Analytical Approach for Force Stability Analysis of Stair Climber

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Abstract

To design and develop a robot for climbing up the stairs as well as for urban search and rescue missions in buildings and cities, it is often necessary to place flipper or swing arms to get better grip of stairs. Stair climber robot should be quick and agile at the same time be able to deal with rough terrain. This paper presents the mechanical structure of stair climber robot with hardware composition and force analysis using classical mechanics method. To find out the effectiveness of the dynamical model the results from the model is compared with simulation and experiments.

Keywords: Stair climbing, Variable configuration, Flipper robot, Force analysis

1 Introduction

For mobile robots, staircase is a very critical terrain to overcome successfully, due to which stair climbing is an important aspect in the evaluation of robots. Climbing up stairs involves two criteria's, overcoming obstacle and climbing up slopes, while maintaining its stability without slipping or toppling backward. Due to these aspects, study of static as well as dynamic stability analysis helps in sorting out problems encountered during climbing up stairs. Tracks have many advantages over the wheel and leg types for stair climbing. Tracked mobile robots have a very large ground contact area [1] that provides improved traction and stability along with ease of control and continuous drive. These robots are having the capability to climb up stairs, overcome obstacles and ground adaptability can provide help in search and rescue operations, hazardous situations, terrorist activity and military explorations.

Previous research work has been carried out on stability analysis on different aspects of stair climber as in Ben-Tzvi[2][3] papers, where he analysed a LMA(Linkage Mechanical Actuator) mobile robot during autonomous climbing and descending of stairs, step height measurement and evaluation of centre of gravity of stair climber. Algorithm implementation was done by him for stability analysis and by Hung-Sang-Song- Dong [4] to improve MACbot controllability in outdoor environment.

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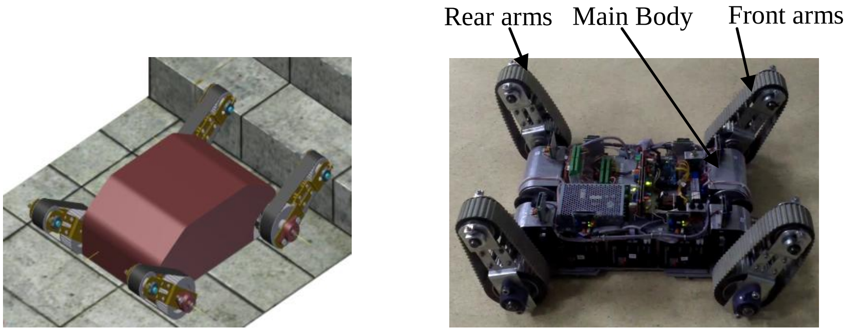


(a) (b)

Figure 1: (a) 3-D CAD model (b) Developed prototype of flipper arm stair climber

Classical mechanics method was used by Tao-Ou-Feng [5] on dynamics and stability in tracked stair climber. Kinematics and dynamic analysis of stair climbing ability for a tracked reconfigurable modular robot was done by Liu- Wang- Li [6] by dividing the process of stair climbing in riser climbing, crossing, and nose line climbing. A relationship between stability and centroid position of stair climbing robot was given by Guo-Song-Bao-Zhang-Tang [7] to restrain the robot from toppling on its side. Stability analysis was done using Denavit–Hartenberg method by Wang- Wu-Deng -Du [8] for tracked robot in climbing stairs.

Most of these studies are carried out on fixed geometry tracked robots that have simple tracks with at least two driven sprockets and two flexible endless track belt. At present very less studies of force analysis have been carried out on tracked mobile robot with variable configuration. In this paper the force analysis of stair climber having flipper arms is carried out. Fig.(1) shows the developed prototype of stair climber, with front and rear flipper arms which can separately rotate about a fixed axis. This configuration is needed to adjust their angle of contact with obstacles and angle of attack to improve the robot's ability to climb the obstacles. With changing nature of terrains; the robot can maintain its balance by controlling its flippers. Dynamics and stability of a tracked mobile robot while climbing stairs have been analyzed and the work is verified through simulation.

1.1 Mechanical Hardware

The stair climber robot is designed and developed with six brushless DC motors; two of them are for four flippers and rest for driving wheels. For the movement of stair climber in the linear direction, four independently controlled motors are used to drive four driving wheels. Two motors are used to drive four independently moving flipper arms. Power is being supplied to all the six motors, computer and other accessories from two Li-Ion battery banks.Timing belts and pulley arrangement systems are used for the purpose of gripping, spinning and climbing. This system provides better traction to the stair climber while travelling over stairs, gap and obstacle for urban search and rescue missions. Flipper arm configuration is divided in two pairs i.e., front flipper and rear flipper. For climbing up stairs and moving over obstacles, front flippers are used. Whereas, to avoid backward tumbling, to increase stability and traction while moving at high speed, in rural area as well as in landslide area or in the rescue missions, rear flippers are used.

2 Force analysis during stair climbing

Stair climber climbs up a staircase through number of steps. This whole process is divided into four steps i.e. approaching, climbing, ascending and leaving. The nature of the forces between the robot flipper track and staircase during each of the step is different based on classical mechanics. It is assumed that the robot is climbing at a very slow speed. The following assumptions have also been made for case of force analysis:

- The mass of the system is uniformly distributed and acts through the centre of gravity (C.G).
- Suspension effect, deformation of flipper track and slippage are neglected.
- Stairs steps are normal and available in Indian houses.

The steps for climbing up stairs by the flipper-tracked stair climber robot are shown in the Fig. (2). to climb up or down the stairs, front and rear flipper tracked arms are controlled to increase traction. Fig. (2)(A) Shows initial position of the robot, while climbing up the stairs as in Fig. (2)(B), front flipper is raised to touch the edge of the first step of the stair. In Fig. 2(C), the front flipper overcomes first step and touches the edge of second step. The robot overcomes the second step and touches the edge of last step of the stairs as in Fig. (2)(D). Fig. (2)(E) Shows a position in which the front flipper is overcoming the last step while the rear one is crossing through the edge of the first step. In Fig.(2)(F), the body of robot overcomes all the three steps while the rear flipper gives support to move forward and Fig.(2)(G) being the static position after overcoming all of the stairs.

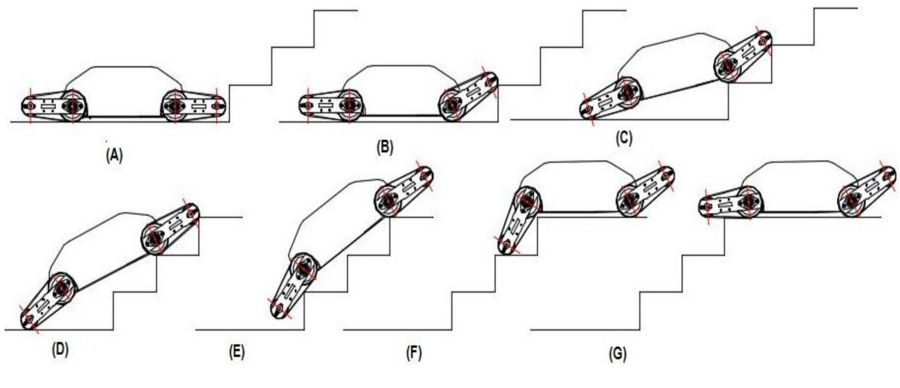
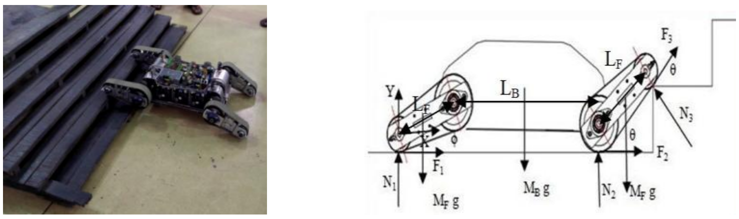


Figure 2: Model configurations for climbing upstairs

Table1: Parameters Used in various equations

Parameters with different nomenclatures	*value*
M= Mass of stair climber	45kg
M_B= Mass of the main body	25kg
M_F= Mass of the flipper	5kg
L_F= Length of the large and small driving pulley system	195mm
L_B= Length between two driving pulley	480mm
θ= Front approach angle	37°
H= Height of each step	150mm
W = Width of each step	200mm
μ= Co-efficient of friction	0.7
g=Acceleration due to gravity	9.81m/s^2
N_i = Normal forces	i=1 to 4
F_i= Frictional forces	i=1 to 4
F_X, F_Y= Force in X & Y direction	-
v =Linear velocity	0.50 m/s
T=Torque	

Approaching:



(a) (b)

Figure 3: (a) Approaching toward the first step (b) Force Representation

Fig.(3) shows that when a stair climber approaches the first step, the traction forces and reaction forces are analyzed on the basis of classical mechanics method. The relationship between frictional forces along X-axis and Y-axis and torque equilibrium are given by Eq. (1)-(3) by using the table 1.

ϕ=Angle between the rear flipper track and ground =17° (assumed)
$N_1 = M_F g$ = 49.05N = N_2
$N_3 = M_F\, g \cos\theta$ = 39.17N
By Using Newton's Second Law,

$$F_X = F_1 + F_2 + F_3 \cos\theta - N_3 \sin\theta \tag{1}$$

Where, $F_1 = \mu N_1$, $F_2 = \mu N_2$, $F_3 = \mu N_3$ as shown in Fig. (3)(b)

$$F_Y = N_1 - M_F g + N_2 - M_F g + N_3 \cos\theta + F_3 \sin\theta - M_B g \tag{2}$$

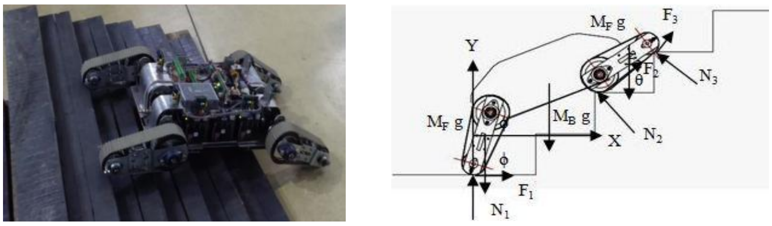
$$T = M_B g\left[L_F\cos\phi + \frac{L_B}{2}\right] - N_3\left[(L_F\cos\phi + L_B)\cos\theta + \left(\frac{H}{\sin\theta}\right)\right] - F_3[(L_F\cos\phi + L_B)\sin\theta] - N_2[L_F\cos\phi + L_B] + M_F g\left[\left(\frac{L_F\cos\phi}{2}\right)\right] + M_F g\left[L_F\cos\phi + L_B + \frac{(L_F\cos\phi)}{2}\right] \quad (3)$$

= 72.21 Nm

Driving Force (F)= $F_1 + F_2 + F_3\cos\theta = \mu N_1 + \mu N_2 + \mu N_3\cos\theta = 90.56$ N

Power = $F.v$ = 90.56 X 0.50 = 45.28 watt

Climbing:



(a) (b)

Figure 4: (a) Climbing the second step (b) Force Representation

Stair climber climbs up stairs with its front flipper while rear flipper supports the whole body, preventing from tumbling backwards as in Fig.(4). By using the classical mechanics, the Eq. (4)-(6) can be obtained from the frictional forces and torque equilibrium.

$\phi=60^{\circ}$ (assumed)

$N_1 = M_F g = 49.05$N, $N_2 = N_3 = M_F g\cos\theta = 39.17$N

By Using Newton's Second Law,

$$F_X = F_1 + F_2\cos\theta + F_3\cos\theta - N_2\sin\theta - N_3\sin\theta \quad (4)$$

Where, $F_1 = \mu N_1$, $F_2 = \mu N_2$, $F_3 = \mu N_3$ as shown in Fig. (4)(b)

$$F_Y = N_1 + N_2\cos\theta + N_3\cos\theta + F_2\sin\theta + F_3\sin\theta - M_B g - 2(M_F g) \quad (5)$$

$$T = M_B g\,[L_F\cos\phi + L_B/2] - N_2\,[2(\sqrt{(W^2 + H^2}))] - N_3\,[3(\sqrt{(W^2 + H^2}))] + M_F g\,(L_F\cos\phi + L_B + (L_F\cos\theta)/2) \quad (6)$$

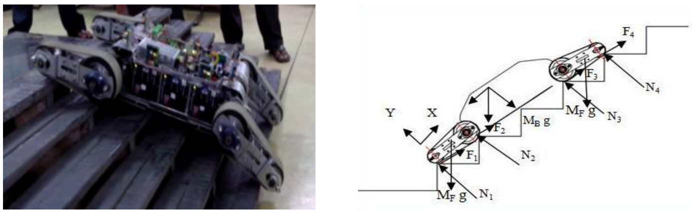
= 65.95 Nm

Driving Force $(F) = F_1 + F_2 + F_3 = \mu N_1 + \mu N_2 + \mu N_3 = 89.17$N

Power = $F.v$ = 89.17 X 0.50 = 44.58 watts

Ascending:

While ascending on stairs, the stair climber aligns in line with the edges of stairs, without sliding down as shown in Fig. (5). At this point, the relations of the frictional forces and torque equilibrium are given below by Eq. (7)-(9).



(a) (b)

Figure 5: (a) Ascending on stairs (b) Force Representation

$\theta \ = \ arc\ (tan\ (H/W))\ =37^{\circ}$, $N_1 = N_2 = M_F g cos\theta$ =39.17 N

$N_3 \ = \ N_4 = M_F g cos\theta \ = 39.17$ N

By Using Newton's Second Law,

$$F_X \ = \ F_1 \ + \ F_2 \ + \ F_3 \ + \ F_4 \ - \ M_B\ g\ sin\theta \ - 2(M_F g sin\theta) \tag{7}$$

$$F_Y = \ N_1 \ + \ N_2 \ + \ N_3 \ + \ N_4 \ - \ M_B g cos\theta \ - \ 2(\ M_F g cos\theta) \tag{8}$$

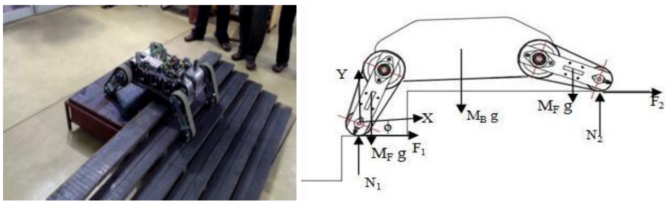
$$T \ = \ M_B g cos\theta \left[\sqrt{H^2+W^2} + \frac{L_B}{2}\right] - N_2\left[\sqrt{H^2+W^2}\right] - \ N_3\left[3\sqrt{H^2+W^2}\right] - N_4\ [4\sqrt{(H^2+W^2)}] \ + \ M_F\ g\ cos\theta(L_F/2) + \ M_F\ g\ cos\theta(L_F \ + L_B + \ L_F/2) \tag{9}$$

$= 51.71$ Nm

Driving Force = $F_{\ 1} + \ F_{\ 2} + \ F_3 \ + \ F_4 \ = \ \mu\ (N_1 \ + \ N_2 \ + \ N_3 \ + \ N_4) \ = 109.67$ N

Power = $F.v$ = 109.67 X 0.50 = 54.83watt

Leaving:



(a) (b)

Figure 6: (a) Leaving the stairs (b) Force Representation

Fig.(6) depicts the state of Stair climber leaving the stairs. The rear flipper supports the whole body by exerting pressure on the last step of stairs helping the stair climber in the forward movement. Friction forces and torque equilibrium equations are given by Eq. (10)-(12)

$\phi = 60^{\circ}$ (assumed), $N_1 = \ N_2 \ = \ M_F g \ = 49.05$ N

By Using Newton's Second Law,

$$F_{\ X} = \ F_1 \ + \ F_2 \ = \ \mu\ (M_F\ g \ + \ M_F\ g) \tag{10}$$

$$F_Y \ = \ (N_1 \ - \ M_F\ g) \ + \ (N_2 \ - \ M_F\ g) \ - \ M_B\ g \tag{11}$$

$$T \ = M_B\ g\ [L_F\ cos\phi \ + \ L_B/2] \ + \ M_F\ g[L_F\ cos\phi \ + \ L_B + \ (L_F\ cos\phi)/2] - N_2\ (L_F\ cos\phi \ + \ L_B \ + \ L_F) \ + \ F_2 \times H \tag{12}$$

$= 72.031$ Nm

Driving Force = $F_1 \ + \ F_2 \ = \ \mu\ (M_F\ g \ + \ M_F\ g) \ = 68.67$ N

Power = $F.v$ = 68.67 X 0.50 = 34.33 watt (13)

From Eq. (10)-(12), we can get the forces in X and Y direction and can calculate the driving torque T and power P during various steps while climbing and ascending through stairs as shown in Eq. (13).

2.2 Stability during Climbing

To ensure stable climbing and no backward tumbling, it is important that front and rear flipper must remain in proper orientation as shown in Fig. 2(A)-(D). During these stages, the rotating rear flipper and robot driving rear small pulley position is relatively post-placed, it is very difficult for it to tumble backward. Fig. 2(E) shows a position in which the front flipper is overcoming the last step while the rear one is crossing through the edge of the first step. Since the tracks of the flipper arm move forward at constant speed v and since the speed is relatively lower when the robot climbs up the stairs, slippage with edges is not considered. As track always remain in contact with the stairs and normal force on wheel N_i can never be zero and the robot never tumble backwards on the stairs. It shows the capability of the tracked robot to adapt to stairs inclination angle by changing its geometry configuration by rotating its flipper arm about a fix axis of rotation.

3 Simulation of Contact Force

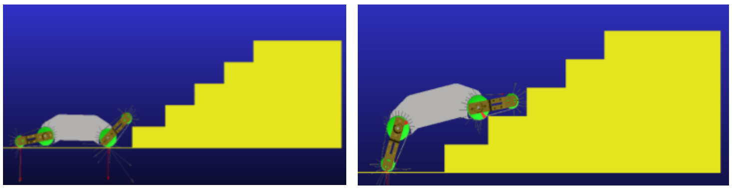


Figure 7: Multi body model of Stair Climber in ADAMS$^{@}$

The 3-D CAD model of the Stair climber, as shown in Fig.(1) , is transferred into an ADAMS$^{@}$ multi-body model using the parasolid interface embedded in INVENTOR$^{@}$. The parasolid CAD file format is considered as a reliable file format for the files to be import in the ADAMS$^{@}$ as there is negligible geometry loss. Perfect geometry is required for the 3D contact problem. Some parts are kept hidden for good visual effect of the simulation. The multi-body model of the climber is shown in Fig.(7). The bearings to support the guide shafts are described by revolute and cylindrical joints. A fixed joint is added in between ladder and ground and revolute joint to corresponding shaft, so that the forces on moving pulleys and arm are transferred. To avoid the function discontinuity caused by the dramatic variation of the damping force while contact-collision occurs, the damping force is set to zero and the penetration depth of the ladders and tracks is considered as negligible. Longitudinal pulling force required for the climber to overcome the resistance and start rolling on flat ground, was used to calculate the resistance torque. The system parameters such as friction and damping in Adams model were adjusted so as to have same resistance torque. The stair climber has 214 moving parts as thread of timing belts are considered as parts during simulation.

Model statistics are explained in Table 2. The Simulation has been performed using ADAMS@ machinery belt feature. The main objective of this study is to calculate the torque coming on each arm during climbing.

Table 2: Model Statics

No. of moving parts	214
No. of revolute joints and fixed joint	12,9
No. of motion	4
Total no. of degree of freedom	590

3.1 Simulation Results

It is very clear from the analysis that the contact between stair and flipper track arm belts is an inelastic impact and value of torque is depends upon the translation velocity. The mass of main body and the each flipper arm has taken 25kg and 5kg respectively as given in Table 1. The maximum value of torque calculated from ADAMS@ is 75 N-m as shown in Fig.8, which varies from the analytical one obtained by Eq. (3), (6), (9) & (12). This may be due to the belt thread profile considered in case of ADAMS@. It is also noticeable that in ADAMS@ analysis coefficient of restitution is not considered which is related with velocity changes. Moreover, it is also important to ensure that there must be no slippage between stair end point and the belt during each cycle of the excitation.

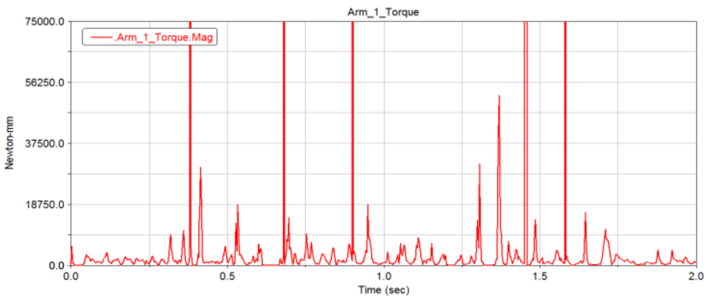


Figure 8: Torque representation on fliiper arms

There is some variation in the theoretical and simulation results due to variable nature of some parameters. Front approach angle θ and angle between the rear flipper track and ground ϕ are variable in nature as flipper can rotate but during analytical calculations of the traction forces and torque their values are assumed as constant.

4 Conclusion

The performance of flipper tracked stair climber has been analyzed for most favorable stairs step-climbing using defined structure and kinetics of flipper arm. A mathematical model has been established, for climbing various steps. Three dimensional relationships between climbing capability and structure parameters of flipper-tracked robot are analyzed. The theoretical value of torque and power during each step of climbing is obtained.

It was observed that the developed stair climber with tracked belts flipper arm can generate a large traction force that is required to overcome the resistance torque. However, as mentioned above, slippage or spinning has been observed when the support point changes. The Stair climber with flipper tracks arm can easily change its inclination angle. It is found that when flipper arms are lying flat, it is favorable for robot channel-crossing. The results of various analyses are useful in obtaining the approximate value of the torque and power with that a climber can safely negotiate. Work is in progress to model the system and perform the same analysis with slippage, spinning in action.

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