (J.P. Merlet, (1992)).

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Due to the preceding, it is also well known that weight/power relation on climbing robots is high while both the useful load capacity and the velocity of serial mechanisms are limited. In contrast with the limitations of the robot legs to climb, the use of a Gough-Stewart platform as a climbing robot (Buehler M., (2002)), solves many of these limitations and opens a new field of application for this type of mechanism. In order to emphasize the great performance of the G-S parallel robot as a climbing robot, it is pertinent to remember that this type of parallel robot is based on a simple mechanical concept that consists of two rings (platforms) linked with six linear actuators joined through universal and spherical joints (this type of structure is also referred as a 6-UPS parallel robot). These characteristics allow to obtain a mechanical structure of low weight and high stiffness, which is able to reach high velocities and develop large forces with a very important advantage: the low cost of manufacturing (D. Lazard, (1992)).

## 2. Leg-Wheel Robots

There is an enormous variety of walking robots in the world today. Most of them have six legs to maintain good static stability, many have 8 legs for greater speed and higher load capacity and there are some that implement clever balancing algorithms which allow them to walk on two legs to move over sloping ground and to climb up and down stairs, like humans do (eg. Such as Honda's Asimo robots). In general, the main motive behind the creation of most of these walking machines is to enjoy experiencing about the physics of motion by applying "state of the art" technologies to control the movement of articulated limbs and joint actuators. After all, it is not an easy task to recreate the efficient yet very complex movements of biological insects and mammals which effortlessly execute various types of periodic gait patterns and adaptive gaits and very high speeds. (Visit the CLAWAR web site to view most of the modern walking robots that have been built in recent years). Unfortunately, due to the very complex and multi-disciplinary nature of this field of research, very few walking robots and multi-legged vehicles have been proven to be the "best and most economical solution" for solving problems in domestic, industrial, construction, military or space applications. It seems as though most of today's small walking robots are only the result of human's fascination with the application and useful for entertainment only. In addition, the majority of large scale 'high-powered' walking robots are still in their "experimental" stages and are not commercially available for bulk purchasing. Most large scale walking robots lack sufficiently intelligent software for solving "real world" problems automatically and in the most cost effective manner possible. With the added flexibility of being able to control the foundation points of the vehicle while traversing over almost any type of irregular surface, comes the increased complexity of foot and joint control to maintain stability and coordinated movements for gait movements. Another major problem is the inherent slowness of legged and walking locomotion, compared to wheeled transport. It would be beneficial for a mobile robot to possess the advantages of extreme rough terrain negotiating flexibility, which multi-degree-of-freedom (MDOF) legs can offer, with the high-speed and simplicity afforded by wheels.

Such a multi-legged and wheeled robot would be able to find practical use in solving difficult transportation type problems in virtually any type of outdoor application where high speed is essential.

Some examples of useful applications for reliable, high speed, and high load carrying capacity walking vehicles include:

- A walking vehicle for paraplegic people or the elderly who cannot walk easily
- Deep sea or planet surveying and exploration on the moon or on Mars
- Automated or tele-remote controlled (semi-automated) construction
- Underground mining
- Automated agriculture (planting and harvesting) eg. Plustech foresting robot
- “Battlebots” to take the place of human soldiers on a battlefield
- Security or police robots that can patrol a defined area and identify or apprehend trespassers
- Firefighting robots that can climb over rough terrain and large obstacles to reach the heart of a fire with a fire extinguisher or water hose.
- Skeletal animatronic machines to take the place of “fake looking” 3D
- computer generated dinosaurs in monster films and science fiction movies. The Curtin University “Hydrobug” project involves the design, construction and testing of a 6-legged “insect-like” hybrid walking vehicle which will be able to carry three adult passengers over rough terrain or very broken ground with gaps, pot holes or obstacles which are too large for wheels to traverse. This vehicle is also designed to continue moving from level ground onto steep inclinations up to 45° to the horizontal. The Hydrobug is designed with the necessary degrees of freedom to walk over extremely rugged terrain using 6 three-degree-of-freedom articulated-limb legs. It will also be able to convert to 4-wheel-drive mode for high speed travel, while it’s legs are fully raised and its feet are kept high off the ground. This type of robot will be able to travel at high speeds on smooth roads.

### 3. Rough Terrain Climber Robots

Rough-terrain robot navigation has received a significant amount of attention recently, most prominently showcased to the broader public by the success of current Mars rover missions. In the future, increased autonomous capabilities will be required to accomplish ambitious planetary missions as well as a whole variety of Earth-bound tasks. This demand has led to the development of numerous approaches to solving the rough-terrain robot motion planning task. The common factor with all such research lies in the underlying characteristics of the rough terrain itself. By the very nature of the task, binary obstacle definitions cannot be exclusively applied to rough-terrain motion planning. Each configuration of the robot operating on the terrain has a characteristic difficulty associated with its attainment. Depending on the properties of the problem being studied, different aspects of the robot/terrain interaction assume high relevance. These factors are consequently included in the terrain abstraction while other aspects are typically chosen to be omitted. Nevertheless, independently of the terrain model used, there remains the specific difficulty associated with reaching a particular configuration.

Further, in near future, robots will take the place of human labor in many areas. They will perform various hazardous duties like fire fighting, rescuing people, demining, suppressing terrorist outrage, and scouting enemy territory. To make use of robots in these various circumstances, robots should have the ability of passing through rough terrain such as steps. There are three types of moving mechanisms for this kind of robots in general : wheel type, track type and walking type mechanism. Robots with wheel mechanism are inferior to robots with track when they are to move on rough terrain. Walking robots have complex

structures so that they are usually difficult to control and slower in speed. In that sense, the track mechanism has advantages in high speed driving and mobility under severe conditions. In spite of these merits, it consumes more energy than the others. Therefore it is needed to design a robot to overcome this drawback. Some recent researches are to develop a novel track mechanism with flexible configurations adaptive to various ground conditions.

4. Wheeled Robots (MSRox)

4.1 MSRox Design

MSRox (Fig. 1) has hybrid mechanism called Star-Wheel (Fig. 2) because of both walking and rolling capabilities.



Figure 1. MSRox



Figure 2. Star-Wheel

MSRox has 12 regular wheels designed for motion on flat or uphill, downhill, and slope surfaces. Also it has 4 Star-Wheels that have been designed for traversing stairs and obstacles. Each Star-Wheel has two rotary axes. One is for its rotation of 12 regular wheels when MSRox moves on flat surfaces or passes over uphill, downhill, and slope surfaces. The second one is for the rotation of Star-Wheels when MSRox climbs or descends stairs and traverses obstacles.

The MSRox mechanism is similar to Stepping Triple Wheels (Saltaren R., R. Aracil) and AIMARS (Advanced Intelligent Maintenance) (Saranli U., M. Buehler). The Stepping Triple Wheels concept for mobile robots allows optimal locomotion on surfaces with little obstacles. AIMARS is a maintenance robot system for nuclear power plants which can conduct simple works instead of workers.

The presented version of MSRox can not steer and the new version of it will be equipped with the steering capability in near future. In doing so, the six left and six right wheels should be driven individually which causes the robot to skid steer similar to PackBot.

**Discussion Of The Locomotion Concepts**

Four main principles - rolling, walking, crawling and jumping - have been identified for full or partial solid state contact. However, additional locomotion principles without solid state contact could be of interest in special environment.

Most of the mobile robots for planetary exploration will move most of their time on nearly flat surfaces, where rolling motion has its highest efficiency and performance. However, some primitive climbing abilities are required in many cases. Therefore hybrid approaches, where for example rolling motion is combined with stepping, are of high interest.

Specification Concept	Min. No. of Motors	Volume	Energy Consumption	Robustness	Inherent Complexity	Stair & Obstacles Traversing	Speed
Rolling - Wheels - Track [13]-[14]	2 - 3	o	+	+	+	-	+
	2 - 3	-	+	+	o	+	+
Walking [2]-[10]	> 3	+	-	-	-	o	o
Crawling [19]	3	+	-	o	o	-	o
Jumping [9]-[10]	3	o	-	-	-	o	o
Triple Wheels [17]-[18]	4	+	o	o	-	+	+
Star-Wheels	2 - 3	+	++	+	-	+	+

‘++’: very good; ‘+’: good; ‘o’: balanced; ‘-’: poor; ‘--’: very poor

Table 1. Comparison of the different locomotion concepts



Table 1 gives an overview of characteristics of the different locomotion concepts. The scoring represents our personal opinion and is of course not unbiased. As can be seen, the rolling locomotion has only little disadvantages, mainly concerning the traversing of stairs and obstacles. This weak point is solved in the proposed Star-Wheel, but the complexity is lowered. The Star-Wheel which is also included in the table (Saltaren R., R. Aracil) was selected as the most promising candidate for the innovative solution.

PackBot which is a special tracked robot has great advantages and very limited disadvantages. One of the disadvantages is due to its flippers. In utilizing PackBot as a Wheel-Chair, the flippers must be very large that causes some problems for the passenger. Another is due to the transmission time from stairs to flat surfaces. In this instance, the contact between PackBot and the terrain is a line which causes serious shock to the robot. The problem is evident in the movie of PackBot motion (Stewart D.).

The power consumption comparison between MSRox and a tracked robot (PackBot) and a walking robot (RHEX) and also a comparison with other stair climbing robots (Table 5) will be presented later in this section.. Also the comparison between MSRox speed and other stair climbing robots is in section XIV (Table 5).

Star-Wheel Design

Deriving the Star-Wheel parameters depends on the position of Star-Wheel on stairs where it depends on two parameters, the distance between the edge of wheel on lower stair and the face of next stair ( $L_1$ ), and the distance between the edge of wheel on topper stair and the face of next stair ( $L_2$ ). By comparing these parameters, three states may occur:

$$L_1 < L_2$$

In this case (Fig. 3), after each stair climbing,  $L_2$  becomes greater and after several climbing it will be equal or greater than  $b$  ( $L_2 \geq b$ ). In this case, the wheel is at the corner of the stair and the robot will fall down to lower stair and a slippage will be occurred.

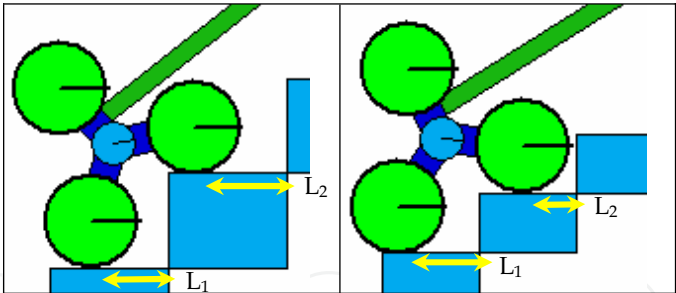


Figure 3. Star-Wheel position when  $L_1 < L_2$  (Left) and  $L_1 > L_2$  (Right)

It should be noted that after each slippage, the robot will continue its smooth motion until next slippage.

$$L_1 > L_2$$

In this case (Fig. 3) after each stair climbing,  $L_2$  becomes smaller until the wheel hits the corner of the stair and the robot will encounter difficulties in climbing stairs. It should be noted that this slippage will continue in all stair climbing, but doesn't stop robot motion.

$$L_1 = L_2$$

In this case the  $L_1$  and  $L_2$  don't change and remain constant while climbing stairs. Therefore the cases A and B are not suitable since the robot will encounter problems while climbing

stairs, but the case C is suitable for climbing stairs smoothly. Thus case C is considered in deriving the Star-Wheel's parameters. It should be noted that the values of  $L_1$  and  $L_2$  for derivation of the parameters may be any values but equal.  $L_1$  and  $L_2$  are assumed equal to the radius of regular wheels ( $L_1 = L_2 = r$ ) (Fig. 4).

In the design of Star-Wheel, five parameters are important which are the height of stairs ( $a$ ), width of stairs ( $b$ ), radius of regular wheels ( $r$ ), radius of Star-Wheel, the distance between the center of Star-Wheel and the center of its wheels ( $R$ ) and the thickness of holders that fix wheels on its place on Star-Wheels ( $2t$ ) (Fig. 4).

For the calculation of radius of Star-Wheels ( $R$ ) with respect to the stair size ( $a$ ,  $b$ ), this equation is used:

$$R = \sqrt{\frac{(a^2 + b^2)}{3}} \quad (1)$$

where  $a$  and  $b$  are the height and width of stairs.

The minimum value of the radius of regular wheels ( $r_{\min}$ ) to prevent the collision of the holders to the stairs (Fig. 5) is derived as follows:

$$r_{\min} = \frac{6Rt + a(3b - \sqrt{3}a)}{(3 - \sqrt{3})a + (3 + \sqrt{3})b} \quad (2)$$

where  $R$  is the radius of Star-Wheels and  $t$  is the half of the thickness of holders.

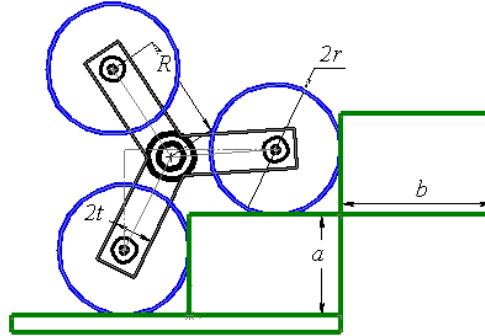


Figure 4. Star-Wheel Parameters

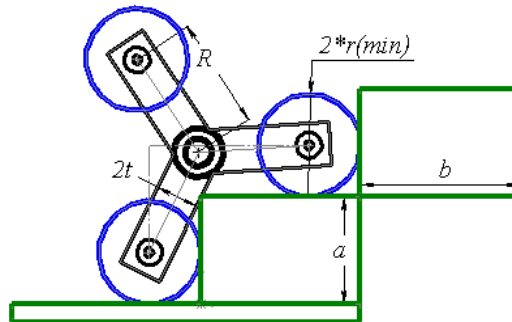


Figure 5. Star-wheel with  $r_{\min}$



The maximum value of the radius of regular wheels ( $r_{\max}$ ) to prevent the collision of the wheels together (Fig. 6) is derived as follows:

$$r_{\max} = \frac{\sqrt{(a^2 + b^2)}}{2} \tag{3}$$

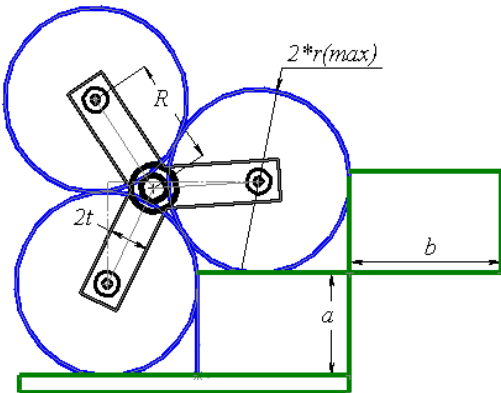


Figure 6. Star-wheel with  $r_{\max}$

The maximum value of the thickness of holders ( $t_{\max}$ ) to prevent the collision of the holders to the stairs (Fig.7) is derived as follows:

$$t_{\max} = \frac{ar(3 - \sqrt{3}) + br(3 + \sqrt{3}) + a(\sqrt{3}a - 3b)}{6R} \tag{4}$$

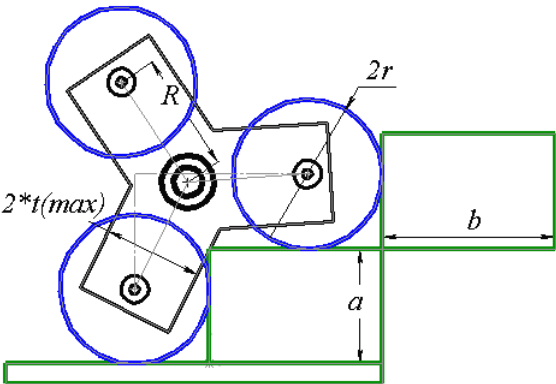


Figure 7. Star-wheel under  $t_{\max}$  condition

Furthermore, the maximum height of stairs that MSRox with specified parameters of Star-Wheels ( $a$ ,  $b$ ,  $r$ ,  $t$  and  $R$ ) can pass through them (Fig. 8) can be derived as follows:

$$a_{\max} = \sqrt{(a^2 + b^2 - r^2)} = \sqrt{3R^2 - r^2} \tag{5}$$

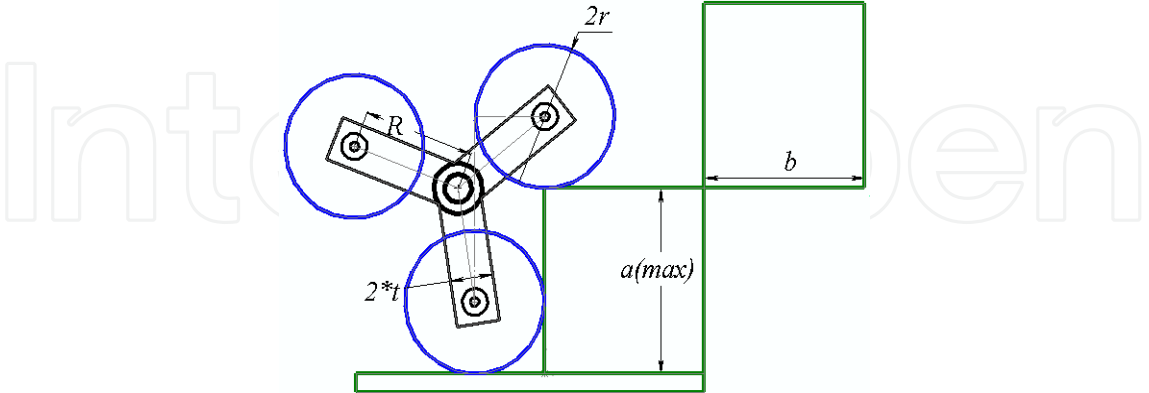


Figure 8. Star-wheel with  $a_{max}$

Star-Wheels have been designed for traversing stairs with 10 cm in height and 15 cm in width ( $a=10, b=15$  cm).

Considering the values of  $r_{max}$ ,  $r_{min}$  and  $t_{max}$  and available sizes of wheels and holders, the radius of regular wheels is resulted equal to 6.5 cm ( $r=6.5$  cm) and the thickness of holders is resulted equal to 4 cm ( $t=2$  cm). Also considering values of  $a$ ,  $b$ ,  $r$  and  $t$ , the radius of Star-Wheels is calculated from (1) equal to 10.40 cm, this parameter, due to the limitation of the chain joints, is considered equal to 10.8 cm.

MSRox having Star-Wheels with above parameters can traverse stairs of about 17 cm in height maximum that is derived from (5).

**MSRox Design Analysis**

*Star-Wheel Power Consumption*

While ascending and descending stairs and while Star-Wheels are rotating, the robot’s weight exerts extra torques to Star-Wheels. Now there are two sources of torques, one source is from the robot’s weight and the other is from the Star-Wheels’ motor.

In some cases, even if the Star-Wheels’ motor is turned off, due to the robot’s weight; the Star-Wheels will rotate. This rotation sometimes becomes faster than the rotation due to the Star-Wheels’ motor which runs the torque negative. These cause the wheels to generate energy back into the system.

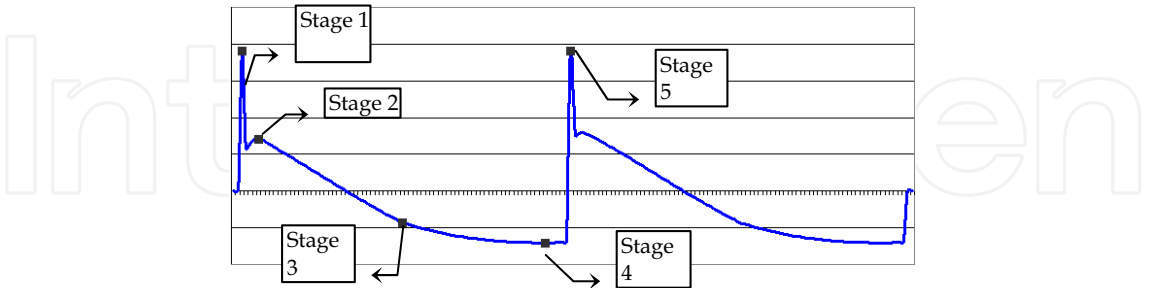


Figure 9. Torque consumption of a Star-Wheel

For example, consider that the robot’s Star-Wheels are rotating on flat surfaces. The torque of one of the star-Wheels from being negative or positive is shown in Fig. 9.

This motion has five stages. Stage 1 (Fig. 10) is the beginning of Star-Wheels’ rotation. Star-Wheels’ motor creates a positive torque to overcome the robot’s weight. Therefore the torque is positive and the motor endures a shock.

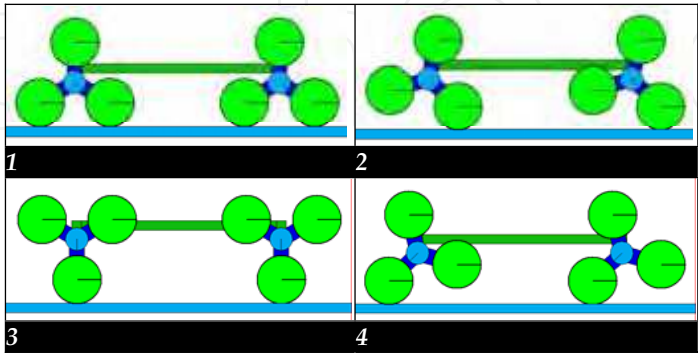


Figure 10. Different stages of Star-Wheels’ rotation

In Stage 2 (Fig. 10) the height of robot’s gravity center increases. In this situation similar to stage 1, Star-Wheels’ motor generates a positive torque to overcome the robot’s weight. Therefore the torque becomes positive (Fig. 9). Stage 3 (Fig. 10) is while the robot is on 4 wheels and the height of robot is maximum. In this, the robot’s weight torques are zero and the Star-Wheels’ angular velocity, due to the initial angular velocity, is greater than the velocity of motor. Therefore the motor rotates with higher speed. This causes not only no power motor consumption but the wheels generate energy back into the system. Therefore the consumption torque is negative (Fig. 9). Stage 4 (Fig. 10) is while the robot is on 4 wheels and the height of robot’s gravity center is decreasing. This stage is similar to stage 3 but with the difference that the angular velocity due to the initial angular velocity is in highest value. Therefore the consumption torque is negative and its value is equal to the value of the consumption torque in stage 2 (Fig. 9). Stage 5 is exactly similar to stage 1 and the robot is on 8 wheels and the height of robot’s gravity center has minimum value. In this stage, similar to the stage 1, due to the collision between the wheels and ground, the motor endures a shock. The greater range of negative torques is between stages 3 to 5, therefore the greater time between stages 3 to 5, the greater negative torques.

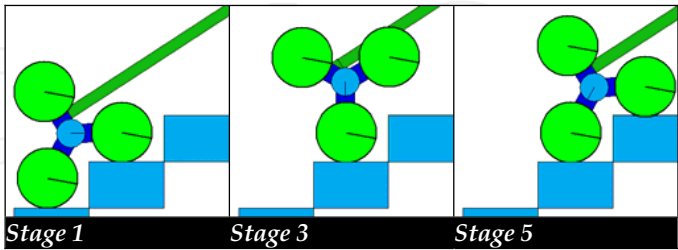


Figure 11. Stages 1, 3 and 5 while climbing stairs

These 5 stages occurs while ascending and descending stairs. Only there is a big difference which is the difference between torque in front and rear Star-Wheels. While climbing stairs

the torque of rear Star-Wheel is greater than the torque of front Star-Wheel and therefore the power consumption of climbing for rear Star-Wheels has greater values.

The time between stages 1 to 3 while climbing is greater than the time between stages 3 to 5 (Fig. 11), so the range of negative values are very smaller.

Vice versa, while descending, the torque of rear Star-Wheel is smaller than the torque of front Star-Wheel and therefore the power consumption of descending for rear Star-Wheels has smaller values.

The time between stages 1 to 3 while descending is smaller than the time between stages 3 to 5 (Fig. 12), so the range of negative values are very greater.

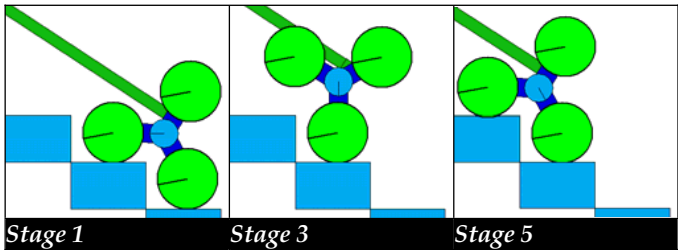


Figure 12. Stages 1, 3 and 5 while descending stairs

Stairs Climbing Power Consumption

After modeling MSRox and simulating its motion in Working Model software for stairs climbing (Section V), power consumption for one of the front and one of the rear Star-Wheels considering 26 rpm for angular velocity of Star-Wheels are calculated as Fig. 13.

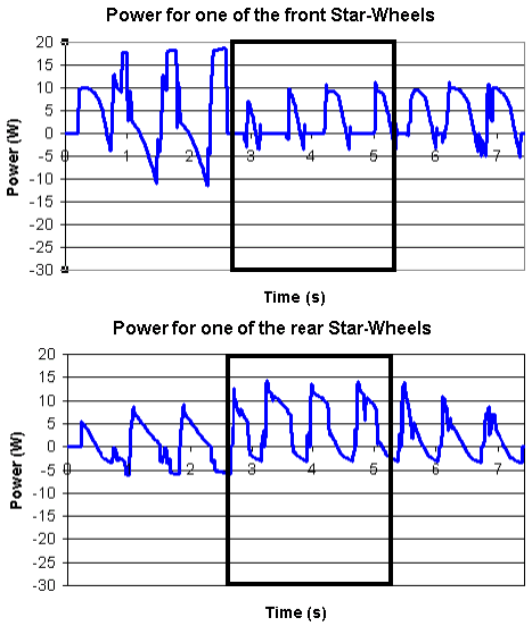


Figure 13. Power consumption for one of the front (Top) and one of the rear (Bottom) Star-Wheels for climbing six stairs

Rectangles in above figures are the time ranges that MSRox is on the stairs and the previous ranges are for transmission from ground to the stairs and the next ranges are for transmission from stairs to the ground. Comparison of above figures between rectangles indicates that the rear Star-Wheels endure the greater torque and require greater power when MSRox is climbing stairs. Combining above figures, the required consumption power for all Star-Wheels for climbing six stairs can be derived as Fig. 14.

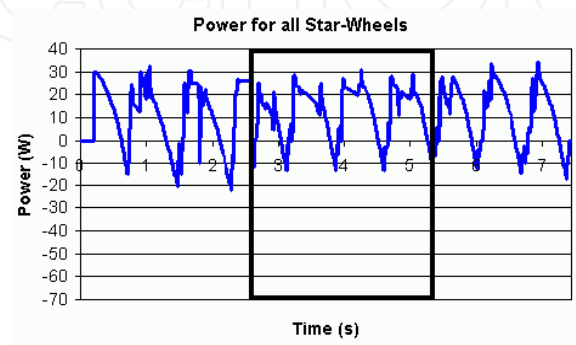


Figure 14. Consumption power for climbing six stairs

Fig. 14 shows that the maximum power of stair climbing is 34.104 W. So, the maximum essential torque for stairs climbing, considering ratio of the power transmission in MSRox system (1.9917), is equal to 6.2889 N.m.

*Stairs Descending Power Consumption*

Also by simulation of MSRox movement in Working Model software for stairs descending, power consumption for one of the fronts and one of the rear Star-Wheels are calculated as Fig. 15.

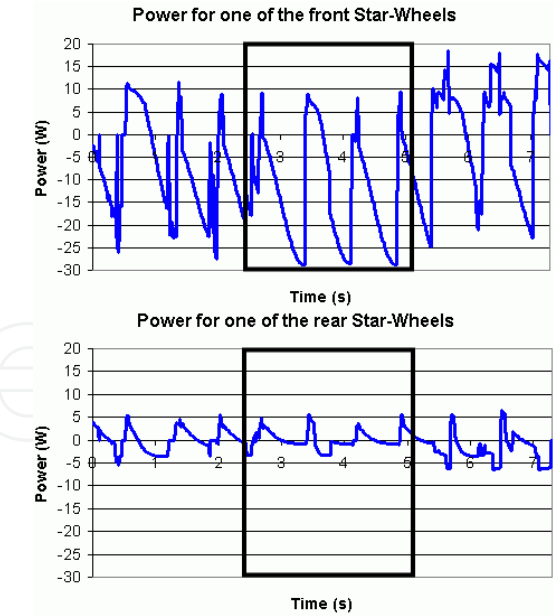


Figure 15. Power consumption for one of the front (Top) and one of the rear (Bottom) Star-Wheels for descending six stairs

Comparison between powers in rectangles of the above figures indicates that the front Star-Wheels endure the greater torque and require greater power while MSRox is descending stairs. The power consumption for all Star-Wheels for descending six stairs is shown in Fig. 16.

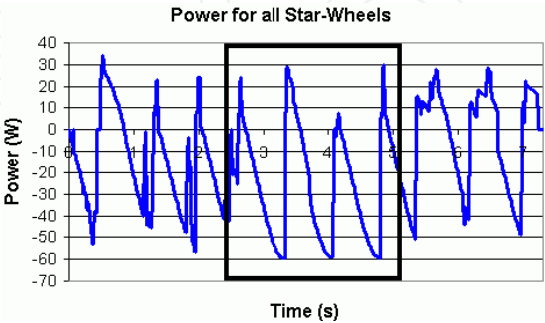


Figure 16. Consumption power for descending six stairs

In Fig. 16 the maximum power is 33.251 W. So the maximum value of essential torque for stairs descending is calculated as 6.1317 N.m. Hence, the maximum required value of power for Star-Wheels active motor for both ascending and descending stairs is equal to 34.104 W. According to Fig. 16, the motor of Star-Wheels must endure negative torques; this means that it must work as a brake sometimes; Therefore, for having the capability of stairs descending, in MSRox, it is essential to have a non-backdrivable motor for rotation of Star-Wheels.

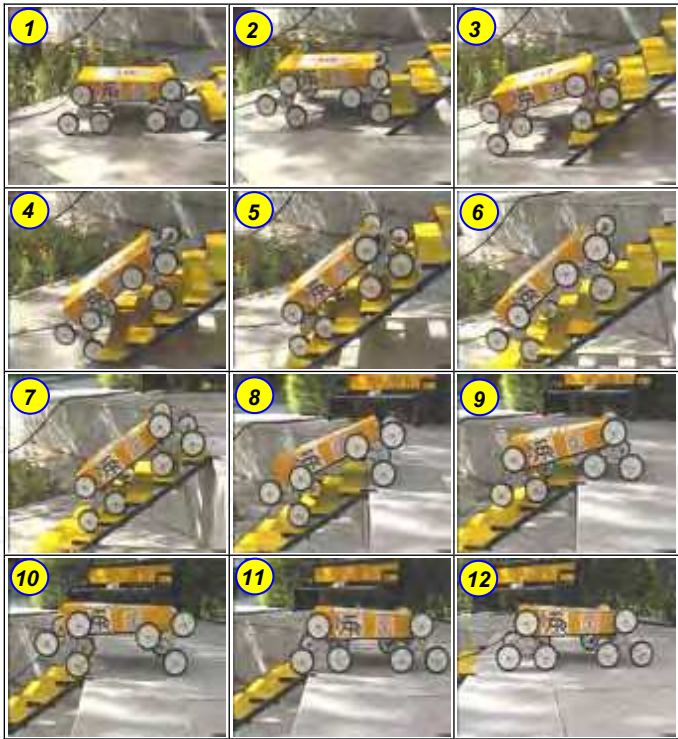


Figure 17. MSRox standard stairs climbing in practice

Comparison between results of static and dynamic design indicates that the results are similar approximately and therefore the two designs are done correctly and are logical.

**Algorithm of Climbing Standard Stairs**

Following computer simulation, the MSRox has been designed and manufactured as it should be and different stages of climbing standard stairs in practice are shown in Fig. 17. Two above figures indicate that the MSRox behavior in simulation and reality are similar to each other and the predicted motion for climbing standard stairs in simulation is repeated closely in practice that indicate that MSRox has been design properly.

**Algorithm of Climbing Full-Scale Stairs**

Beside standard stairs, MSRox can climb stairs with wide range in size, providing their height be smaller than 17 cm.

Also MSRox climbing these stairs (14 cm in height and 37 cm in width) in reality has been tested and different stages of its motion are shown in Fig. 18.

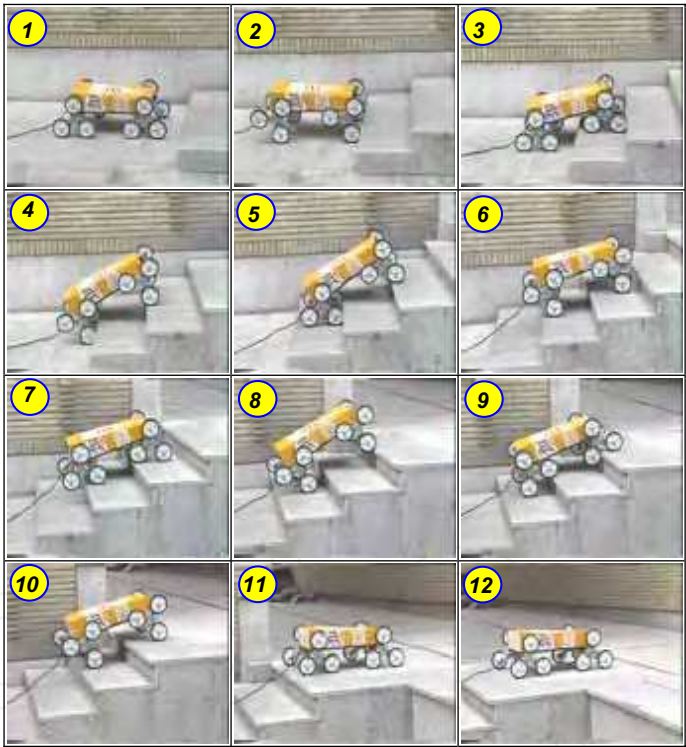


Figure 18. MSRox full-scale stairs climbing in practice

Above figures indicate that MSRox can traverse broad ranges of stairs in size providing the step size is smaller or equal to 17 cm and even if its regular wheels come in contact with the stairs tip or the vertical rise portion of stairs, it can adapt itself toward stairs and finally traverse them, also MSRox movement is independent of the number of stairs.



MSRox Performance to Step Size

The performance of MSRox due to step sizes is discussed through simulation. MSRox motion while traversing 45 stairs with different sizes has been simulated and the results are given in Table 2 and 3.

<div>W</div> <div>H</div>	7	9	12	15	18	21	25	35	45
2	0.47	0.47	0.63	0.64	0.74	0.80	0.91	1.23	1.46
6	0.57	0.58	0.80	0.74	0.74	0.89	0.96	1.24	1.51
10	---	0.80	0.75	0.75	0.80	0.96	0.96	1.24	1.62
14	---	0.75	0.74	1.12	1.13	1.18	1.29	1.29	1.73
17	---	---	---	1.18	1.24	1.29	1.29	1.73	1.78

“H”: Step Height ; “W”: Step Width (cm)

Table 2. MSRox Speed (Second/Stair) While Climbing Different Stairs Size

<div>W</div> <div>H</div>	7	9	12	15	18	21	25	35	45
2	1	0	2	1	3	3	1	10	1
6	2	4	14	11	1	6	5	11	3
10	---	13	5	0	3	5	4	5	7
14	---	6	2	14	8	9	11	2	9
17	---	---	---	9	10	11	9	18	9

“H”: Step Height ; “W”: Step Width (cm)

Table 3. Average Num. Of Slippages in MSRox Motion

The MSRox speed and the number of slippages during the motion depend on five parameters which are friction force, step size (height and width), Star-Wheels size (the distance between the centers of regular wheels), Star-Wheels speed and the distance between the centers of front and rear Star-Wheels. The MSRox has been designed for 10x15 steps size and the number of slippages while climbing this step is zero. Dotted cells in above tables indicate that MSRox can’t climb those stairs due to the high slope of the stair.

Obstacles Traversing

The MSRox can traverse any terrain that has obstacles with maximum height 17 cm. Different stages of traversing rough terrain with two irregular obstacles are shown in Fig. 19.

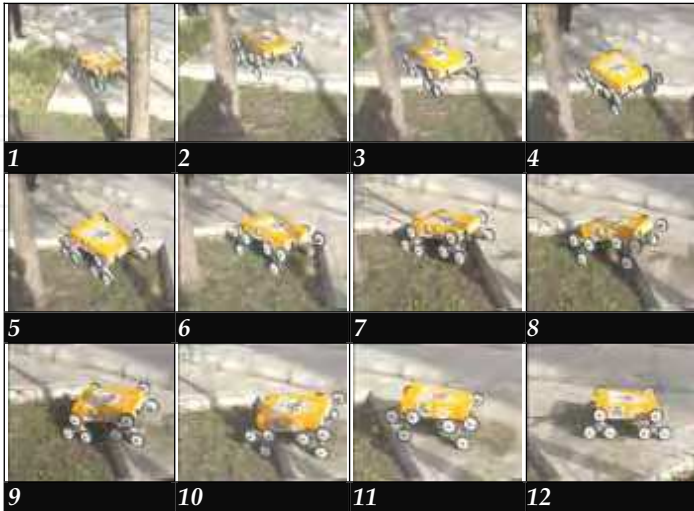


Figure 19. different stages of traversing rough terrain

**Similarity of Star-Wheels and Human Legs**

While traversing stairs or obstacles, the angle of the regular wheels with respect to the robot body, is constant. This phenomenon is the most important ability in MSRox which is vital for the successful climbing.

This feature has been inspired from the human legs where the angle of toes with respect to the human body while traversing stairs is fixed.

This similarity causes the stability of wheels position on the stairs. This also prevents the wheels to rotate in their position freely at the time of climbing and prevents the robot from falling off at the time of descending (Fig. 20).

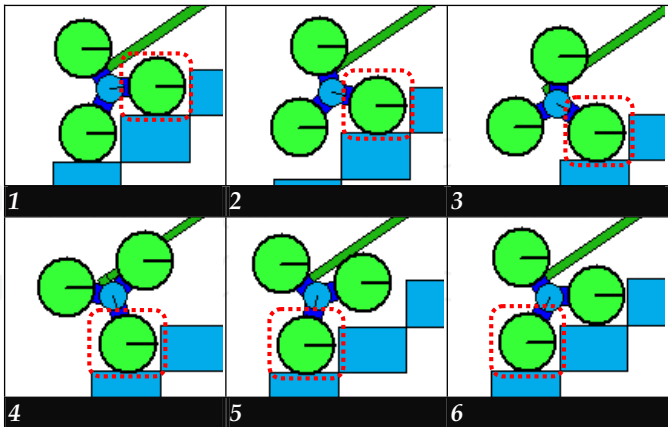


Figure 20. Similarity of Star-Wheels and Human Legs in simulation

This similarity in actual robot is shown in Fig. 21.

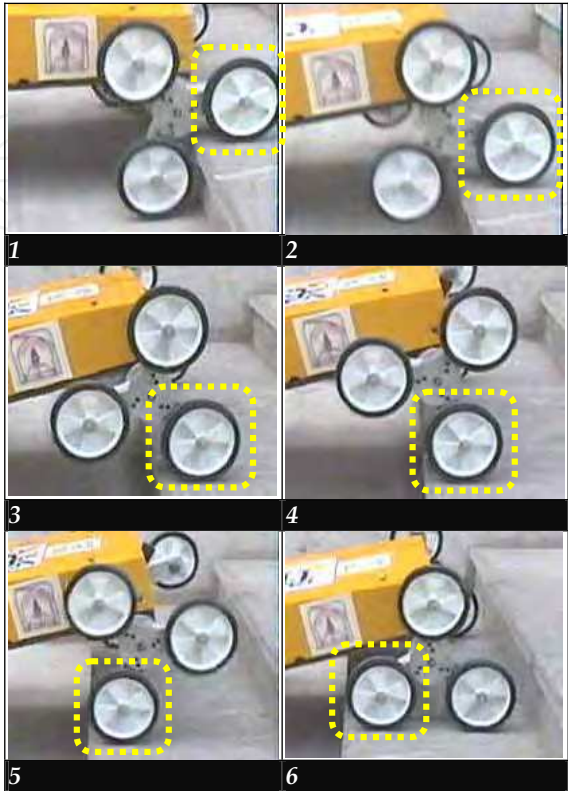


Figure 21. Similarity of Star-Wheels and human legs in practice

According to the above figures the specified wheel has not any rotation and acts as a fixed base for MSRox.

The MSRox Motion Adaptability

While the robot moves on flat, uphill, downhill or slope surfaces, the star-wheels can rotate freely around their axes, that causes the robot adapts itself with respect to the curvature of the path. This adaptability also prevents the shocks that may be caused by the changes of surfaces slope. Also it keeps all 8 regular wheels in contact to the ground and prevents the separation of the regular wheels and the ground.

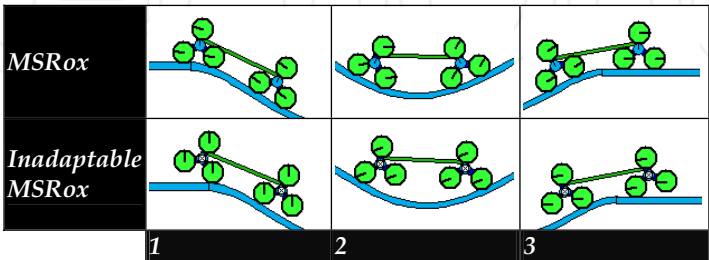


Figure 22. Comparison of MSRox and inadaptable MSRox

Different stages of traversing slope surfaces by MSRox and inadaptable MSRox are simulated in computer (Fig. 22). This capability increases the motion adaptability of the robot. It should be noted that this behavior is due to the gravity force of the robot itself and there is no need for an extra component to get this property. MSRox adaptability in practice is shown in Fig. 23.

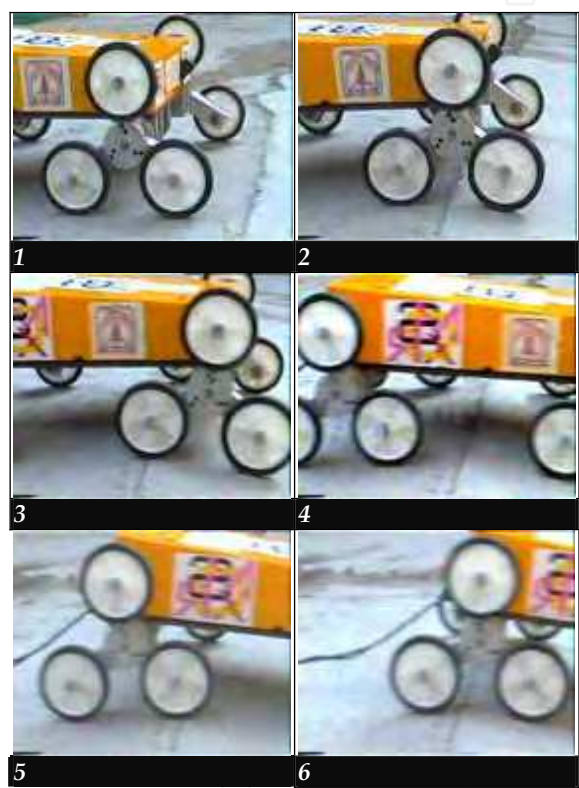


Figure 23. The MSRox adaptability in practice

According to Fig. 23, Star-Wheels can rotate freely around their axes in practice and allow MSRox to adapt itself toward curved surfaces. For example if MSRox didn't have such a capability, front wheels of front Star-Wheels had to rise from ground in stage 3 (Fig. 23), but all wheels of Star-Wheels kept on the ground while traversing this terrain.

**The MSRox Stability**

A question may come to mind that what if the input power of MSRox is cut while climbing stairs? Will MSRox fall down from stairs? To answer this question it must be said that if such an accident occurs, MSRox will only go back smoothly to the latest stair which it has been climbing it and will not happen to fall. (Fig. 24).

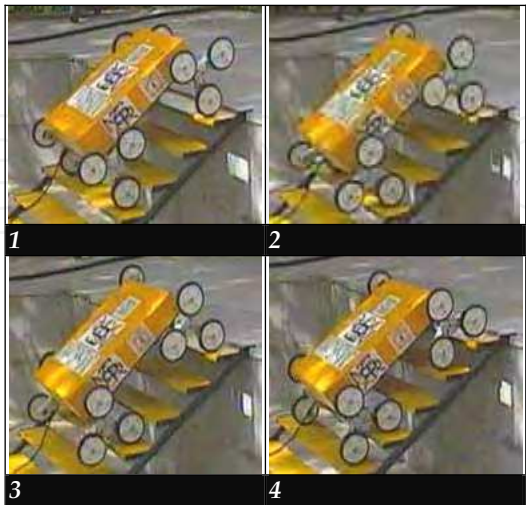


Figure 24. MSRox stability

**MSRox Control System**

The MSRox control system is a microcontroller based system that includes actuators, a sensor and a keypad.

*MSRox's Actuators*

This wheeled mobile robot has two degrees of freedom in mobile mechanism. One degree of freedom is for the 12 regular wheels and the other is for the Star-Wheels and each of them is driven by a 24 V DC motor with specifications in Table 4.

Purpose	Output (Watt)	Gear Ratio
12 regular Wheels	12	1/16
4 Star-Wheels	30	1/75

Table 4. DC Motors

Total required power in MSRox in comparison to RHex and PackBot is very low. RHex with 7.247 kg in weight has six 20 W DC brushed motors with 1:33 gear ratio and the maximum output torque per leg is 3.614 Nm (Steeves C., M. Buehler1). The difference between MSRox and RHex power consumption is due to the wheel-based motion of MSRox and leg-based motion of RHex. PackBot with 18 kg in weight needs 24-300W depending on terrain and use (Wellman P., Venkat Krovi), but MSRox in worst condition needs only 30W. Also MSRox has a clutch (24 V - 12 W DC) that is used as a brake for fixing regular wheel axes when Star-Wheels are rotating and MSRox is traversing stairs and obstacles. This clutch is also used to stop MSRox movement when it moves on flat, uphill, downhill or slope surfaces. According to Table 5 it can be said that MSRox is the fastest stair climber mobile robot that has smooth motion on flat surface due to its wheel-based motion.

5. Conclusion

It can be concluded that the MSRox mechanism works properly and can be used for traversing stairs and obstacles and passing over any uneven terrain.

Speed (Second/Stair)	Robot Name
0.6	Raibert Biped
<b>0.75</b>	<b>MSRox</b>
<1 (from movie)	PackBot
1.5	Honda P3
1.0 - 1.55	RHex
2.6	WL-12RIII
3	Wheel-Leg Biped
10	MelCrab-II

Table 5. Stair Climbing Speeds

Moreover, the robot can be used for applications such as Wheel-Chairs to carry disabled people or for remote Space explorations or battle field identifications to run on rough and unknown terrain.

Comparing simulations and actual tests results, it can be verified that the derivations of Star-Wheels parameters and simulations of MSRox movement on flat or uphill, downhill and slope surfaces, and on stairs and obstacles are perfect and all of the equations have been derived correctly and can be trusted them for other researches on the MSRox behavior.

They also can be used to design Star-Wheels for any other special application or for intelligent and larger-scale Star-Wheels in MSRox II that can ascend and descend stairs and obstacles independent to their size and shape and it even traverse curved stairs.

It is shown, through experiments, that MSRox mechanism can successfully traverse stairs and obstacles and can negotiate uneven terrains. Moreover, the robot can be utilized in the development of wheel-chairs, space exploration, or surveillance where negotiating unknown and rough environments is required. Comparing simulation and actual test results, show that the derivation of Star-Wheels parameters, MSRox motion simulation on different terrains (involving stairs and obstacles), and equations of motion are in full agreement. Therefore, the findings can be trusted for further research on a newer platform called MSRox II which can negotiate more complex terrains such as curved stairs and large and irregularly-shaped obstacles.



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## **Bioinspiration and Robotics Walking and Climbing Robots**

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Nature has always been a source of inspiration and ideas for the robotics community. New solutions and technologies are required and hence this book is coming out to address and deal with the main challenges facing walking and climbing robots, and contributes with innovative solutions, designs, technologies and techniques. This book reports on the state of the art research and development findings and results. The content of the book has been structured into 5 technical research sections with total of 30 chapters written by well recognized researchers worldwide.

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