

Design, Development & Evaluation of a Prototype Tracked Mobile Robot for Difficult Terrain

* Hafiz Muneeb Ilyas, ** Muhammad Ehsan Ali, **Nasir Rehman and *Abdul Rehman Abbasi

Abstract—This paper reports the design, development and evaluation of a prototype tracked mobile robot for task execution in both natural and human-made environments with stair climbing feature. First, different types of locomotion systems used for mobile robots are compared and their pros and cons are presented. Then the mechanism designed for the prototype tracked mobile robot is described with the aid of a CAD model. Finally, the results of field testing of the actual robot are presented and the behavior of tracked mobile robots in presence of slippage is discussed.

Index Terms—Locomotion System, Mobile Robots, Skid Steering, Slippage.

I. INTRODUCTION & MOTIVATION

In recent years, mobile robots are of major focus in robotics research due to their effectiveness in assisting humans in a variety of applications. Mobile Robots are widely used in areas which are insecure or hazardous to humans such as in military and space applications [1, 2].

More recently, mobile robots have also been deployed in situations of disasters for search and rescue of people trapped under the debris of collapsed buildings [3]. Another important area of application of mobile robots is the field of nuclear decontamination and decommissioning. The useful life of hundreds of nuclear facilities all over the world will come to an end in near future and large number of mobile robots would be required to assist humans and to prevent them from high radiation exposure in the decommissioning process [4]. Similarly, decontamination operation such as those required in Fukushima nuclear accident are much demanding.

In contrast to the fixed-type industrial robots, control of mobile robots is quite complicated due to their dynamic working environment and requires sophisticated sensor systems and advanced control methodologies. In addition, proper selection of its locomotion system is crucial for its successful operation.

There are three fundamental configurations of locomotion system for a mobile robot, i.e. rolling, ambulatory and articulated body [5]. Locomotion system based on the endless rotation of wheels or crawlers, corresponds to the rolling configuration, while legged locomotion systems corresponds to the ambulatory configuration. Similarly, slithering or snake-type locomotion system corresponds to the articulated body configuration. In addition, there may be a combination of these three configurations, which is commonly termed as hybrid locomotion system [6].

Each locomotion system in mobile robots has its own advantages and disadvantages. For example, mobile robots, based on wheeled locomotion system provide high speed

maneuverability and high payload capacity. These are relatively simple to construct, energy efficient and easy to control but they have poor terrain adaptability [7]. Furthermore, wheeled mobile robots cannot go through obstacles with height larger than the radius of the wheel and therefore only suitable for flat or smooth terrains [8].

Tracked mobile robots are relatively slow as compared to the wheeled mobile robots, with good payload capacity but less than their wheeled counterparts. Due to their large contact area with the ground, they produce greater friction and consume more energy but have good terrain adaptability and can maneuver on difficult terrains such as on loose sand, grassy plains and rocky surfaces [9]. Moreover, with the addition of articulated tracks called flippers, the inclination of tracked mobile robots can be controlled, which provide increased terrain adaptability, allowing them to go through large obstacles and ascend stairs [10]. Unfortunately, due to the inherent slippage, tracked mobile robots are difficult to control [11].

Legged mobile robots have excellent terrain adaptability when compared to wheeled and tracked mobile robots and pose minimum impact to the environment due to their isolated footholds [12]. However, these are very slow as compared to the wheeled and tracked mobile robots and also have poor payload capacity. Furthermore, due to the large number of actuators, legged mobile robots consume a lot of energy and are also difficult to control [9]. Articulated body or snake-like robots also have excellent terrain adaptability and are useful for narrow or compact spaces [5]. They can maneuver on flat or uneven surfaces and on loose sand as well, but are relatively slow.

In this work, a prototype tracked mobile robot with two articulated flippers is designed and developed for the terminal goal of developing a fully functional assistive mobile robot to execute tasks in hazardous areas. The designed mechanism is described with the aid of a CAD model. Finally, the performance of the actual robot is evaluated and the behavior of the tracked mobile robot in presence of slippage is discussed.

II. RELATED WORK

The suitability of tracked mobile robots, for both indoor and outdoor applications provokes the designers to develop state of the art applications with different configurations and capabilities. A small-sized dual track mobile robot for autonomous mine detection in unstructured environment is developed by [13]. It is equipped with metal detection sensors and capable of navigating through obstacles. Auriga- β , a dual-track mobile robot, developed for fire extinction tasks, weighs 286 kg and equipped with self-stabilized landing platform for

*Design Engineering & Applied Research Lab, KINPOE, Karachi, Pakistan (muneebilyas@hotmail.com, arehman.abbasi@paec.gov.pk)

**Pakistan Institute of Engineering & Applied Science, Nilore, Pakistan (nasjad2003@yahoo.com, ahsen_ee_25@yahoo.com)

mini-helicopters [14]. CoMoRAT (Configurable Mobile Robot for All Terrain) incorporates both wheels and tracks at the same time [6]. The wheels provide smooth motion on flat surfaces while the tracks provide maneuverability on rough terrains. Amoeba-II developed for urban search and rescue applications, consists of two modular tracks connected through a yaw joint, and is capable of changing its posture according to the environment [15]. Brokk, a tele-operated dual-track mobile robot, incorporated with a manipulator, is developed for small-scale demolition tasks in nuclear decommissioning process [4]. HELIOS-VI developed by [5] is a dual-track mobile robot with a pair of articulated flippers. It is capable of climbing stairs with a payload capacity of 120 kg. ResQuake developed for search and rescue operations, is a tracked mobile robot that consists of four independent articulated flippers [16]. It is capable of ascending stairs and climbing obstacles up to 40 cm high. MOBIT is developed by [17] to perform civil and military missions. It is a four wheeled skid-steered platform with four articulated tracks and can operate in wheeled, tracked and legged locomotion modes.

III. DESIGN DESCRIPTION

The designed prototype is a dual track mobile robot with a pair of articulated flippers at front as shown in Fig. 1. This provides good terrain adaptability and the capability of climbing over large obstacles and ascending stairs. The flippers can rotate up to 360° and are powerful enough to lift the vehicle. The lengths of the flippers are the same as that of fixed tracks which provides the capability to flip the vehicle upside down. This helps the robot to regain its posture in case of tipping over without any external effort. The platform is designed in such a way that no part of the body exceeds through the track's surface boundaries. The advantage of this design is that in case of collision it prevents the body parts and especially the sensitive devices and sensors from directly colliding with the obstacles, and only the tracks would have a direct impact.

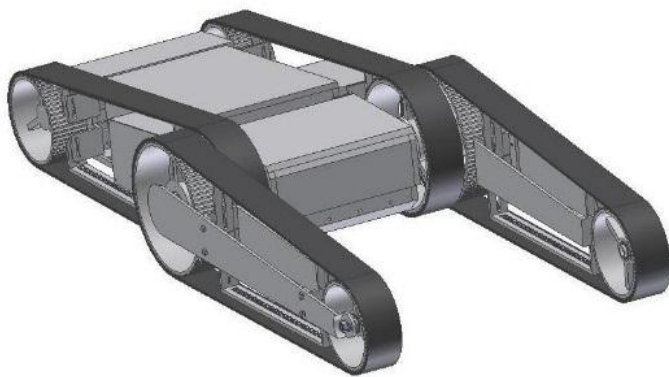


Fig. 1. CAD Model of the Prototype Design

An exploded view of the robot is shown in Fig. 2. Instead of a single piece of casted body, the structure is assembled using modular approach, i.e. by integrating different parts that are bolted to each other. This is advantageous because in order to add more features or components such as a manipulator arm, then instead of redesigning the whole assembly, few parts could be altered which is easy and cost effective.

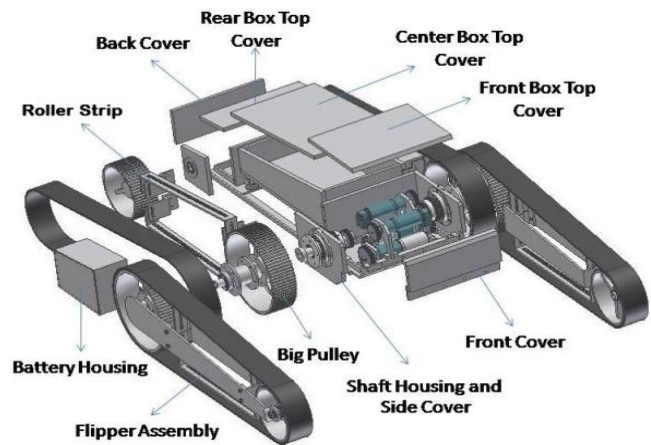


Fig. 2. Exploded View of the Platform

As shown in Fig. 2, the structure consists of a base assembly, side covers, front covers, back cover, top cover, battery housing, roller strips, inner tracks or fixed tracks and outer tracks or flippers. The roller wheels are attached to all four tracks in the gap between the pulleys. This prevents the belt from bending when a force is applied on the belt at the gap between the two pulleys, especially during stair climbing due to the edges of the stairs.

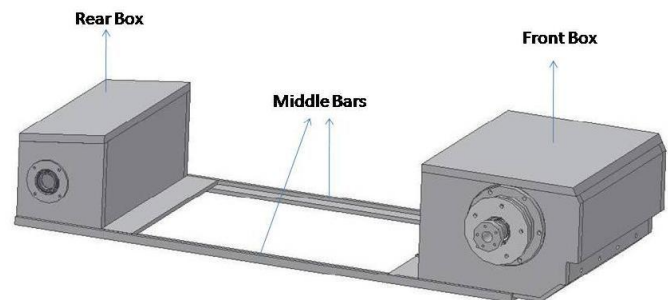


Fig. 3. Chassis Assembly

The chassis assembly comprises three main parts i.e. the front box, rear box and the middle bars, which are used to join the front box and the rear box as shown in Fig. 3.

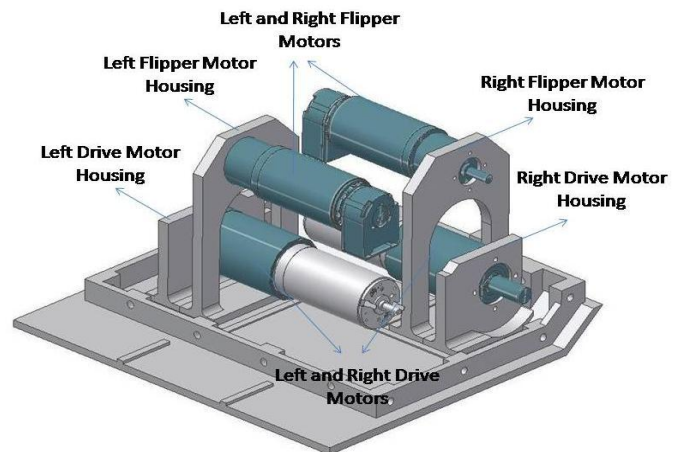


Fig. 4. Motor Housing and Arrangement

All four motors i.e. two motors for actuating left and right tracks and two motors for actuating flippers, are fitted in separate housings on the base plate of the font box as shown in Fig. 4. Installing all four motors at the front locates the center of gravity at the center when flippers are fully stretched. This prevents the vehicle from tipping over when ascending stairs [5]. Also, during normal motion when flippers are folded, the load concentration at either end of the vehicle causes less slippage [11].

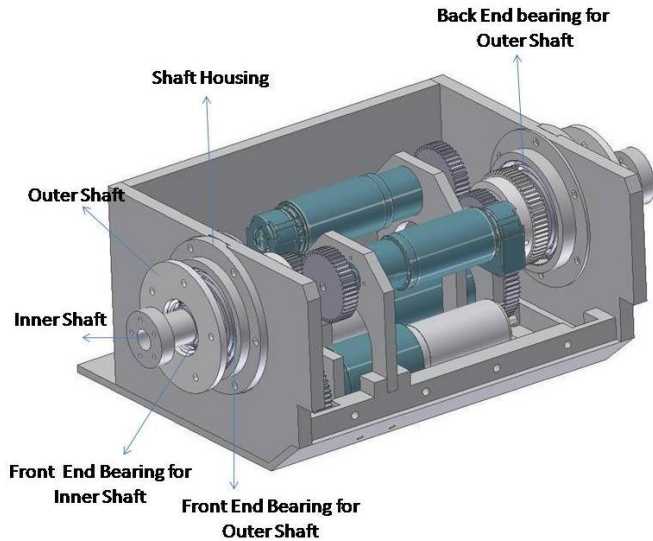


Fig. 5. Illustration of Drive Mechanism

The drive mechanism of the vehicle consists of two concentric shafts on each side as shown in Fig. 5. The outer shaft is the drive shaft and the inner shaft is attached to the flipper. The outer shaft is inserted through bearings in the shaft housing mounted on the side walls. Two bearings are used inside the shaft housing i.e. one at the front end of the housing and the other at the back end. Similarly, the inner shaft is inserted through two bearings inside the outer shaft. The purpose of using two bearings at a certain distance is to minimize the vibration of the shaft that usually occurs when a force is exerted on the shaft if only one bearing is used. These vibrations can cause severe effects like disturbing the gear meshing i.e. moving the gears apart resulting in the slippage of gears during motion or sometimes the gears are totally unmeshed and the drive mechanism totally disconnects from the actuation system. If the gears move too close to each other then it results in loading the actuating shaft or sometimes the shaft is totally jammed causing the motion to stop. Finally, the gears are mounted on the back end of both outer and inner shafts that are meshed with gears mounted on the drive motors and the flipper motors as shown in Fig. 6.

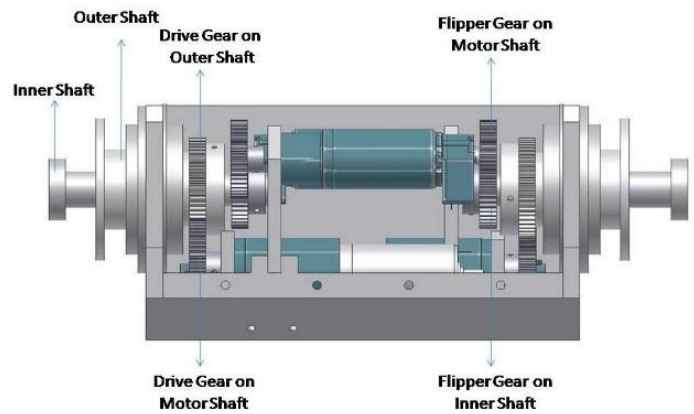


Fig. 6. Gear Meshing and Arrangements

The inner big pulley or the drive pulley is mounted on the outer shaft. The small idler pulley at the back is mounted on the shaft attached to the rear box through two bearings. The outer big pulley is coupled with the inner big pulley via coupling shaft between the two pulleys as shown in Fig. 7.

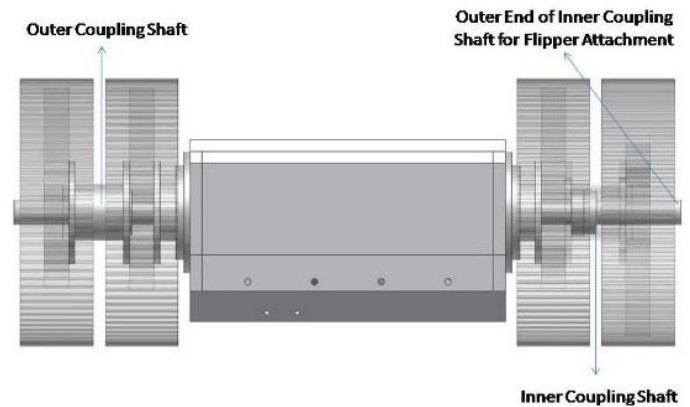


Fig. 7. Illustration of Coupling Shafts

Similarly, the flippers, as shown in fig. 8, are mounted to the inner shaft through an inner coupling shaft inserted through the outer coupling shaft. Fig. 9 shows the pictures of the actual robot in different poses and Fig. 10 shows the actual robot during stair climbing.

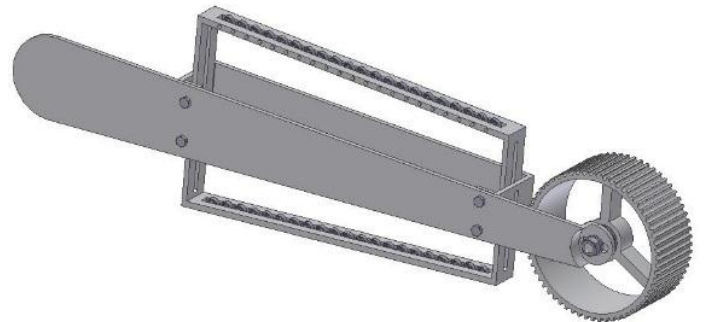


Fig. 8. Isometric View of Flipper Assembly

IV. PERFORMANCE EVALUATION AND DISCUSSION

The designed prototype robot performed well while making the desired moves such as making turns, climbing stairs, and heading forward and backward. The speed is found in the range of 0.9 to 2.9 km/hr (0.25 to 0.8 m/s) for the stair climbing motion to forward motion on flat surfaces. The detailed specifications and performance parameters are summarized in Table I.

The experimental results show that the performance of the prototype tracked mobile robot is satisfactory. The platform was very stable during stair climbing and no loss of traction is observed visually. It is observed that the slippage is unavoidable during turning; however, it can be minimized if the mechanical structure is properly designed and the center of gravity is properly located.

The steering methods used for tracked mobile robots are: skid steering, curved track steering and articulated steering [11]-[18]. Among them, the skid steering method is based on controlling the relative velocities of both tracks and is widely used [11]-[14]-[18]. Skid steering presents two major advantages over alternative wheel configurations, such as Ackerman or axle articulated. First, it is simple and robust in mechanical terms, and second, it provides better maneuverability, including zero-radius turning, using only the components needed for straight line motion [19].



Fig. 10. Actual Robot during Stair Climbing



Fig. 9. Actual Robot in Different Poses

However, since all tracks are aligned with the longitudinal axis of the vehicle, turning requires the tracks to skid laterally [19] which in effect alters the pressure distribution and causes the tracks to slip longitudinally due to loss of traction with the ground [11]-[14]-[18]-[20]. In effect, the non-holonomic constraint of zero lateral velocity considered for standard differential drive mobile robots, such as unicycle or car-like robots becomes invalid for skid-steered tracked mobile robots [19]-[21]-[22], and for this class of under actuated systems, the set of feasible accelerations is restricted and their dynamics are non-integrable [23]-[24]. In addition, due to varying ground surface conditions and track-terrain interactions, it is difficult to obtain an accurate kinematic and dynamic model for tracked mobile robots [18]-[25]-[26]-[27], since it is not possible to predict the exact motion of the vehicle only from its control inputs [11]-[28]. This means that the motion control methods used for standard differential drive mobile robots cannot be used for motion control of skid-steered tracked mobile robots [11]-[19]-[22]-[25]. Although, significant research has been directed at path planning and motion control of unicycle or car-like robots, the counterpart research on skid-steered mobile robots is less frequently reported [19]-[21]-[23]-[26]-[29]. Hence, the motion control of skid-steered tracked mobile robots in skid-slip conditions still remains a challenge. Especially there is a growing need for intensive experimental validation of the existing and new control strategies [23].

TABLE I
SPECIFICATIONS & PARAMETERS OF THE ACTUAL ROBOT

Chassis Length (Pulley Center to Center)	620 mm
Flippers Length (Pulley Center to Center)	620 mm
Width (without flippers)	480 mm
Height	220 mm
Total Mass	30 kg
Payload Capacity	>20 kg
Movable Range of flippers	360°
Maximum Velocity on flat surface	2.9 km/hr
Maximum thrust on flat surface	154 N
Stair Climbing Ability	>30 Degrees
Velocity during stair climbing (with 12 Kg payload)	0.9 km/hr @ 30°
Track belts	8 mm HTD Belts
Drive Motors: Maxon DC Motors with Planetary gear head	90 W x 2
Flipper Motors: Maxon DC Motors with Planetary gear head	70 W x 2

The fundamental issue in the modeling of tracked mobile robots is to relate the interacting forces at the track-terrain interface, the vehicle design parameters and the terrain characteristics [18]. The tractive effort required by the tracks to move over a particular surface highly depends on the characteristics of the surface. Use of coulomb friction forces to calculate the resistance forces is only valid for hard surfaces such as asphalt or pavement, and equations of soil mechanics are required to calculate the resistance forces on natural terrains [18].

Also, the longitudinal slip is not only associated with the turning of the tracked vehicles but may also likely to occur during straight-line motion since the amount of longitudinal slip experienced by both left and right tracks may not be equal on natural terrains. Thus, the slippage effect may cause position and orientation errors that are difficult to be computed by conventional odometric methods, and therefore, use of inertial sensors or external sensors is required to estimate the errors [20]-[30].

The longitudinal slip is defined as [18],

$$i = 1 - \frac{V}{V_t} \quad (1)$$

Where i is the longitudinal slip ratio, V is the actual speed and V_t is the theoretical speed of the track.

The forces acting on a tracked mobile robot during motion are shown in fig. 11. In this figure, F_l and F_r are the thrusts on the left and right wheel pairs or tracks, R_{l1} and R_{r1} are the longitudinal resistance forces exerted by the terrain, V_l and V_r are the forward velocities of left and right wheel pairs or tracks, μ_l and μ_r are the coefficients of longitudinal and lateral resistance, B is the distance between wheel pairs or tracks centers, F_{cent} is the centrifugal force, C is the center of mass (COM), O is the instantaneous center point, and α is the slip angle that appears when the vehicle is turning, measured

between the vehicle's velocity and the longitudinal axis of the vehicle's body frame [18].

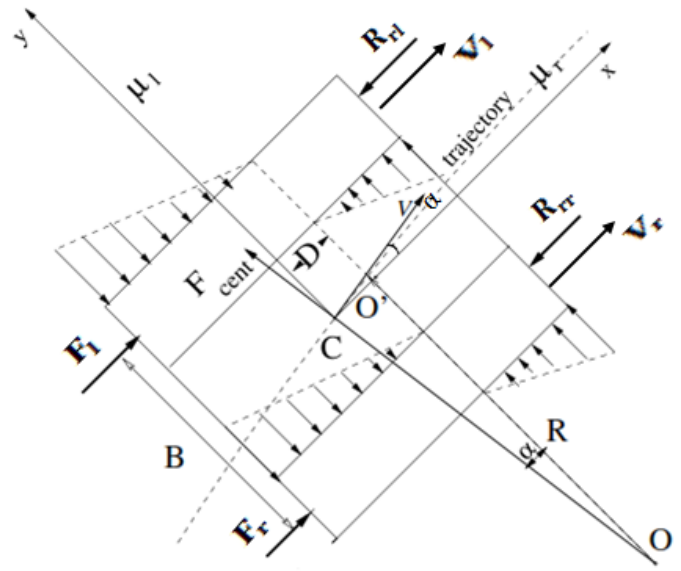


Fig. 11. Forces acting on a skid-steered mobile robot [18]

The actual effect of lateral resistances is also shown in fig. 11 that is different from the ideal case in which uniform lateral resistance forces are assumed along the ground contact points. Uniform lateral resistances can be taken when the vehicle is turning at slow speeds or for zero-radius turning. However, when turning at high speeds, the centrifugal force acting at the center of mass changes the uniform distribution of lateral resistances and to maintain the dynamic equilibrium the vehicle must rotate about at instantaneous center point O' located a distance D ahead of C [18]. When the centrifugal force is very high and the coefficients of lateral resistance are small, the position of instantaneous center point moves away from the geometric center of the tracked vehicle producing excessive skidding due to which the motion stability of the tracked vehicle can be lost [18]-[24]-[29]. Hence, it is necessary to limit the lateral velocity of the vehicle [24].

For a tracked mobile robot executing planar motion as shown in fig. 11, assuming the center of mass at the geometric center of the vehicle, the kinematic equations in vehicle-fixed coordinates can be formulated as [18],

$$\begin{aligned} \dot{x} &= \frac{r}{2} [\omega_L(1 - i_L) + \omega_R(1 - i_R)] [\cos\theta(t) - \sin\theta(t)\tan\alpha(t)] \\ \dot{y} &= \frac{r}{2} [\omega_L(1 - i_L) + \omega_R(1 - i_R)] [\sin\theta(t) + \cos\theta(t)\tan\alpha(t)] \\ \dot{\theta} &= \frac{r}{B} [\omega_R(1 - i_R) + \omega_L(1 - i_L)] \end{aligned} \quad (2)$$

where r is the rolling radius of the track, ω_L and ω_R are the angular velocities of left and right tracks, i_L and i_R are the longitudinal slips of the left and right tracks, $\theta(t)$ is the orientation or heading angle of the vehicle, α is the slip angle, $\dot{\theta}$ is the yaw rate of the vehicle and B is the distance between the left and right tracks.

Under the same assumptions, the dynamic equations for a skid-steered mobile robot in vehicle-fixed coordinates may be formulated as [18],

$$\ddot{x} = \frac{F_l + F_r - m\dot{\phi}^2 R \sin(\alpha) - \mu_r W}{m} - \frac{2M_r}{B}$$

$$\ddot{y} = \dot{\phi}^2 R \cos(\alpha) - \mu_l g \quad (3)$$

$$\ddot{\phi} = \frac{[(F_l - R_{rl}) - (F_r + R_{rr})]B}{2I_z} - \frac{M_r}{I_z}$$

where M_r is the moment of turning resistance, and I_z is the moment of inertia about z-axis.

The dynamic equations (3) show that the system is under-actuated, since dimensions of configuration space is greater than the input space. The lateral dynamics describes acceleration constraint that is non-integrable. As a result, it can be regarded as a second order non-holonomic constraint.

The future work will include the measurement of vehicle parameters such as translational and angular velocities, slippage and slip angle in real time using onboard sensors. Furthermore, integration of manipulator arm to enhance the capabilities of the mobile platform and design and development of control systems for autonomous operation are also underway.

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