Comparison of performance of different traction systems for Terrainean Robots

Dip N. Ray[1*], A. Maity[2], and S. Majumder[1]
[1] Surface Robotics Lab, Central Mechanical Engineering Research Institute (CSIR), Durgapur, India
[2] General Engineering Design, Central Mechanical Engineering Research Institute, Durgapur, India

[*] Corresponding author (email: dnray@cmeri.res.in)

Abstract

Traction is the key component of an outdoor mobile robot. Essentially traction can be achieved by various means including rolling, walking, crawling & hopping. However the mobility vis-à-vis terrainability of a system can be greatly increased using wheels or tracks of various configurations. As such, higher level of operational performance can be achieved through an appropriate design of traction mechanism. This paper deals with some essential features of these approaches with special reference to tracked systems.

All Terrain Robot series developed by CMERI e.g. ATR – I & II, Sub-terrainean Robot (SR), Outdoor Mobile Robot (OMR) are a few selective examples showing various capabilities for tracked mobile robots. In these examples the design configuration changes from simple trapezoidal shape to many other forms with active traction support through re-configurable track geometry. This provides necessary passive compliance and better terrainability. The traction design of a specific mobile robot system is generally guided by the application requirements. In such cases it is extremely difficult (if not impossible) to design a traction mechanism universal for all possible applications. The work reported here however, will provide more insight and necessary formalism to design and build a tracked-mobile robot operating in the difficult outdoor and hostile environment.

Keywords: Tracked system, traction, terranean robots, passive compliance

1 Introduction

The field of the outdoor mobile robot has gained momentum after its wide and versatile applications, but till now, developing an All Terrain Robots for outdoor robotics is a challenging task. Innovative locomotion principles are needed for the efficient movement in rough terrains. Various special mechanical/electronics designs/ systems have been proposed using legs (walking machines) or other active means to climb over obstacles. However, these concepts are mechanically very complex and require sophisticated active control and good stability for locomotion. To negotiate the undulation of the terrains researchers are still trying to find optimum solution. Climbing staircases is a very important issue not only for outdoor robotics, but also for indoor robotics. Most of the All Terrain Robots are using either pivoted wheel or a set of wheels connected by belts that can swivel or rotate as a complete system. Besides they are most of the times robust, complex and high-energy consuming. CMERI has developed a few outdoor mobile robots both with wheel and tracked belt. Also different configurations have been tried for reaching an optimum solution.

This paper compares all these traction mechanisms of tracked/wheeled outdoor mobile robots. All these configurations have been used in various prototypes developed in CMERI, Durgapur and are named 'All Terrain Mobile Robot' (ATR-I), Modified All Terrain Mobile Robot (ATR-II), Sub-terrainean Robot series (SR1, SR2, SR3) and Outdoor Mobile Robot (OMR).

1.1 Related works

The Numbers of works are being carried out all over the world with tracked and wheeled robots for outdoor applications. People are doing research for an optimum solution for traction for All Terrain Robot. All these prototypes are suitable for a particular type of terrain only. A few important ones are discussed below.

The Yujin Robotics Robhaz DT-3 [1] is a skid-steered tracked vehicle with a novel articulated design that is capable of climbing stairs, traversing rough terrain and has powerful drive train. It is robust and can carry a payload of 45 Kg. This robot is heavy, expensive and having low ground clearance.

Toin Pelican series of robots [2] have been built by Toin University of Yokohama for victim search. The crawling part of this robot is composed of six different parts, and it can change the form by the condition of the running way. Running on flat ground raises front and back. The robot in this posture doesn't do crawling of the horizontal part on the ground. Because of this, a spin turn and a pivot turn can be done easily. And, there is a little friction, and good running of the efficiency is possible so that a horizontal part may not do on the ground.

The Redback robot [3] designed by the ARC Centre of Excellence for Autonomous Systems of the University of New South Wales, Sydney is a low-cost advanced mobility robot for education and research. It is also a crawler type robot having four different crawler systems as four wheels that can also separately spin on their axis keeping other end fixed along with producing simple horizontal motion. In spite of the low-cost and made from various easily available parts, it can climb stairs and overcome obstacles that are even more challenging to larger robots.

Mars Exploration Rovers of Jet Propulsion Laboratory, NASA (Spirit, Opportunity, Rocky7, FIDO, Sojourner) are the most well known rocker bogie type rovers. The design has six wheels, the front wheels being capable of steering. Sample Return Rover (SRR), a JPL developed prototype [4] is also an “All Terrain Explorer” with four wheels. The wheels can be independently steered.

SOLERO (Solar-Powered Exploration Rover) [5] of Autonomous Systems Lab (ASL), Swiss Federal Institute of Technology, Zurich is another solar powered exploration rover that is also consuming optimum energy for exploration with the aid of some efficient mechanical systems. The “Shrimp” structure is much simpler due to its passive mechanical design. SOLERO has one wheel mounted on a fork in the front, one wheel in the rear and two bogies on each side. The parallel architecture of the bogies and the spring suspended fork provide a high ground clearance while keeping all 6 motorized wheels in ground-contact at any time. This ensures excellent climbing capabilities over obstacles three times higher then the wheel radius and an excellent adaptation to all sorts of terrains. The front fork has two functions: its spring suspension guarantees optimal ground contact of all wheels at any time and its particular parallel mechanism produces a passive elevation of the front wheel if an obstacle is encountered. The front wheel has an instantaneous centre of rotation situated under the wheel axis, which makes it possible to get on an obstacle.

Another such terrain negotiable robot of ASL is CRAB [6], where the robot has two parallel bogies connected at the bottom through the middle wheel and at the top with a rotational joint to prevent hyper-statism.

Another new concept of a robust All Terrain Mobile Robotic system is SWARM-BOT proposed by F. Mondada *et. al*. [7] The system moves with the help of motor power tracks. Each track can move in different speeds to generate turning and rotation at the spot. These two tracks allow SWARM-BOT to move in moderately rough terrain, with more complex situations being addressed by SWARM-BOT configurations.

From the above discussions it is obvious that lots of researches are going on with traction system worldwide, but no optimum solution has been reached. Most of them are suitable for only a particular type of terrain (either sandy or hilly or marshy).

1.2 Track-soil Interaction Model

According to M.G. Bekker [8] the soil develops two different stresses under a rigid wheel. One is caused by the weight of the vehicle (normal stress), while the other is shear stress generated by the driving moment. So the soil under a rigid wheel is under dual loading, namely it is compressed by the weight of the vehicle and it is also sheared due to the driving moment created by the peripheral force. Their initial research effort concentrated on the mathematical description of the physical action, taking place at the soil-wheel interface. Bekker developed formulas for the vertical or normal interaction (e.g. shrinkage, rolling resistance), while Janosi's equation [9] is widely applied for modeling the shearing action. Both are based on data obtained by using soil test instruments, that is, they used empirical factors for describing the actual vehicle mobility phenomenon on the basis of data measured by soil test instruments. Researchers have long proved the lack of universal applicability of Bekker’s method, but Janosi's formula for modeling the shearing action at the soil-wheel interface has been successfully used during the past fifty years. Janosi's equation is given as follows:

$$F_t = A\tau_{\max}\{1-\frac{K}{sl}[1-\exp-(\frac{sl}{K})]\} \quad [\mathrm{N}] \qquad (1)$$

Where, F_t = Tractive Force; A = Ground contact area for a tracked vehicle [m^2]; l = Length of the area [m]; $\tau_{\max}$ = Maximum value of the shear stress [N/m^2]; $\tau_{\max} = c + \mu\sigma$ (N/m^2); C = Internal cohesion of the soil (N/m^2); μ = Coefficient of internal soil friction; σ = Normal soil stress under a wheel; K= Shape factor of the shear diagram [m]; s = Slip

The above expression (1) depicts the relation between mainly Tractive force, Ground contact area and the Track length. The conclusion from this expression is that with the increase of Ground contact area or the Track Length or both the Tractive force increases. Tractive force helps the tracked vehicles for positive traction that means more the Tractive Force more the Positive Traction and stability and hence less the chance of slippage. It is clear from the expression that F_t is proportional to A and from the graph (Fig. 1) F_t increases with l. In the prototypes developed at CMERI, attempts have been made to optimize the contact area for better traction.

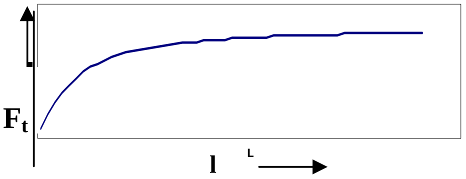

Fig. 1: Curve for Tractive Force (F_t) & contact length (l)

2 All Terrain Robot (ATR-I)

The All Terrain Mobile Robot (ATR-I) developed in CMERI, Durgapur has the following major system specifications.

- *Name: ATR-X 50*
- *Size: 950 X 650 X 350 mm*
- *Weight: 83 Kg*
- *Endurance: 1.5 Hr*
- *Speed: 0.5 m/s (avg); 1 m/s (max)*

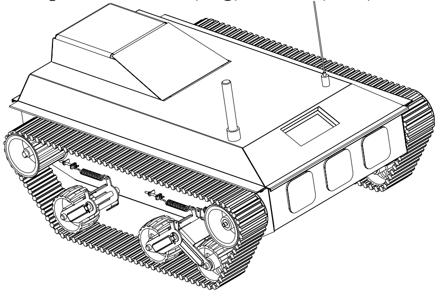

Fig. 2(a): The 3D Model of ATR-I showing the grass hopper like traction system

The schematic models of ATR-I for analysis of traction are shown in Fig. 2(b) and 2(c).

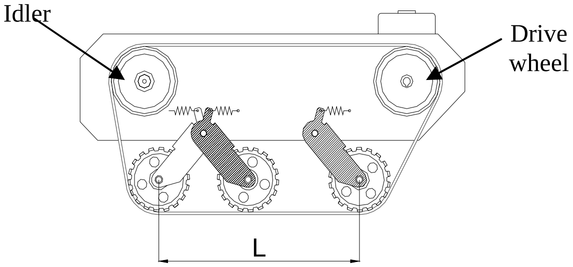

Fig. 2(b): Traction system of ATR-I showing contact length of tracked belt (L) with ground at normal condition

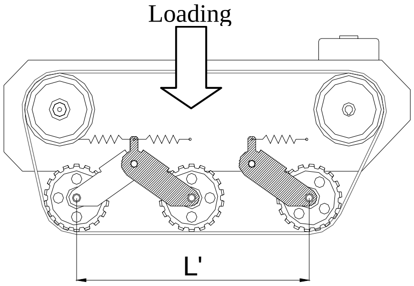

Fig. 2(c): Elongated contact length (L') of the tracked belt with ground under loaded condition

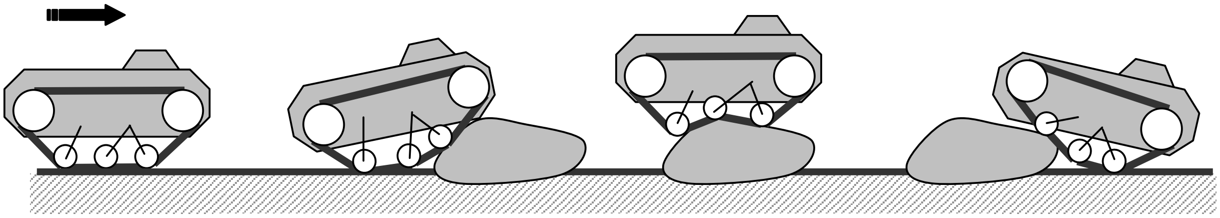

Fig-3 - Terrain Negotiation Sequence of ATR-I

2.1 Description of the Traction System

The configuration of the suspension system used here is called “Grasshopper Configuration” as the six ground wheels mimic the six legs of a grasshopper. The motors are directly connected to the driver wheels at the upper part of the vehicle. A track belt transmits the power to the ground wheels from the driver wheels as well as helps in positive tractions. The ground wheel arms are pivoted and are attached to separate suspension springs. These springs arrest the flattening of the ground wheel supports. The tensions of the springs are adjustable. A single idler is pinned on the other end of the vehicle and spring loaded to consume the occasional shock of the belt. These arms/ springs also help ATR-I to wrap the tracked belt over the contour of the obstacles for better traction. The trapezoidal configuration of the belt gives better approachability for stair climbing. The following figure shows the terrain negotiation sequence of ATR-I.

2.1.1 Advantages

1. This traction system is load compliant [10] that means with the increase in load, the track belt adjusts its length (from L to L') for better traction
2. Due to the grasshopper configuration the system is also terrain compliant
3. The ground clearance can be adjusted to some extent by adjusting the tensions in the springs
4. Trapezoidal shape of the belt gives better approachability for stair climbing
5. The central ground wheels are adjusted to share more reaction to reduce slip/ friction while turning.

2.1.2 Disadvantages

1. The traction system is a complex one
2. Huge shock load can flatten the ground wheel support systems with reduction in ground clearance
3. Regular care and maintenance is an important factor for such a complex traction system
4. Assembly and disassembly is difficult

3 Sub-terranean Robot (SR) Series

The Sub-terranean Robot (SR) is a hybrid and amphibian vehicle with capability of operation in both land and water. The broad system specification of SR:

- *Size*: 550 X 250 X 270 mm
- *Weight*: 42 Kg
- *Endurance*: 0.5 Hr
- *Speed*: 0.5 m/s (avg); 1 m/s (max)

Fig. 4: The Sub-terranean Robot (SR-1) with rigid suspension. This was developed for rescue operation in flooded coal mine galleries.

3.1 Traction Systems

Three completely different configurations (for SR1, SR2, SR3) have been used for different applications areas. SR1 has tracked belt and fixed ground wheels configuration (Fig. 4). This configuration works well on wet, muddy land. The skid-steer configuration (SR2), as shown in Fig. 5 also performed satisfactorily on dry land. For coal mine tunnels, a system (SR3) with large diameter wheels were used with swivel mechanism (configuration 3) at the driven end for differential steering was found to be suitable (Fig.7). In the following sections detailed discussions have been made on these three different configurations.

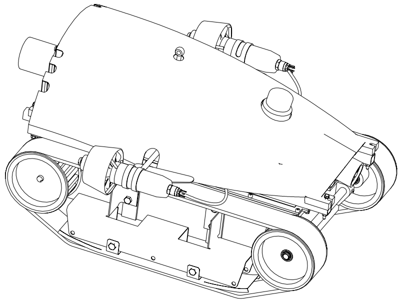

Fig. 5: The skid-steer configuration of SR2

3.2 Traction system of SR - 1

The SR1 the tracked belt is wrapped over three small ground wheels fixed to a rigid support. As in case of ATR-I the drive motors are attached to driver wheels with slightly larger diameter than the ground wheels. Ground wheels rotate freely on their own axis and the total ground wheel assembly is rigidly fixed to the body. As a result there is no provision for any passive compliance. The obstacle negotiation sequences of SR1 have been shown in Fig. 6.

3.2.1. Advantages

1. This configuration is suitable for sandy/ muddy field due to its large contact area (‘A’ in the Eqn. 1)
2. Rigid ground wheel support maintains a constant ground clearance
3. Being a simple system needs less care and maintenance, easy to assemble and disassemble

3.2.2. Disadvantages

1. In undulated surface all the three ground wheels may not touch the ground and as a result better traction is not always maintained
2. The shock load is directly transmitted to the system and hence may cause problem to the components
3. Chips/ flakes easily enter the space between the ground wheels and the track belt and jam the belt motion
4. Rigid ground wheel support provides no compliances to the system

3.3 Traction system of SR - 2

The skid-steer configuration was tried as second configuration for better performance of SR on sandy land. Instead of three ground wheels, a smooth steel plate with flange on both the two sides (for arresting the belt from slipping out) was used. The contact surface of the plate and the tracked belt has been kept as frictionless as possible. This skidding plate was bolted to the ground wheel support plate. The tracked belt driven by the driver wheels moves over the skidding plates and provides traction and power. The obstacle negotiation sequences was same as the SR1, because the ground wheel assembly is same except for the ground wheel set replaced by steel skid plate.

3.3.1. Advantages

1. The complete part of the belt under the plate is rigidly in contact with the flat ground
2. Easy assembly & disassembly
3. Due to large bearing area the system is very efficient on flat sandy/ muddy land

3.3.2. Disadvantages

1. The inner portion of the tracked belt is constantly rubbing with the skid plate and may jam occasionally
2. Frictional loss is high
3. Difficulty in crossing over the obstacles

3.4 Traction system of SR – 3

SR3 was wheeled model. To achieve large ground clearance, larger diameter of the wheel (300mm) was chosen. A swivel mechanism has been incorporated at the rear wheels for easy turning. The wheels are directly mounted to the shafts/axles attached to the body of SR3. Drive was provided directly to the front wheels. Here no tracked belt has been used and no power is being transmitted to the rear wheels. The obstacle negotiation sequences for the large diameter wheel configuration of SR3 have been shown in Fig. 8.

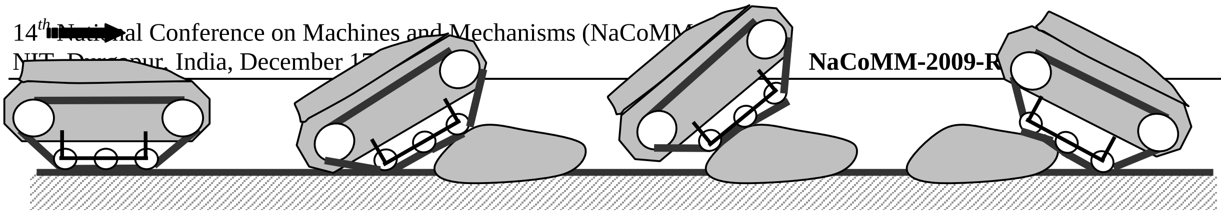

Fig. 6: Obstacle over ridding of SR with fixed ground wheel assembly

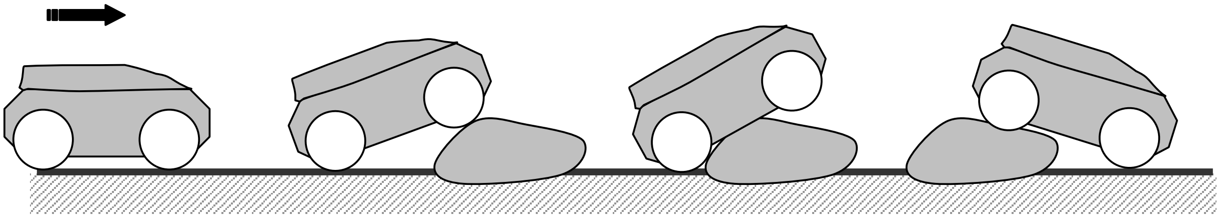

Fig. 8: Obstacle negotiation of SR with large diameter wheels

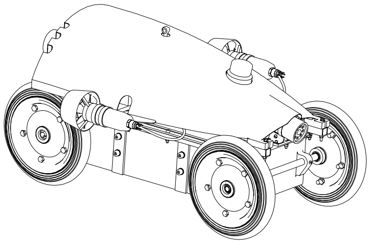

Fig. 7: The wheeled configuration of SR3

3.4.1. Advantages of configuration 3

1. The large diameter wheels provide better ground clearance
2. This system performed well on mine floor
3. As the wheels are directly mounted on the shafts/ axles, it is easy to assemble & disassemble
4. Simple, low cost and maintenance free system
5. The rubber tyres absorb shock load to some extent

3.4.2. Disadvantages

1. This wheeled configuration was not found suitable for working in sandy/ muddy surface due to its smaller contact area
2. It has no provision for passive (load or terrain) compliance
3. Occasional loss of traction due to belly touch down

4 Modified All Terrain Robot

The Modified All terrain Robot is an upgraded version of the ATR-I and also known as ATR2. This is also a tracked configuration (Ref. Fig. 10).

- *Size*: 800 X 650 X 520 mm
- *Weight*: 61 Kg
- *Endurance*: 0.5 Hr
- *Speed*: 0.5 m/s (avg); 1.2 m/s (max)

Fig. 10: Prototype of Modified ATR (ATR2)

4.1 Traction System

ATR2 has been reshaped to minimize the slipping of the tracked belt and to increase the stability. One of the three ground wheels is powered by means of chain- sprocket assembly. All the three ground wheels are connected by a tracked belt. Here the transmission system and the traction system have been separated for better performance.

4.1.1 Advantages

1. As the traction system and transmission system are separated, performance of the system is better.
2. Due to its low height, the system is more stable than any other configurations.

Belly touch down

4.1.2 Disadvantages

1. System has low ground clearance
2. No provision for passive (load or terrain) compliance

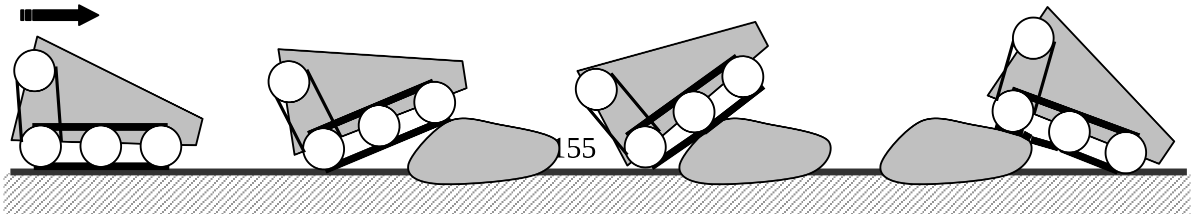

Fig. 9: Schematic diagram showing ATR2 crossing obstacles

3. Lack of stair climbing/ obstacle over riding capability
4. The shock load is directly transmitted to the system

5 Outdoor Mobile Robot 1 (OMR1)

This version of the robot is specially designed for stair climbing capability. Outdoor Mobile Robot (OMR1) has the following major specifications.

- *Size*: 1000 (1250 with attachment) X 670 X 315 mm
- *Weight*: 45 Kg
- *Endurance*: 0.5 Hr
- *Speed*: 0.5 m/s (avg); 1.5 m/s (max)

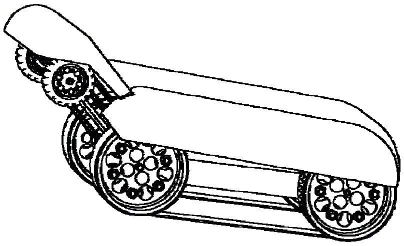

Fig. 11: The stair climbing model of OMR1

5.1 Description of the Traction System

OMR1 is specially designed with a stair climbing attachment. The diameters of the wheels are increased than all the earlier version of terranean robots for better terrainability. This model is also made compact. The motors are directly mounted to the front wheels. The rear wheels are driven by the tracked belt. The wheels for climbing staircases are driven by the partial power transmitted by means of a chain- sprocket. This attachment can be swiveled to suitable angles for stair climbing. The large diameter wheels also help to overcome large obstacles and to climb up staircases easily. The obstacle negotiation sequence of OMR1 is shown in Fig. 12.

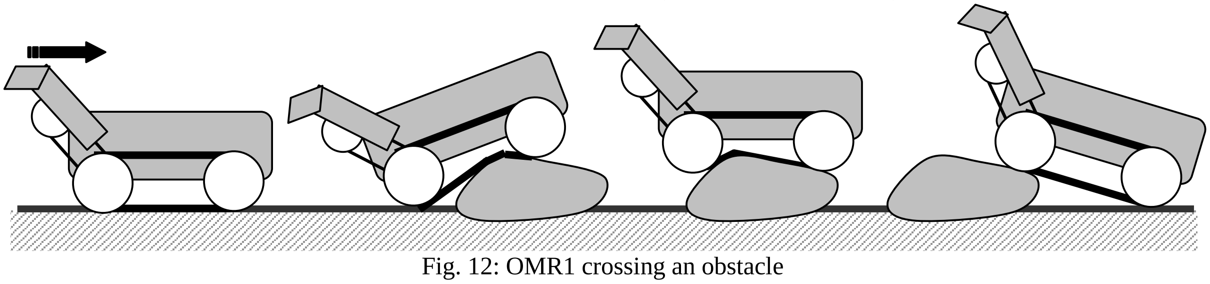

Fig. 12: OMR1 crossing an obstacle

5.1.1. Advantages

1. Large diameter wheels give enough ground clearance for outdoor terrainability
2. The compact shape of OMR1 is providing better stability
3. The system is best suited for stair climbing and obstacle over ridding
4. It can easily cross a wide ditch with the help of stair climbing attachment

5.1.2. Disadvantages

1. The system has no facility for passive (load or terrain) compliance
2. The shock load is directly transmitted to the system
3. The long distance between the two wheels may cause a problem

6 Outdoor Mobile Robot 2 (OMR2)

This version is another special version of Outdoor Mobile Robot and known as OMR2. The specialty of OMR2 is that it and can run on both the sides (top and bottom) facing up due to its symmetric configuration. The system specifications of OMR2 are as follow.

- *Size*: 1090 X 795 X 320 mm
- *Weight*: 38 Kg
- *Endurance*: 1.0 Hr
- *Speed*: 0.5 m/s (avg); 1.5 m/s (max)

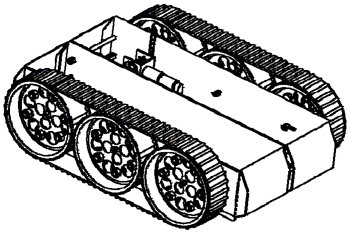

Fig. 13: Symmetric configuration of OMR2

6.1 Description of the Traction System

This system has two identical, separate compartments. These compartments are connected to one another by a lead screw and guide bars. One of the compartments can move side wise for increasing its width. The traction system of OMR2 is very simple. Two wheels are directly connected to the motors and the power is transmitted to the other wheels by means of the track belt. The wheels are made larger for equal symmetric ground clearance on both the sides (top or bottom). This system will follow the same sequences as ATR2 while over riding any obstacles.

6.1.1. Advantages

1. Large diameter wheels give enough ground clearance for outdoor terrainability

2. Capability of running on both sides of the track helps the system if turned down while overriding any large obstacle
3. Most simple and maintenance free system
4. Due to its capability of widening itself, the system experiences less skid while turning

6.1.2. Disadvantages

1. Lack of stair climbing/ obstacle over riding capability
2. There is no provision for passive (load or terrain) compliance
3. The shock load is directly transmitted to the system

7 Comparison of Traction systems

All the traction systems discussed above are different from each other in various aspects. They have been designed depending upon the field of applications. The system which is performing well on sandy surface may not prove suitable for muddy land or rocky surface. In spite of identical power of the motors, battery rating, belt specifications the traction of different system are different. As a result the quantitative comparison of all these traction systems may not be possible as well as feasible also. But qualitative comparison can be done with respect to different parameters. The priority of these parameters may change depending upon the types of applications. Some of these parameters may be contact area, stability, ground clearance, compactness, compliances, simplicity, maintenance, capability of stair climbing/ obstacle over riding. In the following tables traction systems of different models have been compared qualitatively. The parameters are assigned impact factors from 1 to 7 for different traction systems. The lowest value is assigned the impact factor 1 and the highest value being 7 for most of the parameters. For the parameters – simplicity and maintenance, the most simple and nearly maintenance free system has been assigned the highest impact factor (i.e. 7). Other values are interpolated in that said scale accordingly. This gradation style is purely relative and can vary from author to author.

For tracked systems the contact length and the width of the belt has been measured. For the bearing area of wheels the measurement has been taken with the system resting on sand, soil, concrete floor and an average value has been considered. Ground clearance is an easily measurable parameter. The height of the C. G. (Centre of Gravity) of a system has been estimated from the accurate distribution of the weight of individual components in 3D CAD Model. The weight to volume ratio contributes to compactness of the system. The higher value represents higher compactness. The stair climbing (maximum permissible height of the stair case) capability for wheeled or tracked belt wrapped over single set of wheels/ timing pulleys is calculated as one third of the wheel/ timing pulley diameter. For ATR-I and two configurations of SR (i.e. SR1 and SR2), the permissible height has been considered as two third of height of the trapezoid.

Table-1: Bearing area of the robots

Configurations	***ATR***	***SR Series***			***ATR2***	***OMR1***	***OMR2***
Parameter		***SR1***	***SR2***	***SR3***			
Bearing area (m^2)	0.112	0.0234	0.0378	0.0	0.066	0.084	0.0768

Table-2: Height of C.G. (for Stability)

Configurations	***ATR***	***SR Series***			***ATR2***	***OMR1***	***OMR2***
Parameter		***SR1***	***SR2***	***SR3***			
Height of CG (mm)	235	161	158	166	213	160	186

Table-3: Ground Clearance

Configurations	***ATR***	***SR Series***			***ATR2***	***OMR1***	***OMR2***
Parameter		***SR1***	***SR2***	***SR3***			
Ground Clearance (mm)	120	52	45	62	60	117	52

Table-5: Compactness of the configurations

Configurations	***ATR***	***SR Series***			***ATR2***	***OMR1***	***OMR2***
Parameter		***SR1***	***SR2***	***SR3***			
Compactness (x 10^{-3}) (m^3/Kg)	2.6	8.6	8.7	8.8	4.4	4.7	7.3

Table-6: Stair climbing capability

Configurations	***ATR***	***SR Series***			***ATR2***	***OMR1***	***OMR2***
Parameter		***SR1***	***SR2***	***SR3***			
Stair climbing capability (mm)	193	113	113	200	48	100	100

Table-7: Qualitative comparison of various parameters

Configurations	**ATR-I**	***SR-1***	***SR -2***	***SR -3***	**ATR2**	**OMR 1**	**OMR 2**
Parameters							
Contact area	7	2.2	3	1	4.5	5.5	5.1
Stability	1	6.8	7	6.4	2.7	6.8	4.8
Ground clearance	7	1.6	1	2.4	2.2	6.8	1.6
Compactness	1	6.8	6.9	7	2.7	3	5.5
Compliances	7	0	0	0	0	0	0
Simplicity	2	3	2	3	6	2	5
Maintenance	1	3	2	3	6	4	6
Stair climbing	6.7	3.6	3.6	7	1	3.1	3.1
Column wise sum of grade(s)	**32.7**	**27**	**25.5**	**37.8**	**25.1**	**35.2**	**32.1**

Percentage	***58***	***48***	***46***	***53***	***45***	***56***	***50***

All these values are compared and assigned the gradation as discussed above. The factor ‘simplicity’ was estimated from the track geometry and configuration of wheel, drive and suspension systems.

5 Conclusions

From the above table it is quite obvious that ATR-I has the best traction configuration as compared to other traction systems used in different prototypes. The most advantageous features of ATR-I are passive compliance and higher ground clearance. The compactness of the system can be increased by judicious distribution of internal sub-systems. But it may be difficult to make the traction system simple and maintenance free due to the presence of compliance mechanism. The traction systems of the first two versions of SR have nearly equal impact factors, but the third one is slightly higher due to the use of simple wheel based system. The knowledge learnt from these developments has been used in the latest versions of OMR (i.e. OMR1 and OMR2). As a result the traction systems of OMR1 and OMR2 are improved. As a future scope of work another version of ATR may be designed and developed with light weight structure and active (adding automated tension adjustment mechanisms) compliance.

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