Development of Reconfigurable Outdoor Mobile Robot-a Design Optimisation Approach

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Abstract

A number of outdoor mobile robots have been designed to achieve specific operational characteristics. It is obvious such robots can offer excellent operational capabilities within a narrow and constrained domain. However with change of mission parameters and operating environment such superiority can no longer be exhibited by many systems. For example tracked mobile robot shows exceptional operating behaviour in outdoor marshland, sand and similar types of soil conditions whereas its operating behaviour is much inferior compared to a wheeled robot for paved robot environments. The main dichotomy faced by a designer is to select which one is the most suitable under given conditions, tracked, wheeled or legged. This paper tries to find a solution to this dilemma through design optimisation using reconfiguration capabilities as the unique deterministic feature. This research is being carried out using Autodesk Inventor as a provider of 3D modelling tools together with multibody simulation software ADAMS of MSC Software Corporation. The parameters taken into consideration include kinematic and geometric description, drive transmission including length of links, pitch length of belt, approach angle ground clearance and many more. This study clearly shows that the selection of a specific geometry of a drive mechanism alone is not suitable for design of an outdoor mobile robot.

Keywords: Outdoor, Tracked, Mobile Robot, Reconfiguration and Analysis

1 Introduction

Mobile robots are useful to offer a diverse set of functionalities. Applications range from military and police operations, explosive and ordinance disposal to planetary exploration and many more. To achieve efficient locomotion in outdoor rugged terrain the robot needs to be specially designed to operate in hostile environment. Globally researchers are posed with the challenge of developing a robot capable of adapting to diverse terrain profile. This calls for a configuration space-based selection approach.

In general to achieve locomotion, any of the following configurations is used by the researchers, tracked, wheeled or legged. This paper presents an analytical approach for selection of a specific configuration e.g. tracked configuration in this case discarding other means like wheel and legged. In general tracked mobile robots provide a superior operational capability over the other locomotion means in terms of positive traction, compliance etc particularly when dealing with outdoor and rugged terrains. This paper is organized as follows: next sub-section describes the state-of-the-art around the world.

2 Literature Survey

Advancements in the field of indoor robotics have been quite substantial, but designing robots for outdoor environment is still an exigent task. For methodical and well organized movement on rough terrains unorthodox and fresh ideas are needed. In order to move over obstacles, several types of locomotion methods are available. Among them legged motion is mechanically intricate, requires higher level of control and better stability for locomotion. Researchers are still vexed trying to find the optimum solution for terrain adaptability. Globally this problem is tackled by means of using larger diameter wheels or wheels connected by belts capable of swivelling as a complete system. Limitations in using these systems include robustness, complicated control and high energy consumption. Robotic research institutes, universities and industries have manufactured a number of mobile robots which are mostly classified as tracked, wheeled, legged, wheel-legged, leg-wheeled, segmented, climbing and hopping.[2] Various robot configurations available worldwide can be classified as shown in Table 1.

Table-1: A brief list of robots made over the years [2]

Tracked Robots	*Wheeled Robots*	*Legged Robots*	*Hybrid Robots*	*Limbless Robots*
Packbot (iRobot); Talon (Foster-Miller); Gladiator (CMU); Microcrawler (Sandia); MR-1 & MR-5 (ESI); Andros Series (Remotec)	Spinner (National Robotics Engineering Consortium); SCOUT (University of Minnesota); Stanley (Stanford); Inflatable Rover (JPL); Throwbot (Draper); Alice (EPFL); Millibot (CMU)	Sprawlita (Stanford); Bug2 (Draper); Ratbot (Draper); Big Dog (Boston Dynamics); Scorpion (Franck Kirchner); : Frog (JPL); Hopping robot (JPL); Self-reconfigurable minefield (Sandia); Hopping robot (Sandia); Lemur (Stanford/JPL); RiSE (Boston Dynamics); Mecho-gecko (iRobot)	Wheel-legged: Roller-Walker (Hirose Lab); Retarius (Lockheed Martin); ATHLETE (JPL); Octopus (EPFL); Shrimp (EPFL); Leg-Wheeled:SCOUT (University of Minnesota); SpikeBall (Draper); RHex (Boston Dynamics); Mini-Whegs (CWRU)	HISS (Draper), Rubble Snake (Draper), HMTM (Draper); Clarifying Climbing Robot (Clarifying technologies)

CSIR-CMERI boasts for development of a number of indigenously built mobile robots, as listed below in Table 2

Table 2: Robots built at CSIR-CMERI

Robot	*Type*
All Terrain Mobile Robot (ATR)	Tracked
Outdoor Mobile Robot (OMR)	Tracked or Wheeled [Interchangeable Configuration]
Sub-Terrainean Robot (SR)	Tracked or Wheeled [Interchangeable Configuration]
Modified All Terrain Mobile Robot (ATR-II)	Tracked
Outdoor Mobile Robot version 2.0 (OMR-II)	Wheeled
Serpentine Robot	Segmented

World-wide wheeled robots are accepted as the most favorable modes of locomotion over rough terrains but the problems faced include capability to overcome obstacles and handling tricky situations like high centering. Terrain roughness and steering curvature actively control maximum speed of wheeled robots. So we use tracked robots. A number of exceptional tracked mobile robots are available: PackBot, Remotec-Andros robots–Andros Mark V, Wheelbarrow MK8 Plus , AZIMUT, LMA, Matilda, MURV-100, Helios Robots, Variable configuration VCTV, Ratler , MR-7, NUGV, and Talon by Foster-Miller .

Some legged robots [3] also provide answers to these problems, but we are not covering them in this paper. The focus is on reconfigurable architecture. Based on the requirement, we designed four models and dynamic simulations of those were performed in MSC ADAMS. Design optimization of the models were done to find out the best possible configuration among these.

3 Kinematic Modeling

As far as control-design and simulations are concerned, dynamic models have been helpful, but they are too complicated for navigating robots in real time. The proposed robot models will have the same equations, so a single model analysis will be sufficient enough. The Y axis of the robot is kept lined up with forward direction motion and the local frame is supposed to have its origin at the central area marked by both tracks as shown in Fig. (1). Similar to a differential drive, track vehicle is guided by two inputs: velocity of left and right track (V_l, V_r). The kinematic equation would be as,

$$(v_{x,} v_{y,} \omega_z) = f_d (V_l, V_r) \tag{1}$$

In Eq. (1) ($v_{x,} v_y$) is the vehicle's linear velocity with respect to its local frame and ω_z is angular velocity. Now control action of the motion required can be found from the inverse kinematic problem as shown in Eq. (2)

$$(V_l, V_r) = f_i (v_{x,} v_{y,} \omega_z) \tag{2}$$

In case of planar motion, the Instantaneous Centre of Rotation (ICR) of a vehicle considered as a rigid body is defined as the point in the plane where the motion of the vehicle can be represented by a rotation and no translation occurs.

During planar motion it is not sufficient to analyze the entire motion of the vehicle but also the motion of the tracks on the contact surface with the terrain has to be taken into account. The angular velocity of the track is same as that of the vehicle since it does not rotate about vehicle's Z-axis.

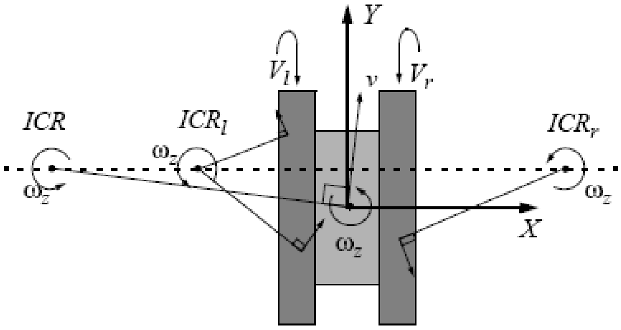

Figure 1: Instantaneous centres of rotation on the plane. Entire vehicle follows a circular course about ICR as a rigid body, defined by ICR_l and ICR_r [4].

For ease the track is also modeled with the rolling speed of the track which is why an extra degree of freedom is required. So motion of points on a track is composed of track rolling and vehicle motion. Thus the plane ICR differs from that of the entire vehicle as shown in Fig. (1). Now geometrically ICR can be represented by,

$$x_{ICR} = \frac{-v_y}{\omega_z} \text{ and } y_{ICR} = y_{ICR_l} = y_{ICR_r} = \frac{v_x}{\omega_z}$$

$$x_{ICR_l} = \frac{V_l - v_y}{\omega_z} \text{ and } x_{ICR_r} = \frac{V_r - v_y}{\omega_z} \tag{3}$$

In the equations marked as Eqn. (3), v = (v_x, v_y) is the translational velocity of the vehicle in local coordinates. Computing the inverse functions, the translational and rotational speeds can be obtained as

$$v_x = \frac{V_r - V_l}{x_{ICR_r} - x_{ICR_l}} y_{ICR},$$

$$v_y = \frac{V_r + V_l}{2} - \frac{V_r - V_l}{x_{ICR_r} - x_{ICR_l}} \frac{x_{ICR_r} + x_{ICR_l}}{2} \text{ and } \omega_z = \frac{V_r - V_l}{x_{ICR_r} - x_{ICR_l}} \tag{4}$$

Inverse kinematic relations can also be expressed as,

$$V_l = \sqrt{\| v \|^2 - y_{ICR}{}^2 \omega_z{}^2} + x_{ICR_l} \omega_z \tag{5}$$

$$\text{and} \quad V_r = \sqrt{\| v \|^2 - y_{ICR}{}^2 \omega_z{}^2} + x_{ICR_r} \omega_z \tag{6}$$

4 Description of the Design Concept

Traction is an essential component of an outdoor mobile robot. A suitable design can result in higher optimal performances. The design of traction mechanism varies from one model to another according to applications and requirement. It has been observed that use of arm or leg reduces traction and limits mobility, so any form of leg/arm is discarded since mobility is one of the primary concerns of terrain adaptability. Continuous tracks enjoy a lot of advantages over wheels. Compared with wheels tracks have higher performance, optimized traction system, better power efficiency and lower ground impact. Two different kinds of stresses develop under a rigid wheel. One is due to the weight of the vehicle and the other is due to the shear stresses developed by driving moment

Mg Bekker and Janosi developed formulas for normal and shearing interaction respectively which were developed from soil test instruments. Bekker's formulas applications were restricted but Janosi's shearing interaction models have been used universally [1].

$$F_t = A\tau_{\max}\{1-\frac{K}{sl}[1-\exp-(\frac{sl}{K})]\} \quad [N] \tag{7}$$

Here:
A = the ground contact area for a tracked vehicle [m2], l = the length of the area [m], $\tau_{\max}$ = the maximum value of the shear stress [N/m]

$$\tau_{\max} = c + \mu\sigma \tag{8}$$

c = the internal cohesion of the soil (N/m^2), μ = coefficient of internal soil friction, σ = normal soil stress under a wheel (N/m^2), K = shape factor of the shear diagram [m], s = slip

Tractive forces for both the wheel and track-belt configurations were calculated. It was revealed from the above equations that increase in the ground contact area and track length or both resulted in an increase in the tractive force. The more the tractive force less is the chance of slipping.

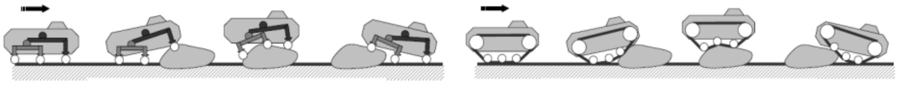

Figure 2: Passive terrain compliance-wheeled and tracked configuration [5]

It has been already noted that track belt configuration has several advantages over the wheeled configuration in terms of enhanced bearing area, positive traction and uniform load distribution over the soil, spot turning etc. The passive compliance difference between wheeled and tracked configuration is shown in Fig. (2).

The proposed system has to explore mostly in the outdoor rugged rough terrains,

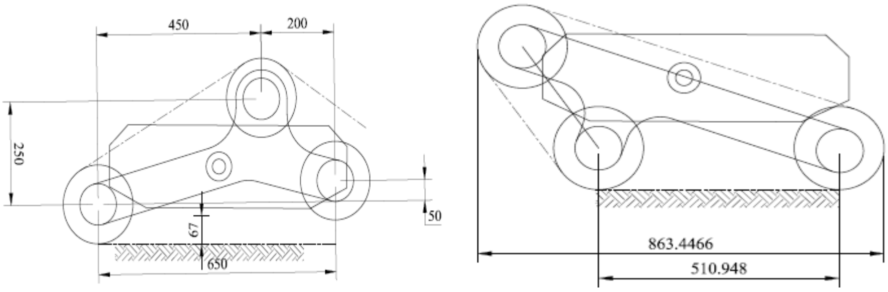

Figure 3: Proposed Concept Model – 01

marshy lands, sandy area, rocky or hilly areas or areas with larger undulations. For this purpose larger ground clearance is necessary along with obstacle over ridding capability. Obstacle over-riding is somehow related with the approach angle. Based on the above requirements the following configurations using links, pulleys and tracked belts have been designed and analyzed. The analysis has been presented in brief below.

First of all, the belt lengths readily available in the market were taken into account and then the four models were designed with different arm lengths and pulley diameter, keeping the payload same. As it has to move over rough terrain change of configuration is imperative. The first concept model as shown in Fig. (3) uses a rigid Y-shaped link with three pulleys of same size (outside diameter is 381 mm) for each side. All the pulleys are identical. The link can rotate about a hinged point placed at the middle of the link to generate a new configuration. A tracked belt has been used for traction and transmission of power to all the pulleys. The belt lengths for both these configurations are same as mention above. The maximum ground clearance is only 67 mm. However the major disadvantage of this configuration is that a huge amount of power will be required to rotate the link about its hinge point. The overall maximum length of the system will be 863.45 mm. All dimensions in the schematics are in millimeter.

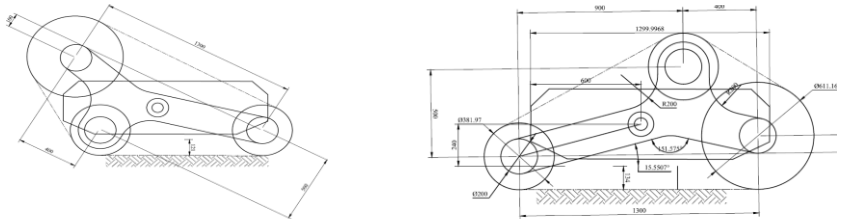

Figure 4: Proposed Concept Model - 02

The second concept model as shown Fig. (4) differs from the first one in terms of using the third pulley of larger diameter (approximately 610 mm). Otherwise it uses similar Y-shaped link with three pulleys wrapped with double sided tracked belt. The belt length has increased to 4377 mm. This length is constant for both the configurations. The maximum overall length of the system is around 1805 mm. The maximum ground clearance that can be obtained is around 124 mm which is higher than the first one. However the disadvantage is same as before i.e. it needs huge power to rotate the link and it may not be possible to rotate the link while the system is in motion.

The third concept model use two rigid links rather than a single link. The Y-shaped configuration is formed by a straight link another shorter link hinged at angle with the straight one. The shorter link is rotated to generate different configuration for over-riding on obstacles of different size and shape. Here two pulleys are identical (diameter is 190.99 mm) and third one is larger in diameter (302.76 mm). The belt length has to be kept constant in spite of the rotation of the shorter link as well as two different configurations have to be generated. Fig. (5) shows two different configurations and the corresponding belt lengths are 2479.8 mm and 2468.9 mm. This negligible difference will be compensated by adjusting the tension of the belt. Here the maximum overall length of the system is approximately 950 mm. The maximum ground clearance is around 250 mm. Approach angle has been provided for the ease of riding over any obstacle.

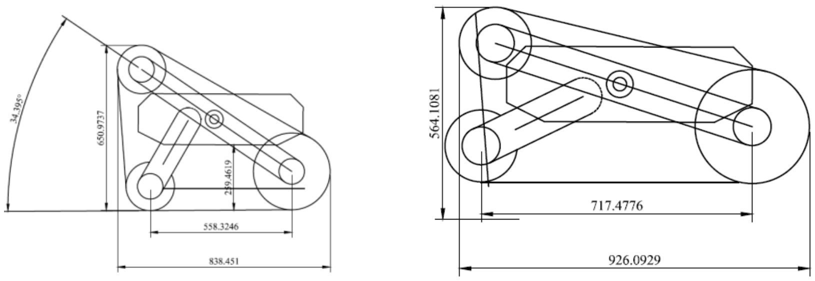

Figure 5: Proposed Concept Model – 03

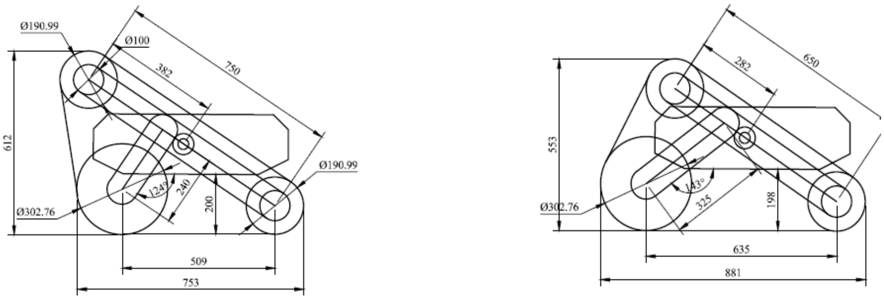

Figure 6: Proposed Concept Model – 04

The fourth concept model uses two flexible links to form the Y-shape for better over-riding capability. Here the straight link as well as the shorter (branch) link is telescopic in nature. This will help the system to keep the belt length constant as well as obtain different approach angles for over-riding the obstacles. As shown in Fig. (6) the length of the straight link changes from 650 mm to 750 mm (stroke is 100 mm) whereas the length of the short link changes from 240 mm to 325 mm (stroke is 85 mm). The dimensions of the pulleys are same as in the concept model 03. In this model only the larger pulley has been used to approach during over-riding obstacles in comparison to the concept model 03. The maximum overall length is 881 mm and the ground clearance is constant at around 200 mm.

5 Modeling and Dynamic Simulations of the Robotic System

Dynamic simulations of the robotic systems were performed to analyze functionality and expected capability for performing design optimization. In order to perform the dynamic simulations the proposed models were constructed using Autodesk Inventor 2014 and then exported to ADAMS. The experiments were performed keeping in mind the mass distribution, inertia properties, contact and friction forces between the links and track. To choose the best possible model it was imperative to know how various components interact during simulation and generate forces. ADAMS the multibody simulation software was used to test the prototypes of the proposed models. This is the primary step for any model design reducing time and cost.

The simulations were studied to optimize and validate the design and observe the mobility. Each and every part of the robot system was given an optimal weight before simulating the entire model. The locomotion was analyzed from time to time and instabilities if any produced were removed so that the robot remains in stable configuration all the time. The weights of the different links were changed from time to time until a favoured combination of the part weights was achieved.

The data resulting from the simulations were analyzed to serve three basic purposes which are the following:

i. The terrainability of the robot is analyzed by means of studying the different simulations involving the robots and various environments.
ii. The spring forces on the various links were analyzed to get a robust idea on the suspension system.
iii. The torque required to drive the robot with the maximum payload over various terrains was also analyzed.

5.1 Terrainability Analysis

A number of simulations were performed with the proposed models on tracks with several types of obstacles. A few of the tests are displayed in Fig. (7).

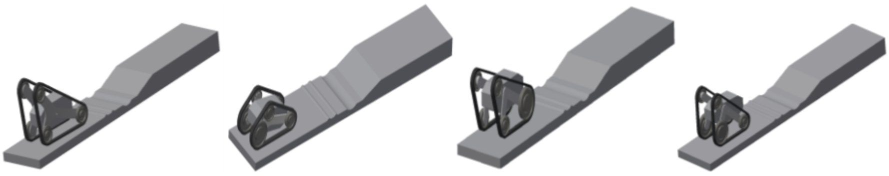

Figure 7: Proposed model 1 (top-left), Proposed model 2 (top-right), Proposed model 3 (bottom-left), Proposed model 4 (bottom-right)

Overcoming Extended Bumps: The typical configurations of the robots make it possible for them to overcome bumps on the road with ease. The central marker variations of the models give an insight to the difference in terrainability of the proposed models. The graphs shown in Fig. (8) depict the variations. Here the proposed models are denoted as PM and central markers as CM.

Crossing Ditches: Reconfigurable tracks allow the robots to adapt to problematic terrains by moving the links. It was analyzed after several simulations that ditches with depth of 0.475m can be successfully crossed by the proposed models

5.2 Analysis of Spring Forces.

Spring forces developed throughout the models were analyzed in order to find the optimal stiffness values which would lead us to the best possible configuration.

The graphs generated (as shown below) show the forces generated in the suspension spring systems in all the proposed models. The models were made to overcome two cylindrical bumps along the same track. The spring forces for the major suspension system was analyzed and compared with the help of the graphs as shown below.

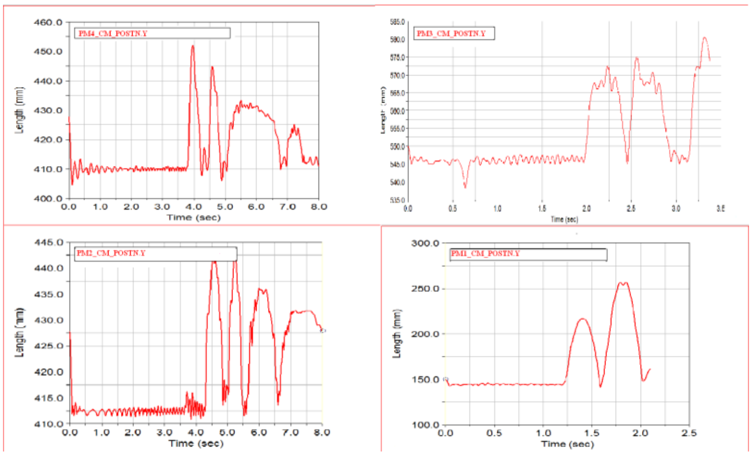

Figure 8: PM4 CM Position (top-left), PM3 CM Position (top-right), PM2 CM Position (bottom-left), PM1 CM Position (bottom-right)

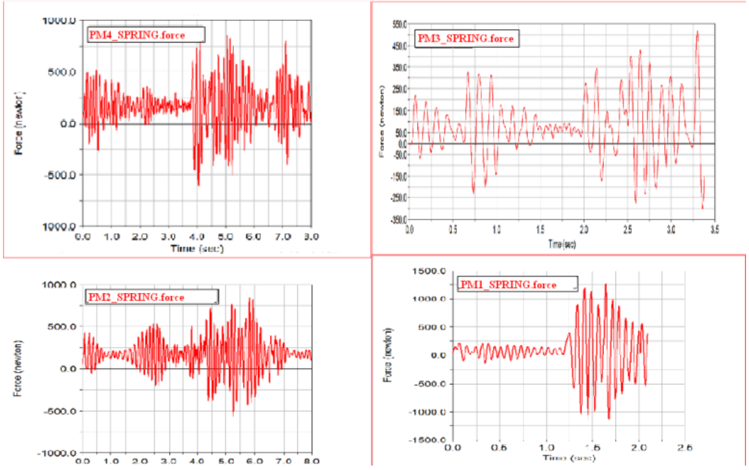

Figure 9: PM4 Spring Force (top-left), PM3 Spring Force (top-right), PM2 Spring Force (bottom-left), PM1 Spring Force (bottom-right)

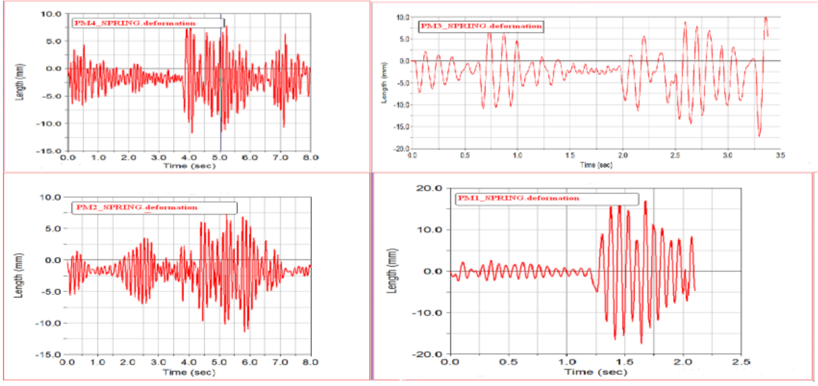

Figure 10: PM4 Spring Deformation (top-left), PM3 Spring Deformation (top-right) PM2 Spring Deformation (bottom-left), PM1 Spring Deformation (bottom-right)

The forces and deformations of the springs varied from model to model but the spring parameters were kept constant. In order to provide tension to the belt an initial preload of 30 N was used. The spring constant and damping coefficients of the springs were taken to be 70 N/mm and 3.2E-2 N-s/mm. The graphs show that the compression of the springs during the simulation process was roughly within 15 mm. Each model generated graphs in different time spans; this was because the initial starting distances of the models differed but this minor problem will have no effect on the end results. The spring forces are shown in Fig. (9) and the deformations are shown in Fig. (10)

5.3 Torque requirements for maximum payload

Simulations were performed in order to analyze the maximum possible payload that can be driven by the robots and identify the motors needed to perform this action. Now in all the models a driving torque of 14.7 Nm was provided. Brushless DC motors were selected to provide the necessary torque. Taking into account the weight of the links the maximum payload that can be driven by the proposed models with ease was found to be approximately 127 kg. Torque calculations were computed keeping in mind that the robot can generate enough power to climb up inclined planes. In order to ensure motion under inclined conditions the torque expression [2] was found to be

$$T \geq \frac{WR}{2}(\mu_s \cos\alpha + \sin\alpha)\left(\frac{1}{\eta_{gear} k_{gear} \eta_{track}}\right) \tag{9}$$

In Eqn. (9) α is the angle of inclination, R is the outer radii of the track, W is total weight, μ_s is the coefficient of static friction, η_{gear} is the gear efficiency, k_{gear} is gear ratio and η_{track} is track efficiency.

6 Conclusions

The proposed models were constructed with the primary motive of constructing a terrain adaptive mechanism with reconfiguration capability. The graphs generated from various simulations were analyzed and the proposed model number four was selected as the most suitable configuration though it has complexities.From analyzing the graphs it was evident that the forces generated and the deformations undergone by the spring suspension system and the central marker deflections are least for model four. The primary problems of robots in field operations were addressed and the design was developed by analyzing the functionality and orientations. This model holds the answer to a number of problems relating to locomotion of robots on rugged terrain. Selection methodology adapted here will not only be a benchmark for future researches regarding terrain adaptability but will allow more innovative design concepts to come forward. Now before developing the real prototype it was imperative to make virtual prototypes and multibody simulation in MSC ADAMS for reducing the time and cost and aiding in optimizing the robot design.

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