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Stair Climber Smart Mobile Robot (MSRox)

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Abstract. MSRox is a wheeled mobile robot with two actuated degrees of freedom which enables it to have smooth motion on flat surfaces. It has the capability of climbing stairs and traversing obstacles, and adaptability toward uphill, downhill and slope surfaces. MSRox with 82 cm in length, 54 cm in width and 29 cm in height has been designed to climb stairs of 10 cm in height and 15 cm in width; nevertheless, it has the capability of climbing stairs up to about 17 cm in height and unlimited widt.

In this paper, the motion systems and the capabilities of MSRox are described. Furthermore, experimental results of stair climbing and a comparison of the results with others are presented.

Keywords: mobile robot, stair climber, smart, wheeled

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. Many researches have been conducted toward the design of stair climbing and obstacle traversing robots during the past decade. However, a few 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 (Buehler et al., 2001; Saranli et al., 2000; Buehler; Steeves et al., 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 used practically. Koyanagi proposed a six wheeled robot that could climb a stair (Koyanagi and Yuta, 1999). Kumar offered a wheelchair with legs for people with disabilities which could climb a stair (Wellman et al., 1995; Krovi and Kumar, 1999). Halme offered a robot with movement by simultaneous wheel and leg propulsion (Halme et al., 2001). Quinn built Leg-Wheel (quadruped and hexapod) robots (Mini-Whegs) that could ascend, descend and jump stairs (http://biorobots.cwru.edu/ ; Quinn et al., 2001). Kmen invented a wheelchair with wheels (iBOT 3000) that could climb stairs by human support (Kamen et al., 1999; http://www.independencenow.com/nonsecure/ibot/index.html). Also NASA designed Urban Robot which was a Tracked robot. It could climb stairs and curbs using a tracked design instead of wheels (http://robotics.jpl.nasa.gov/tasks/tmr/homepage.html). The Urban Robot (Urbie) led to the PackBot platform of iRobot (http://www.irobot.com). 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 Moghadam, 2003a, b).

2. MSRox Design

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

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 the rotation of 12 regular wheels when MSRox moves on flat surfaces or passes over uphill, downhill, and slope surfaces.

Table 1. Compare of the different locomotion concepts.

Specification concept	Min. no. of motors	Volume	Energy consumption	Robustness	Inherent complexity	Stair & obstacles traversing	Speed
Rolling–Wheels Track	2–3	o	+	+	+	−−	+
(http://robotics.jpl.nasa.gov/tasks/tmr/homepage.html; http://www.irobot.com)	2–3	−	+	+	o	+	+
Walking (Saranli et al., 2001; Buehler; Steeves et al.; Koyanagi and Yuta, Wellman et al., 1995; Krovi and Kumar, 1999; Halme et al., 2001; http://biorobots.cwru.edu/; Quinn et al., 2001)	>3	+	−	−	−−	o	o
Crawling (Crespi et al.)	3	+	−−	o	o	−	o
Jumping (http://biorobots.cwru.edu/; Quinn et al., 2001)	3	o	−	−	−	o	o
Triple Wheels (Siegwart et al., 1998; Nakayama et al., 1988)	4	+	o	o	−	+	+
Star-Wheels	2–3	+	++	+	−	+	+

'++': very good; '+': good; '0': balanced; '–': poor; '−−': very poor.

Figure 1. MSRox.

Figure 2. Star-Wheel.

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 (Siegwart et al., 1998) and AIMARS (Advanced Intelligent Maintenance) (Nakayama et al., 1988). 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.

3. 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.

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

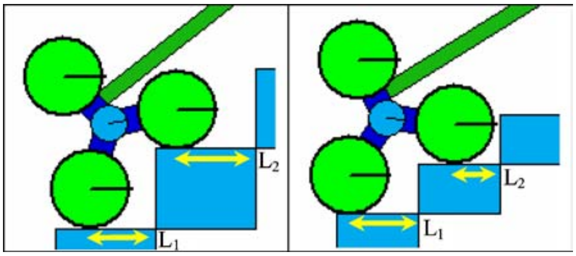

Figure 3. Star-Wheel position when $L_1 < L_2$ (left) and $L_1 > L_2$ (right).

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 (Siegwart et al., 1998) 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 (http://robotics.jpl.nasa.gov/tasks/tmr/movies/Air10FPS240x180.mov).

The power consumption comparison between MSRox and a tracked robot (PackBot) and a walking robot (RHex) is presented in Section 13. Also the comparison between MSRox speed and other stair climbing robots is in Section 14 (Table 5).

4. 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.

(A) $L_1 < L_2$

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.

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

(B) $L_1 > L_2$

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.

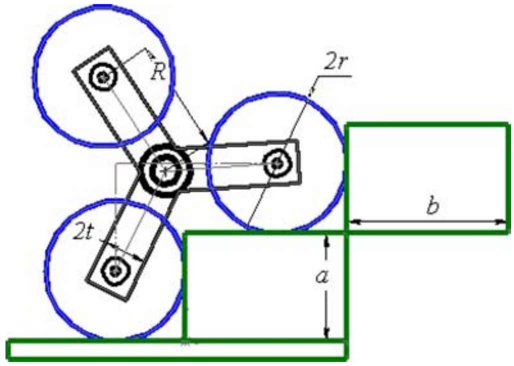

Figure 4. Star-Wheel parameters.

(C) $L_1 = L_2$

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:

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

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:

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

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

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

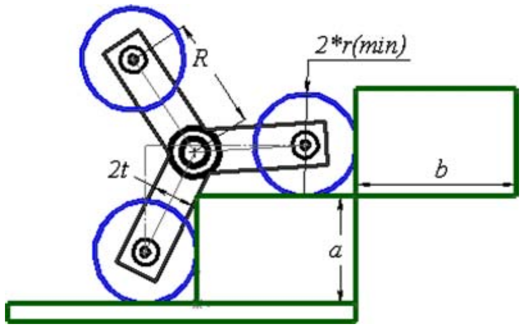

Figure 5. Star-wheel with $r_{\min}$.

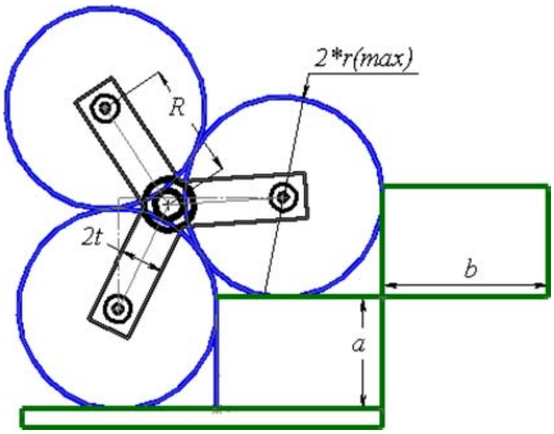

Figure 6. Star-wheel with $r_{\max}$.

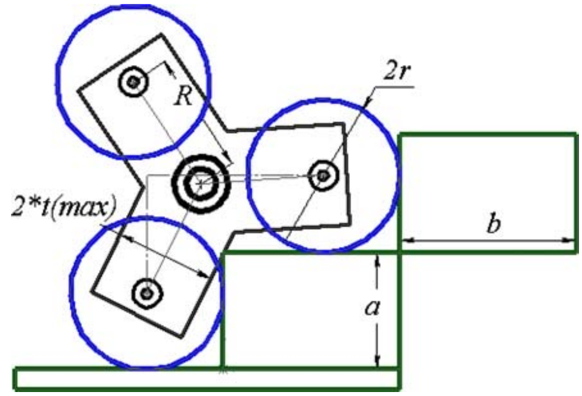

Figure 7. Star-wheel under $r_{\max}$ condition.

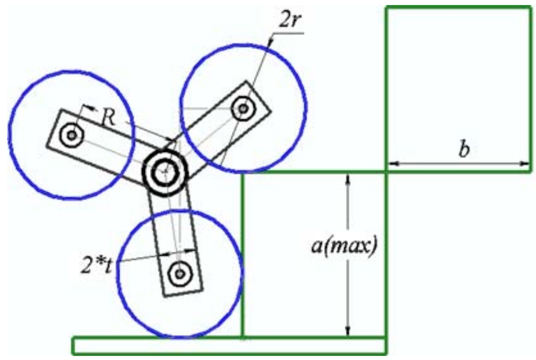

Figure 8. Star-wheel with $a_{\max}$.

derived as follows:

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

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:

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

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:

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

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).

5. MSRox Design Analysis

5.1. Static Design

MSRox is symmetric with respect to the main axis, so half of it can be considered for calculation. The free body diagram of the half of MSRox is shown in Fig. 9. Where T_1 and T_2 are the reaction torques in one of the front and one of the rear Star-Wheels axes. F_{1x}, F_{1y}, F_{2x}, F_{2y} are the reaction forces on one of the front and one of the rear Star-Wheels axes in x and y directions. f_1, f_2, N_1 and N_2 are respecting friction forces and stairs reaction forces in contact to stairs (other wheels don't have any contact with stairs). m_b and m_s are the half of the mass of MSRox's body and the mass of each Star-Wheel. θ is the angle between the holders and horizontal line and ø is the angle of MSRox's body with respect to the horizontal line that is equal to stairs slope when MSRox is on stairs.

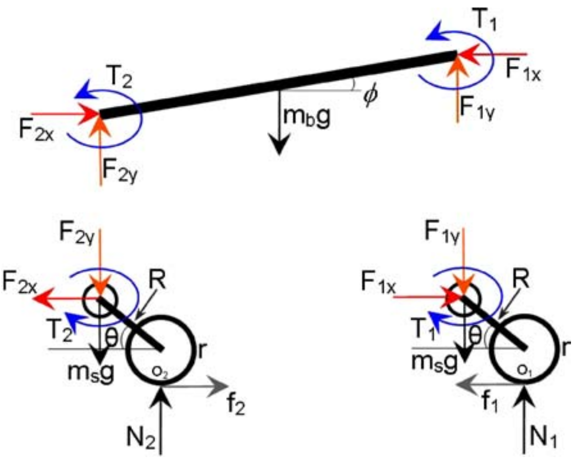

Figure 9. The free body diagrams of MSRox's main frame and Star-Wheels.

Equilibrium equations are derived as follows:

$$F_{1x} = F_{2x} = f_1 = f_2 = f \quad (6)$$

$$N_1 = F_{1y} + m_s g \quad \text{and} \quad N_2 = F_{2y} + m_s g \quad (7)$$

$$N_1 + N_2 = F_{1y} + F_{2y} + 2m_s g = (m_b + 2m_s)g = mg \quad (8)$$

where m is the half of the mass of MSRox.

Also considering Star-Wheels free body diagrams and (6), (7), T_1 and T_2 are derived as follows:

$$T_1 = N_1 R\cos(\theta) - f(r + R\sin(\theta)) \quad (9)$$

$$T_2 = N_2 R\cos(\theta) + f(r + R\sin(\theta)) \quad (10)$$

Comparing (9) and (10) indicates that T_2 is greater than T_1 and consequently N_2 is greater than N_1.

Furthermore, adding T_1 and T_2 which is the half of the essential torque of MSRox's Star-Wheels and (8), it can be concluded as follows:

$$T_1 + T_2 = mgR\cos(\theta) \quad (11)$$

where the $(T_1 + T_2)_{\max}$ is occurred at $\theta = 0$ (Fig. 10).

Hence, the maximum value of the essential static torque for all Star-Wheels is derived as follows:

$$T_{all} = 2^*[T_1 + T_2]_{\max} = 2mgR = MgR \quad (12)$$

where M is the mass of MSRox.

Considering the mass of MSRox (11.5 kg) and (12) and the power transmission ratio (1.9917), the essential static torque of the active motor of Star-Wheels is resulted as:

$$T_{all} = 6.11739 \quad (\mathrm{N \cdot m})$$

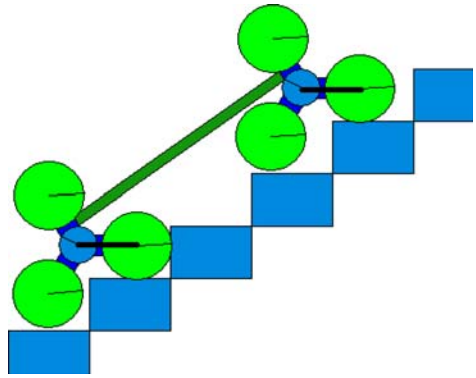

Figure 10. MSRox at $\theta = 0$ condition.

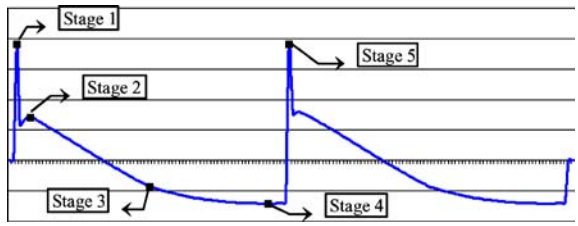

Figure 11. Torque consumption of a Star-Wheel.

It should be noted that the slope of stairs didn't appear in above equations because the worst condition ($\theta = 0$) occurs when MSRox is traversing stairs. If the slope of stairs is smaller than 30 degree (i.e. for stairs with 8 cm in height and 15 cm in depth, the slope = 28.07 degree), θ is never equal to zero and the worst condition does not depend on the value of θ and depends on the slope of stairs.

5.2. Dynamic Design

5.2.1. 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.

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. 11.

This motion has five stages. Stage 1 (Fig. 12) 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.

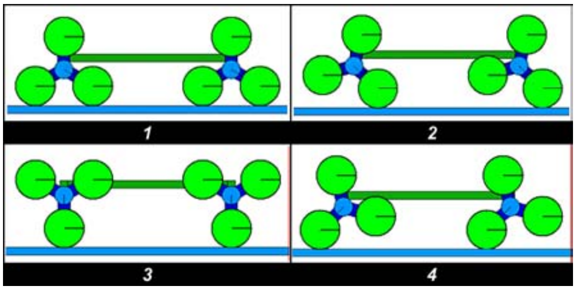

Figure 12. Different stages of Star-Wheels' rotation.

In Stage 2 (Fig. 12) 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. 11).

Stage 3 (Fig. 12) 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. 11).

Stage 4 (Fig. 12) 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. 11).

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.

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. 13), 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. 14), so the range of negative values are very greater.

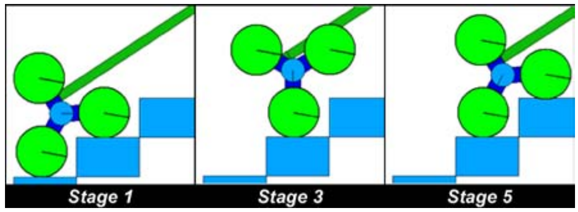

Figure 13. Stages 1, 3 and 5 while climbing stairs.

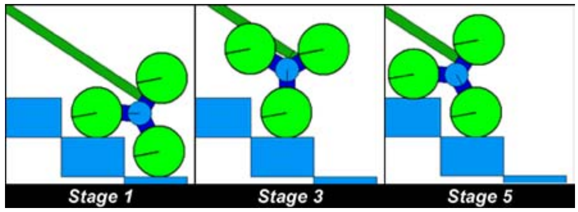

Figure 14. Stages 1, 3 and 5 while descending stairs.

5.2.2. Stairs Climbing Power Consumption. After modeling MSRox and simulating its motion in Working Model software for stairs climbing (Section 5), 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. 15.

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

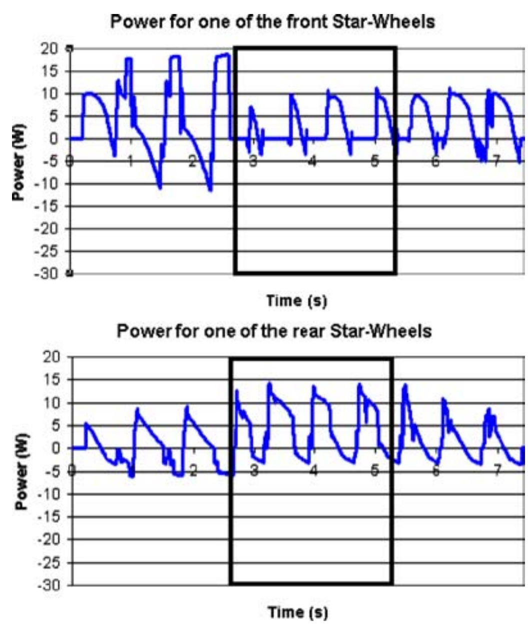

Figure 15. Power consumption for one of the front (Top) and one of the rear (Bottom) Star-Wheels for climbing six stairs.

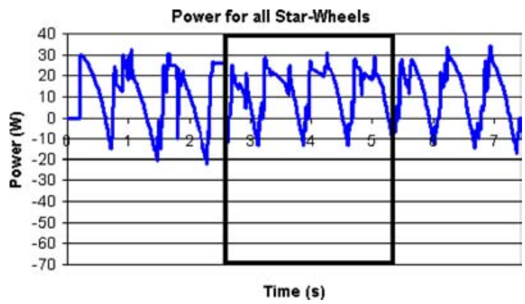

Figure 16. Consumption power for climbing six stairs.

figures, the required consumption power for all Star-Wheels for climbing six stairs can be derived as Fig. 16.

Figure 16 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.

5.2.3. 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. 17.

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. 18.

In Fig. 18 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

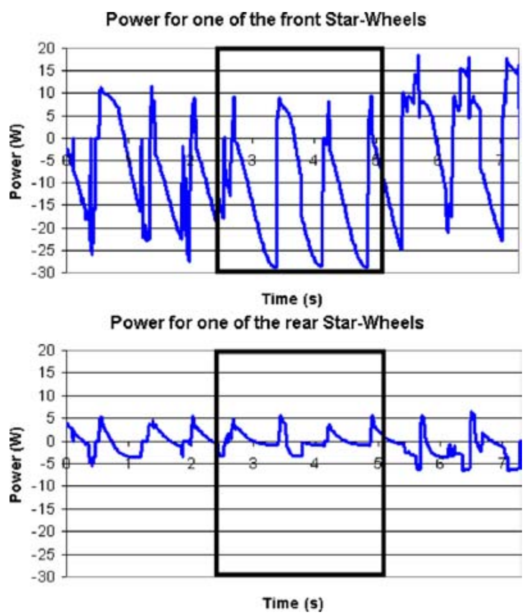

Figure 17. Power consumption for one of the front (Top) and one of the rear (Bottom) Star-Wheels for descending six stairs.

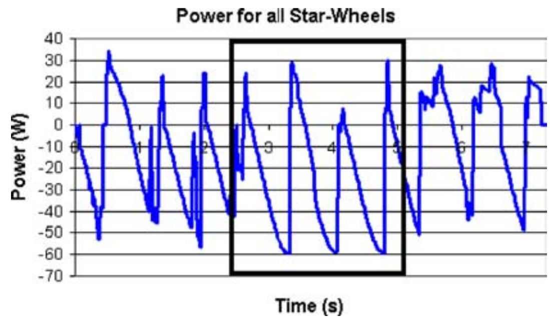

Figure 18. Consumption power for descending six stairs.

of power for Star-Wheels active motor for both ascending and descending stairs is equal to 34.104 W.

According to Fig. 18, 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.

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.

6. Algorithm of Climbing Standard Stairs

Stairs with 10 cm in height and 15 cm in width are standard stairs for MSRox that MSRox climbs each of them in 0.75 s. Before manufacturing MSRox, different stages of climbing standard stairs were simulated as Fig. 19.

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. 20.

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

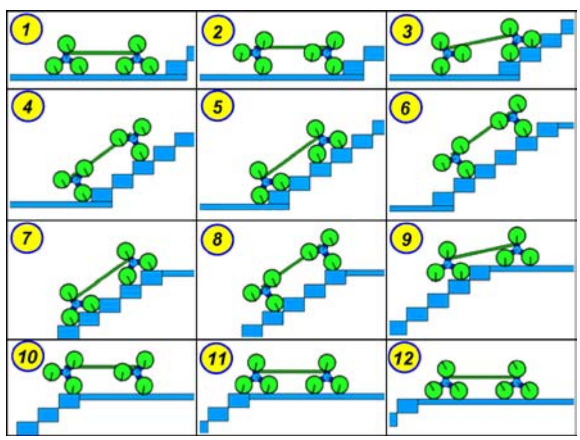

Figure 19. MSRox standard stairs climbing in simulation.

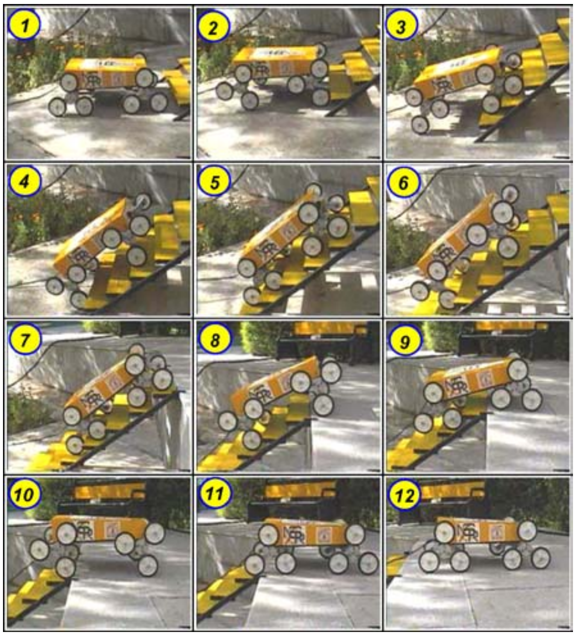

Figure 20. MSRox standard stairs climbing in practice.

is repeated closely in practice that indicate that MSRox has been design properly.

7. 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.

Climbing stairs with 14 cm in height and 37 cm in width has been simulated in computer (Fig. 21).

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. 22.

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.

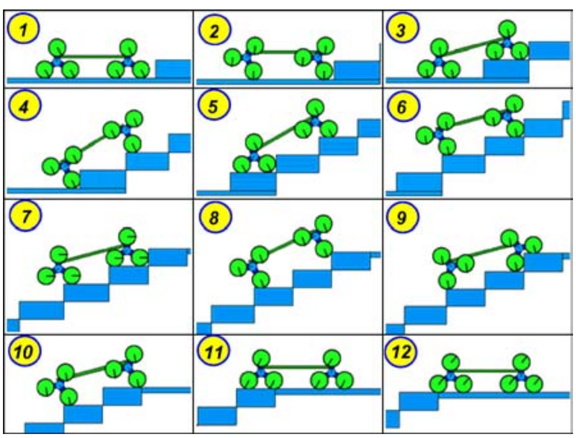

Figure 21. MSRox full-scale stairs climbing in simulation.

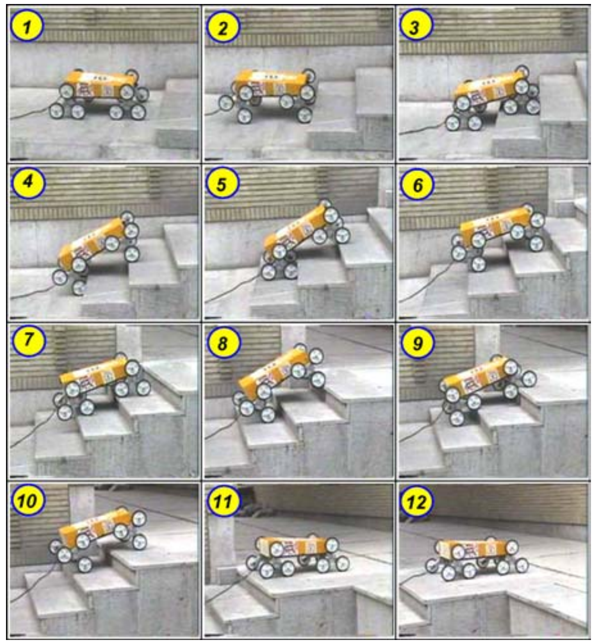

Figure 22. MSRox full-scale stairs climbing in practice.

8. 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 Tables 2 and 3.

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 10×15 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.

9. 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. 23.

10. 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

Table 2. MSRox speed (second/stair) while climbing different stairs size.

H/W	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 3. Average num. of slippages in MSRox motion.

H/W	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).

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. 24).

This similarity in actual is shown in Fig. 25.

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

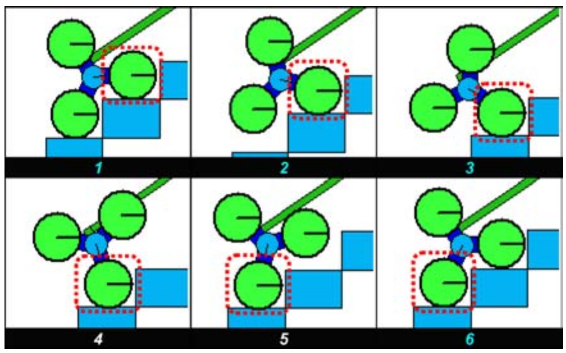

Figure 24. Similarity of Star-Wheels and Human Legs in simulation.

11. 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.

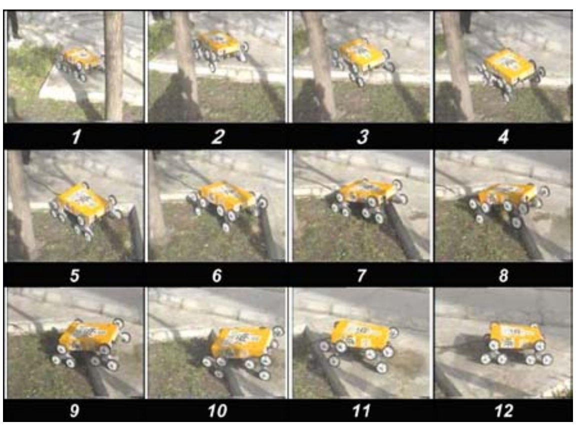

Figure 23. Different stages of traversing rough terrain.

Different stages of traversing slope surfaces by MSRox and inadaptable MSRox are simulated in computer (Fig. 26).

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. 27.

According to Fig. 27, 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. 27), but all wheels

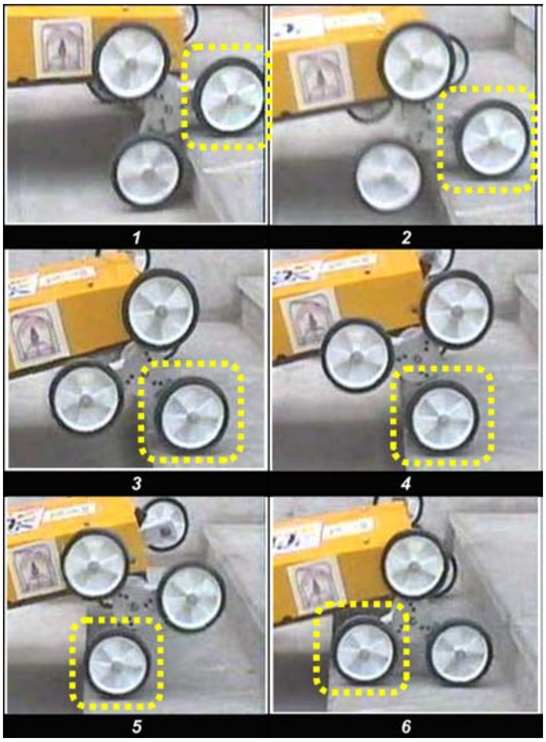

Figure 25. Similarity of Star-Wheels and human legs in practice.

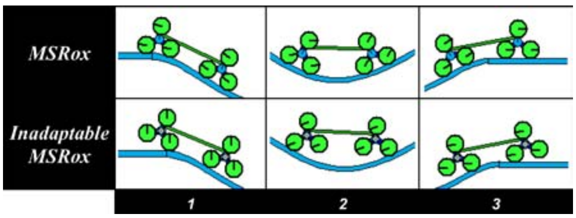

Figure 26. Comparison of MSRox and inadaptable MSRox.

of Star-Wheels kept on the ground while traversing this terrain.

12. 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. 28).

13. MSRox Control System

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

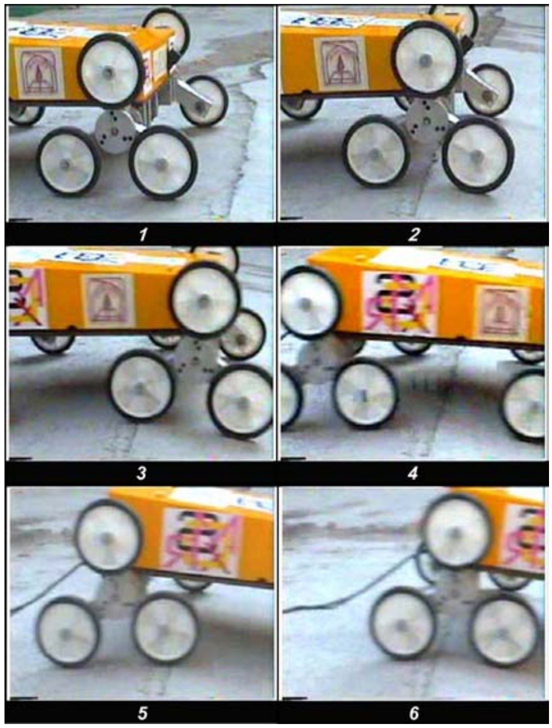

Figure 27. The MSRox adaptability in practice.

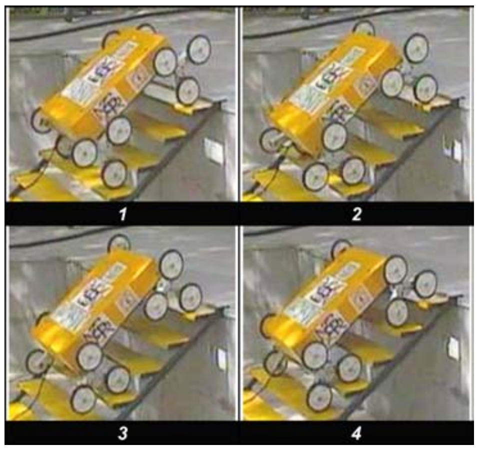

Figure 28. MSRox stability.

13.1. 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.

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 (http://ai.eecs.umich.edu/RHex/RHexversions.html). The difference be-

Table 4. DC motors.

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

Figure 29. The MSRox's photoelectric sensor.

tween 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 24-300 W depending on terrain and use (http://robot.spawar.navy.mil/home.asp?item=showrpasset&table=UGV&ID=30&robpa=5), but MSRox in worst condition needs only 30 W.

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.

13.2. MSRox's Sensor

MSRox can recognize stairs and obstacles with the help of a photoelectric sensor (Fig. 29) which is connected to the microcontroller board and sends signals to it when its rays hit the stairs or obstacles.

14. MSRox Speed

MSRox climbs each stair in 0.75 s and we can reduce this time by increasing the speed of Star-Wheels rotation.

The stair climbing speeds of MSRox and other stair climber robots in the world have been shown in Table 5.

It should be noted that all of the robots except MSRox in Table 5 are legged or leg-wheeled robot that don't have smooth motion on flat surfaces or have low speed motion while climbing stairs and traversing obstacles.

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.

Table 5. Stair climbing speeds.

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

15. 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.

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.

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