A Three-wheeled Mobile Robot for Traversing Uneven Terrain without Slip: Simulation and Experiments

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A wheeled mobile robot can move on uneven terrains without slip if the axle length can change or the wheels are allowed to tilt laterally in a fixed axle-length vehicle. This paper deals with the analysis, design and experimentations with a wheeled mobile robot where the wheels can tilt laterally. The wheels of such a wheeled mobile robot must be equipped with two degrees of freedom suspension mechanism which allow the wheel lateral tilt and also ensure that the wheel-ground contact is maintained on the uneven terrain. A modification of the common trailing arm suspension mechanism, with the suspension split into two parts, is considered. A prototype three-wheeled mobile robot is implemented with the two degree-of-freedom suspension. Simulations show that the three-wheeled mobile robot can traverse uneven terrains with very little slip and experiments with the prototype on a representative uneven terrain confirm that the slip is significantly reduced with the two degree-of-freedom suspension. Three representative paths, namely a straight line, a circular arc and a path representing a lane change is used to illustrate the capability of the three-wheeled mobile robot prototype to traverse an uneven terrain with very little slip.

1 Introduction

There is an increasing interest on mobile robots capable of traversing uneven terrains without slip. Wheel slip leads to wastage of energy which is at a premium for applications such as planetary exploration. It also leads to localization errors, especially when only on-board instrumentations are used. Waldron argued that two wheels connected to fixed-length axle undergo slip (Waldron, 1995) when moving on uneven terrain. To overcome this slip researcher have proposed two approaches -- the variable axle length (VLA) approach (Choi et al., 1999) allows the axle length to vary when the mobile robot moves on uneven terrain and the second approach (Chakraborty and Ghosal, 2004 and 2005) allows the wheel to tilt laterally. This lateral tilt capability has also been termed as passive variable camber (PVC) (Auchter et al., 2009). However, there is very little experimental evidence available on wheel slip and wheeled mobile robots traversing uneven terrains. This paper deals with analysis, design, implementation and experimentations of a wheeled mobile robot with torus shaped wheels which can tilt laterally.

There are well-known instances of wheel mobile robots for use on uneven terrains -- NASA has developed the six wheeled robots, Spirit and Opportunity with rocker bogie suspension (Lindamannon et al., 2006) and the four wheeled NOMAD (Rollins et al., 1998), using transforming chassis to deploy from a stowed configuration. ISAS developed the five wheel robot, Micro5 (Kuroda et al., 1999) with PEGASUS mechanism. Siegwart's innovative design for wheeled locomotion in rough terrains used six wheels (Siegwart et al.,2002). Hoshinos's interconnected differential suspension mechanism mobile robot is four wheeled (Hoshino et al., 2004). In an alternative approach, Lee and Velinsky (2009) proposed the use of omni-directional wheels with ball wheel drive mechanisms in a mobile robot for traversing uneven terrain. Three wheel ground contact points are enough for mobile robots on uneven terrains. In this paper, we consider a three wheeled mobile robot capable of traversing uneven terrain with very little slip and equipped with a modified trailing arm suspension.

For wheel with lateral tilt capability, a two degree of freedom suspension mechanism is required -- one for maintaining wheel contact with terrain and other for lateral tilting of wheel. Tharakeshwar (2012) proposed five possible two degree of freedom suspension mechanisms and presented simulation results of a three-wheeled mobile robot, with the proposed suspension mechanisms, traversing uneven terrains. Based on the amount of slip, the deviation of the wheeled mobile robot (WMR) from the desired path and ease of manufacturability, two of the proposed suspension systems, namely split and fit trailing arm suspension (SFTA) and a double four-bar suspension mechanism, were found to be most promising.

In this paper we present a detailed modeling, analysis, design and experimentation of a three-wheeled mobile robot with the two degree-of-freedom SFTA suspension mechanism. The features of the SFTA suspension mechanism and the simulation results of three-wheeled mobile robot equipped with the SFTA suspension, showing its capability of traversing uneven terrains with minimal slip, is presented in Section 2. The detailed design of the suspension is presented in Section3. The three-wheeled mobile robot is designed with torus shaped wheels which are connected to a platform by the two degree-of-freedom suspension systems. The motor drives, controller and the power source are taken from a commercially available LEGO Mindstorms kit (LEGO, 2012) and the complete design of the wheeled mobile robot along with power transmission and programming are presented in Section 4. The prototype wheeled mobile robot with the SFTA suspension was made to traverse on uneven terrains. A description of the uneven surface, the inputs to the robot, the results and discussion on the experimentation are presented in Section 5. Finally, the conclusions are presented in Section 6.

2 WMR with SFTA Suspension

In this section we present the details of the split and fit trailing arm (SFTA) suspension mechanism and simulations of a three-wheeled mobile robot *with* and *without* the suspension traversing on uneven terrain. The simulations show that the slip can be minimized and path accuracy can be increased when the suspension mechanism is used and the rear wheels are allowed to tilt laterally.

2.1 Suspension mechanism

The main requirement of a two degree-of-freedom suspension mechanism is that the wheel is able to tilt laterally while maintaining contact with the uneven terrain. The existing trailing arm suspension used in automobiles (Brady, 1989) was modified to achieve two degrees of freedom. The trailing arm suspension mechanism is split into two parts **A** and **B** with a depression on **A** and protrusion on **B** respectively. In the depression on **A**, threading is provided to hold a screw. A through hole through part **B** is drilled for inserting screw. These two parts are re-fitted with a screw passing through **B** screwed to **A** allowing rotation of one part with respect to other part. This produces the lateral tilt of the torus-shaped wheel. The two ends of **part A** and **part B** are connected to robot **platform** and **wheel** respectively. A torsion spring **S1** with spring stiffness of 20N-mm-deg^{-1}, damping coefficient of 0.65 N-mm-s-deg^{-1} and pre-load of 250N-mm is kept in between **Platform** and **Part A**. Another torsion spring **S2** with spring stiffness of 5 N-mm-deg^{-1}, damping coefficient of 0.65 N-mm-s-deg^{-1} and pre load of 110 N-mm is used between **Part A** and **Part B**. These spring and damping parameters were arrived after extensive simulation study of WMR with SFTA suspension on flat and uneven surfaces with bumps and ditches. Figure1 below shows a solid model of the SFTA suspension mechanism.

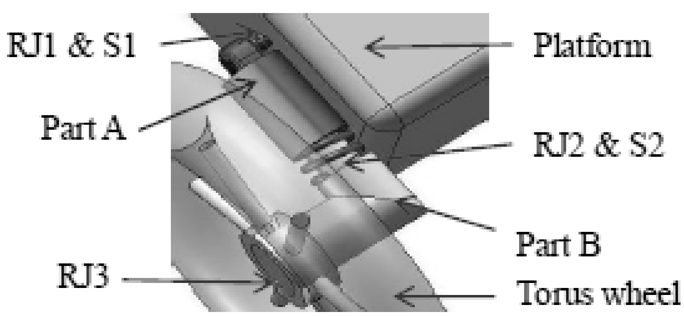

Figure 1: SFTA suspension mechanism

2.2 Modeling of uneven terrain

An uneven surface with small slopes and smooth peaks was constructed using cement plaster on a frame of 1m x 1.5m for experimentation. On this constructed surface, the height is measured at six hundred points. This data points serves as input to surface generation in software Solidworks (2008) modeling tool and the uneven surface was generated. The generated surface is imported to ADAMS/View (2010) for simulations. The surface maximum slope/grade is about 1 in 4 and the maximum height of the peak is 50mm -- this is about 1.2 times the major radius and 3 times the minor radius of the torus wheel used in the three wheeled mobile robot. Figure 2 shows the uneven terrain and its sectional views used for simulation. The physical experimental surface is shown in section 5.

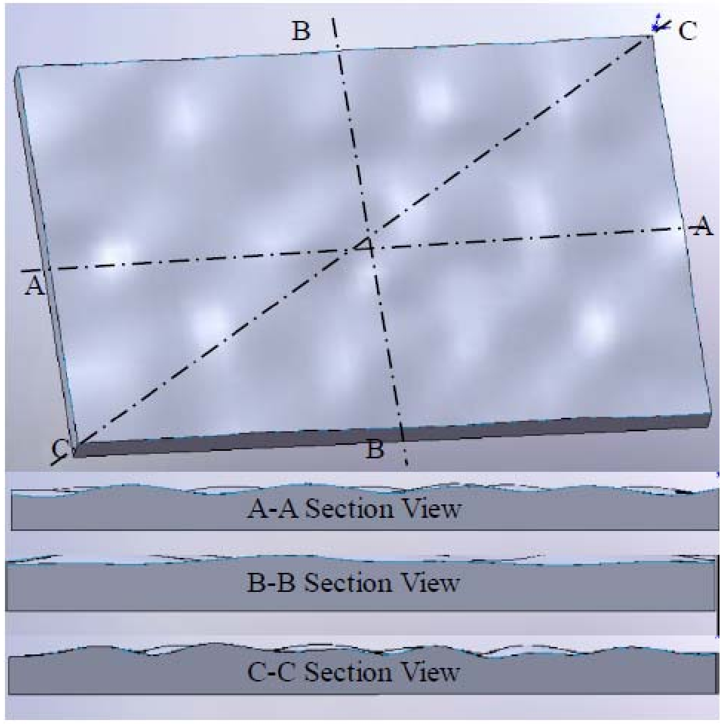

Figure 2: Modeled uneven surface from measurements

2.3 Modeling and simulation

The three-wheeled mobile robot with the SFTA suspension was modeled using the commercial software ADAMS/View (2010). Two rear wheels are allowed thirty degrees lateral tilt on either side. The platform has triangular shape with mass of 1Kg. The two radii of the torus shaped wheel are 45 and 15mm, respectively. The mass of suspension mechanism is 0.15Kg. The total aggregate mass of the WMR is 1.2Kg and is very close to the weight of the prototype. The mass inertia tensor components are $I_{XX} = 9.02E007$ kg-mm^2, $I_{YY} = 1.57E+008$ kg-mm^2, $I_{ZZ} = 7.41E+007$ kg-mm^2 , $I_{XY} = 9656.01$kg-mm^2, $I_{ZX} = 1.58E+006$ kg-mm^2, $I_{YZ} = -2188.56$ kg-mm^2 and the distance between the three wheels is 20cm. The complete ADAMS/View model of the three-wheeled mobile robot on uneven terrain is shown in figure 3.

Simulations are performed using the software ADAMS/View. The differential direct analysis of the 3-WMR the rear wheels and steering to the front wheel, the motion of the WMR is obtained. The inputs are given to two rear wheels using rotational joint motion command in MOTION pallet. Wheels are connected to wheel hub through a revolute joint. At this revolute joint a motor is fixed. For these simulations, the centre line velocity of the rear wheels is chosen to be 7.2 Kmph or 2m/sec. Steering input to the front wheel is done using STEP input function to result in straight line, circular and lane change trajectory. A step input can be created using: *STEP (time,*

t_0, y_0, t_1, y_1) function where these arguments correspond to: time (defining time as the dependent variable), initial time, initial function value (displacement in this case), final time, and final function value. The lateral tilts of the rear wheels are passive. Wheel ground contact is modeled as solid to solid contact type with dynamic resistance at the contact point is chosen as 0.9 and 0.8, respectively.

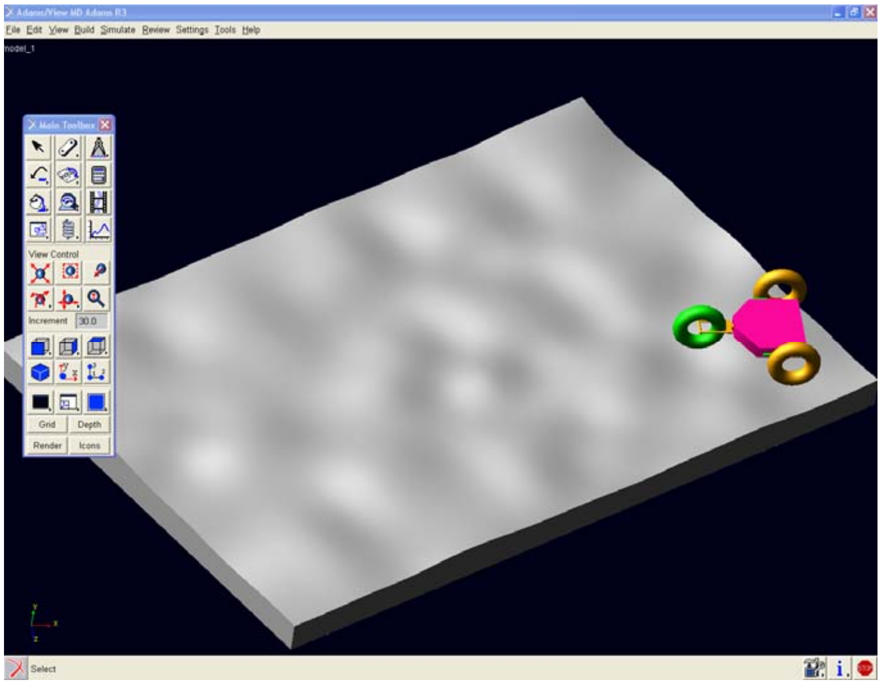

Figure 3: ADAMS/View model on the uneven surface

Three simulations, namely a straight line, a circular arc and a path representing a lane change are studied with and without SFTA suspension, i.e., the rear with and without lateral tilt capability. Simulation results are discussed next.

2.4 Results and discussion

With velocity input to rear wheels and zero steering input to front wheel, simulation was performed of with and without the SFTA suspension mechanism. The slip velocity is estimated at wheel-terrain contact point as function of time. The simulation results are presented in figure 4 below and it shows that SFTA leads to a 50 to 60% reduction in slip as compared to the case when the SFTA suspension is not used in a straight line motion. Figures 5 show the comparison when a WMR is made to trace a circular arc and again the SFTA suspension leads to a 20 to 35% reduction in slip. Figure 6 shows the results obtained when the WMR is made to perform a lane change maneuver, and for this case also, the use of the two degrees of freedom SFTA suspension leads to a 20 to 30% reduction in slip.

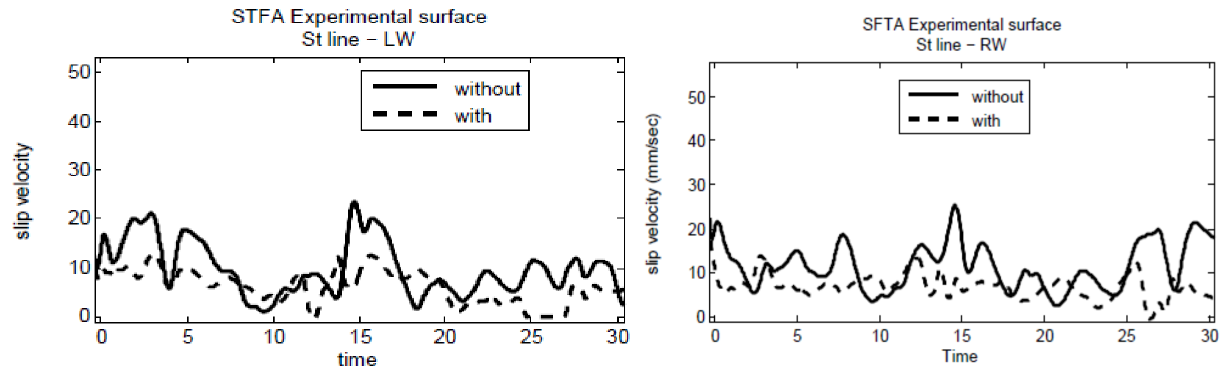

Figure 4: Slip velocity (left – left wheel, right—right wheel) for straight line path

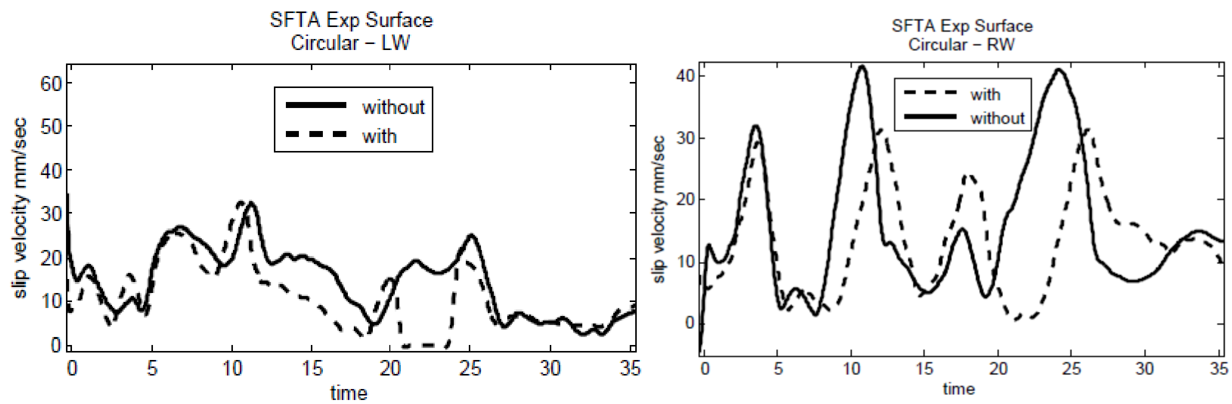

Figure 5: Slip velocity (left – left wheel, right—right wheel) for circular arc path

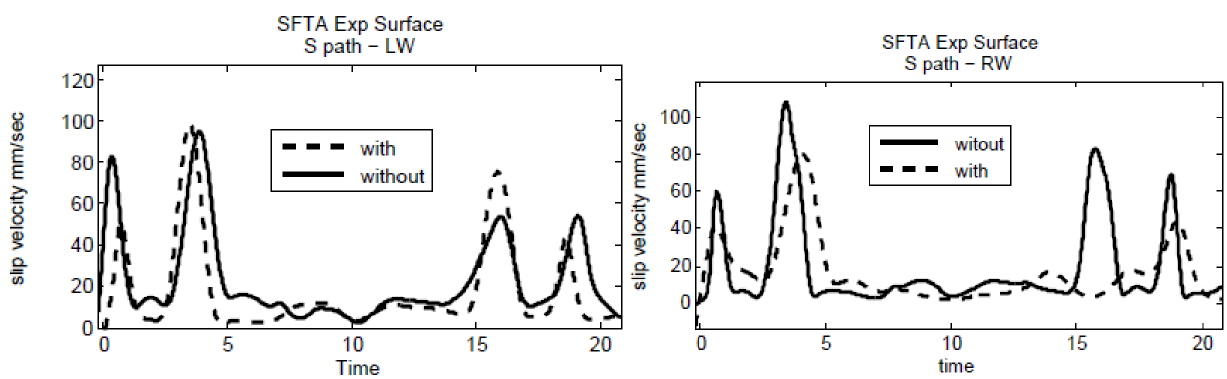

Figure 6: Slip velocity (left – left wheel, right—right wheel) for lane change maneuver

Due to the reduction in slip, the path traced by the WMR centre of mass will deviate less from the desired path. The paths followed by wheeled mobile robot centre of mass for the three cases are shown in figures below. In figure 7, for a straight line motion the maximum path deviation with and without suspension is 28.7mm and 40.8mm, respectively. The maximum path deviation is 14.2mm and 56.8mm with and without suspension for a circular path. This is shown in figure 8. In lane change simulation, path deviation is presented in figure 9 shows maximum deviation as 16.2mm and 33.2mm with and without suspension respectively. It can be clearly seen, that the performance in terms of wheel slip and path deviation is much better with the SFTA suspension.

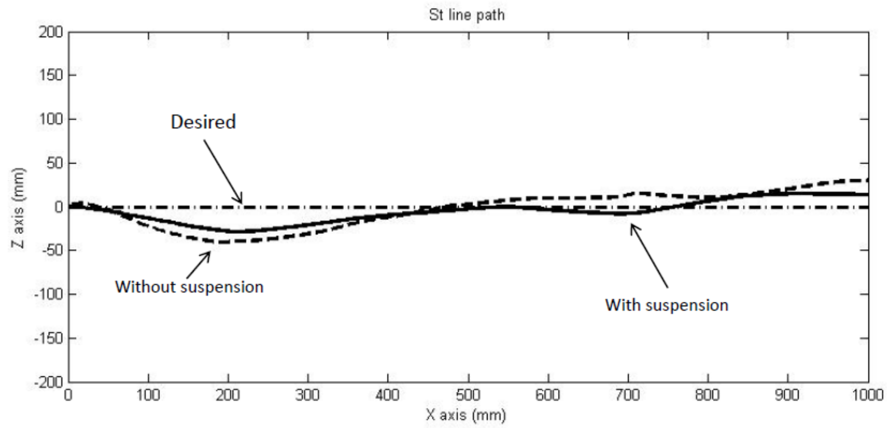

Figure 7: Path of CM in straight line motion from simulation

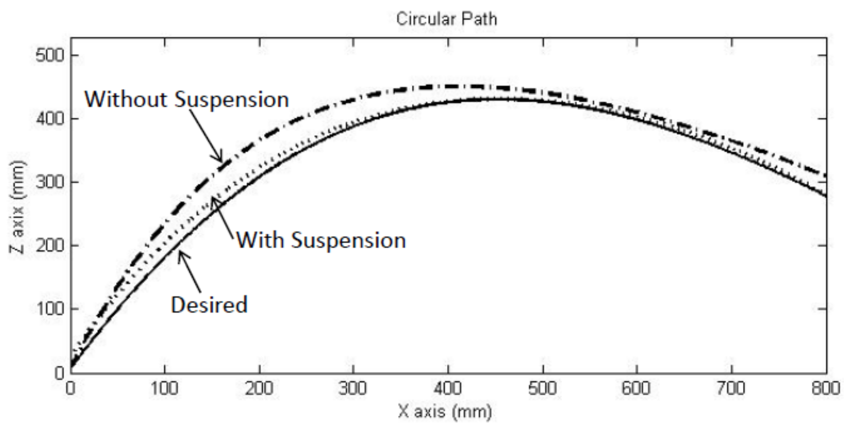

Figure 8: Path of CM in circular motion from simulation

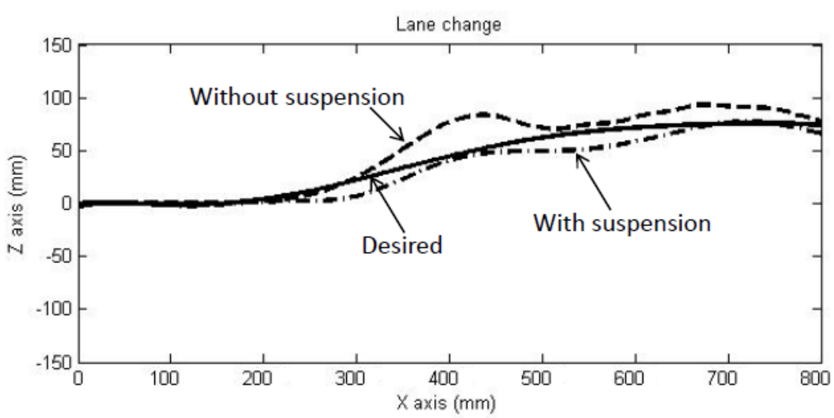

Figure 9: Path of CM in lane change motion from simulation

3 Design of WMR with SFTA Suspension

In this section, design considerations, detailed 3D modeling of SFTA suspension mechanism, springs used and other parts in the wheeled mobile robot are presented. It may be noted that a CAD software Solidworks (2012) was used to design the full system. It may also be noted that we chose to use motors, controller and power source from the commercially available LEGO Mindstorm NXT kit (2012) primarily due to availability, compactness and ease of programming. All other components for the prototype were manufactured as per design.

3.1 Design considerations /requirements

Some of the basic constraints of in the required WMR are as follows:

1. Toroidal wheel with high coefficient of friction. Toroidal wheels are required for point contact and the ability of the wheel to tilt laterally on uneven terrain (Chakraborty and Ghosal, 2004 and 2005).
2. The weight of the prototype should be small (around 1Kg) so that it could be driven with motors available in the LEGO Mindstorm NXT kit.
3. The lateral tilt joint location should be as close as possible to the wheel centre.
4. Lateral tilt angle is limited to 30^0 on either side.
5. Torque transmission from motors to wheels should be accurate at all lateral tilt positions of the wheel.

The above mentioned considerations are met in the manufactured prototype.

3.2 CAD modeling

The CAD modeling of the main components of the WMR with the SFTA suspension is discussed below.

3.2.1 WMR platform

As our wheeled mobile robot is three wheeled, the shape of the **platform** is a trimmed triangle with cut section at centre to accommodate NXT motors and controller. It was designed to withstand the weight of the controller, three motors, suspension mechanism parts and suspension forces. The material chosen was acrylic for its easy machinability and its ability to withstand the loads.

3.2.2 Part A and Part B

The two main parts of the SFTA suspension are **Part A** with depression and **Part B** with protrusion. A through hole is made along axis of **Part B**. The small end of **Part B** will be kept in the **Part A** depression and a long screw is mated to the threads provided in the **Part A**. This screw holds the part A and B assembly. A spring S2 is fixed between A and B. Stoppers are provided to limit the lateral tilt angle. Three low friction polymer bearing (LFPB) is used to reduce friction.The figure 10 shows the details of **Part A** and **Part B**.

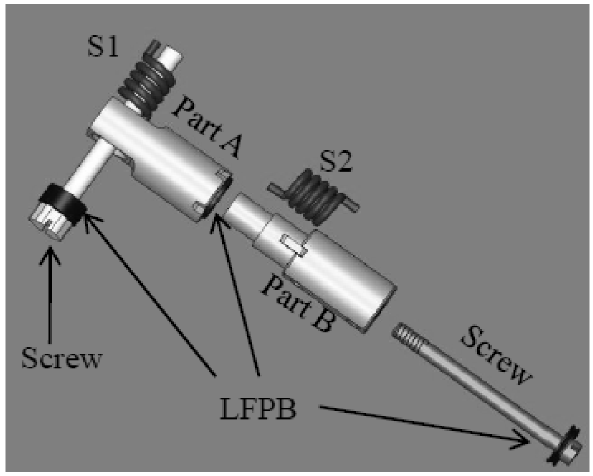

*Figure 10: **Part A** and **B** assembly*

3.2.3 Wheel assembly

A toroidal plastic wheel with rubber coating is used as wheel in our WMR. A suitable size wheel hub from LEGO elements is fixed permanently to the toroidal wheel. A lift arm with two pins and axle, as shown in figure 11, attached to the hub completes the wheel assembly. The other ends of the two pins are inserted on the holes provided on **Part B**.

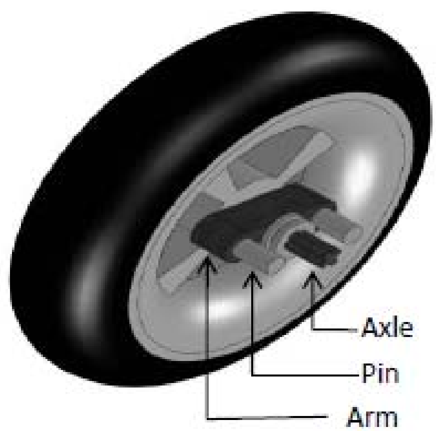

Figure 11: Wheel assembly

3.3 Spring design

The springs used in the suspension mechanism are torsion springs. A torsion spring **S1** is used between **Platform** and **Part A**. Another torsion spring **S2** is used between **Part A** and **Part B**. Torsion springs between these parts are arranged by inserting the coil ends in the holes provided on the parts by force fit. These sizing of the springs are finalized by trial and error method. First, we finalized the springs **S1** suitable for vertical travel of wheel by navigating the WMR on plane surface with a bump. For spring **S2**, the sizing is such that the wheels *do not tilt* under the self-weight of the robot *on a flat terrain*. The stiffness of the springs used is 19.27 and 5.18 N.mm/deg which is close to springs used in simulation.

3.4 Assembly of the SFTA suspension

After prototyping all parts to the specified dimensions, the suspension mechanism was carefully assembled. A spring **S1** between **Platform** and **Part A** is inserted in the holes provided on the parts. A hexagon bolt is used to fix the **Part A** with the **Platform**. A low friction polymer bearing is used between **bolt** and **Part A** to reduce the friction. Another low friction bearing between **Part A** and **Part B** is used to reduce the friction between this parts when lateral tilt of wheel results in the rotation of **Part B** with respect to **Part A**. A bolt between **Part A** and **Part B** holds the parts and allows lateral tilt. The wheel assembly two pins are fixed into holes on **Part B** permanently. The figure 12 shows the assembly of the SFTA suspension.

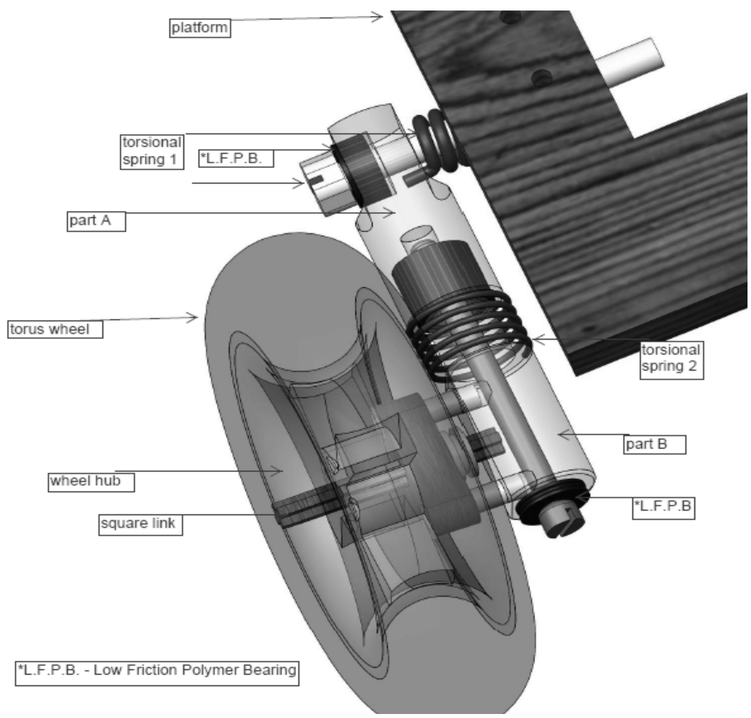

Figure 12: Assembly of SFTA suspension

4 Fabrication of WMR with SFTA Suspension

Once the SFTA suspension mechanism is designed, the next task is to build the wheeled mobile robot with this suspension. The section explains the building of robot, how the power is transmitted to the wheels and design consideration for the location of the center of mass. The final WMR prototype is shown in figure 14.

4.1 Building the robot

We used some of the components of LEGO Mindstorm NXT kit. The main components are controller unit, battery and the motors. The use of LEGO components allows us to quickly build the wheeled mobile robot. The controller is also easily programmable so that less effort is required to move the WMR along arbitrary paths. All the three motors (two for driving the rear wheels and one for steering the front wheel) are fixed on the platform discussed earlier. The SFTA suspension mechanism is also fixed on one side of the platform through base and fasteners. The plastic toroidal wheel discussed earlier is fixed to the other end of the SFTA suspension mechanism. There is an arrangement to lock the lateral tilt capability so that the behavior of robot *without suspension* could be studied easily. On the platform a small hole at the centre of mass was drilled to insert a marker for drawing the path traced by the WMR on the uneven terrain.

4.2 Power transmission

One of the key challenges in building the WMR was to transmit power from the motors to the torus shaped wheels, with lateral tilting and vertical motion, traversing the uneven terrain. Several concepts such as using flexible cables were attempted. Finally we narrowed down to the use of bevel gears and two-degree-of-freedom Hook or universal joints. The use of Hook joints allowed motion transmission even when the wheels were tilted or moving vertically. The transmission arrangement is shown schematically in figure 13.

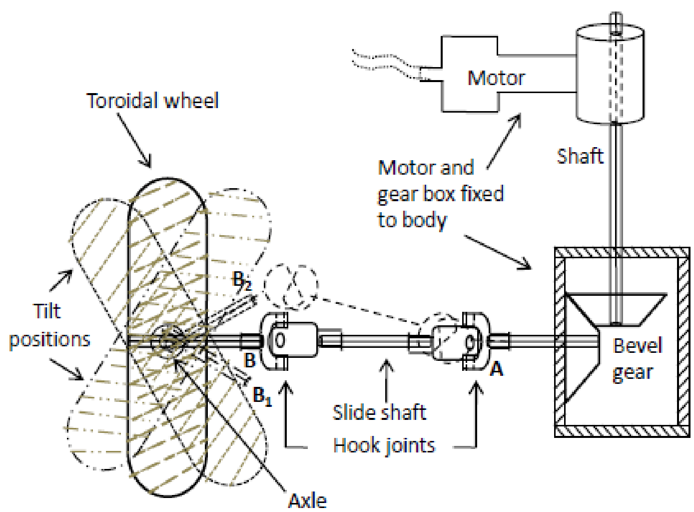

Figure 13: Bevel gears and Hook joints to transmit power to wheels

4.3 Centre of mass

The location of the wheel-ground contact points and the centre of gravity point places major role in stability of robot. This is more so in case of the WMR traversing an uneven terrain. The centre of mass was computed from the CAD model and also checked by simple balancing experiments.

As mentioned earlier a hole was made in the platform at the location of the centre of mass and a marker pen was fixed at the centre of mass. The marker pen could trace the path taken by the WMR centre of mass on the uneven terrain.

5 Experimentation, Results and Discussion

The controller in the LEGO Mindstorm kit controls all the three motors in the WMR. The three desired inputs for the two rear wheel and the front steering wheel can be easily downloaded from a PC using wireless bluetooth technology or by USB and stored on the local controller memory. The desired inputs, for simple paths, can also be keyed in and stored. This simplicity was one of the main reasons for choosing the LEGO Mindstorm NXT kit. The LEGO kit, however, is not very accurate and precise and, in addition, it is difficult to collect or measure data such as wheel velocity. With the LEGO kit it is also not possible to collect or measure the wheel slip data. Nevertheless, the performance of the WMR with and without suspension could be easily differentiated by the marker placed at the centre of mass of the WMR. The final protopype is shown below in figure 14 where all the important components are also marked. Figure 14 also shows the two extreme wheel lateral tilt positions on a flat ground.

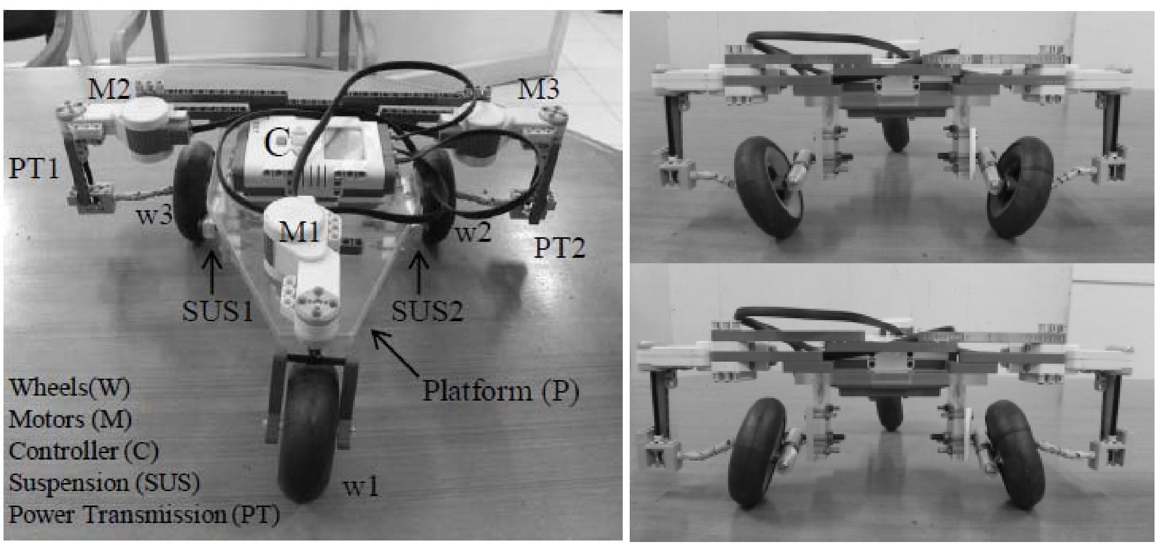

Figure 14: WMR prototype on flat surface and extreme lateral tilt positions of +/- 30 degrees

The uneven terrain is assumed to be smooth and hard -- terrains with loose soil, dirt, water etc. are not considered in this work. An uneven surface was built with cement plaster and painted with white color to mark the path of the robot. The uneven surface is similar but not exactly same as the surface used for simulation and discussed earlier[1] and is shown in figure 15. It may

[1] To create exactly same surface would require sophisticated CNC machining operating with the graphics data file of the surface.

be noted that the similarity is in the grade (1 in 4) and heights of bumps and ditches on the uneven surface.

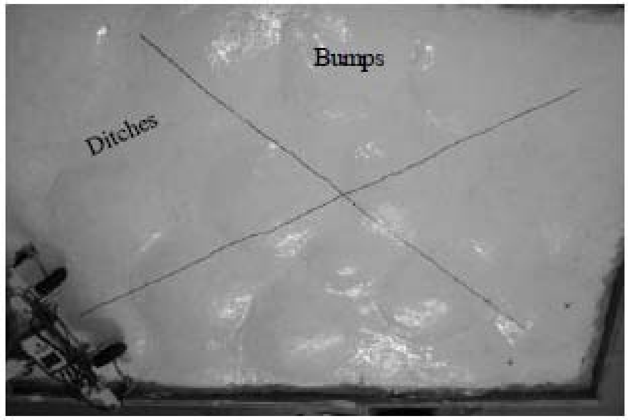

Figure 15: Constructed experimental surface

The WMR with SFTA suspension mechanism was made to move on the uneven terrain. The lateral tilt angle is allowed to be 30^0 on either side. Three trajectories, namely a straight line, a circular arc and a lane change motion were attempted. We also performed the three motions *without* the SFTA suspension. The experimental results are presented next.

5.1 Straight line motion

With power input to the rear wheels and zero input to the steering, we navigated the WMR on uneven terrain with and without SFTA suspension. The simple straight line program can be keyed using NXT program as a single beam. The two rear wheels are controlled by MOTOR blocks at ports B and C. The run time of motors and power are given as 30sec and 75 with an up arrow for forward motion. Steering wheel is connected to port A with zero power input for straight line motion. Figure 16 shows four snap shots of the WMR performing a straight line motion. The path of the centre of mass projected on surface is shown in same figure. The experimentally obtained path of CM is shown in the figure 17 which also shows the desired path and simulation results with and without suspension for comparison. From the graphs, it is clear that the deviation from a desired path is less when the suspension is present, both in simulation and experiments. The plot of the error from the desired straight line along the path length is shown in figure 18. The maximum path deviation from the desired straight line path is about 25 mm and 47 mm with and without suspension in the experimentation, respectively. It is clear that the WMR with the SFTA suspension deviated less from the desired straight line path and hence, we can conclude that the slip is less when the wheels are allowed lateral tilt.

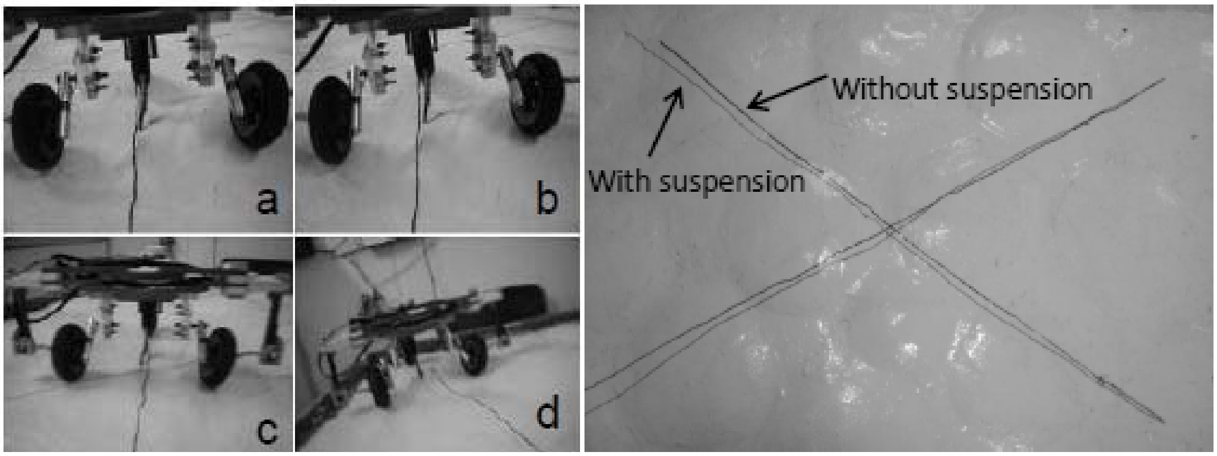

Figure 16: Snap shots of experimentation and path of CM

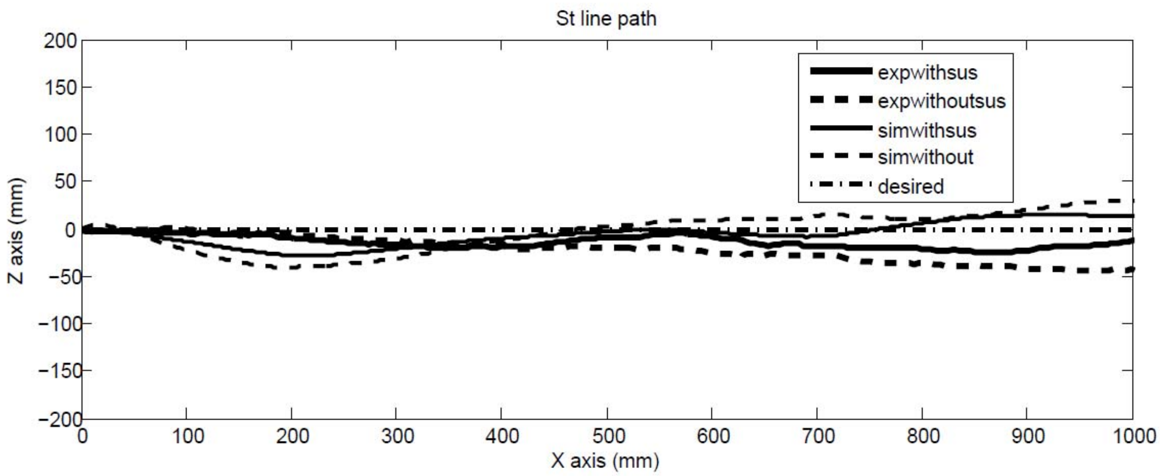

Figure 17: Path of CM in straight line motion

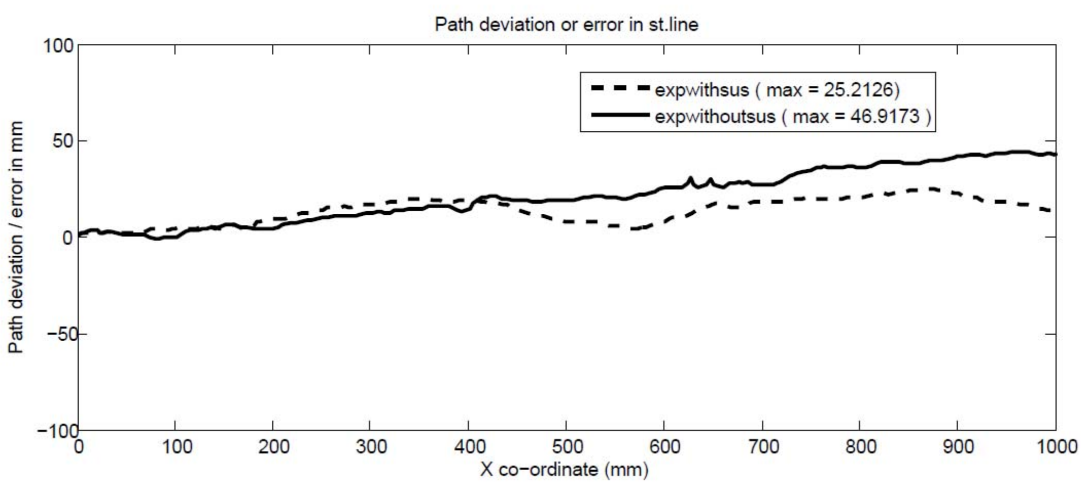

Figure 18: Error plot in straight line motion (experimental values)

5.2 Circular motion

In the similar way as explained above, the same mobile robot was tested on uneven terrain with a circular trajectory. Three inputs – two power inputs to rear wheels and steering input to front wheel were given. The two rear wheels connected to port B and C are given 30sec run time with power input as 75. Port A for steering is connected in parallel to port B and C. The run time of motor A and power are given as 30deg and 100 with an up arrow for clockwise motion. Wait for coast controller is used to keep the steering at 30deg till the completion of port B and C run time completion. The experiment is carried out twice – once with lateral tilt and other without tilt. Figure 19 shows the final path of the centre of mass as the robot traces a circular trajectory. The path of CM and the desired circular path are shown in figures 20 for experiments and simulations. Figure 21 shows the variation of error along the trajectory during experiments. The maximum path deviation error is measured to be about 16 mm and 93 mm with and without suspension. One can clearly, observe that the deviation from the desired path is less when the suspension is used and the wheels are allowed to tilt laterally. The performance of the WMR *without* suspension was particularly poor on one trial as it got stuck at a bump whereas when the SFTA suspension is used, the WMR traversed the uneven terrain more easily and smoothly.

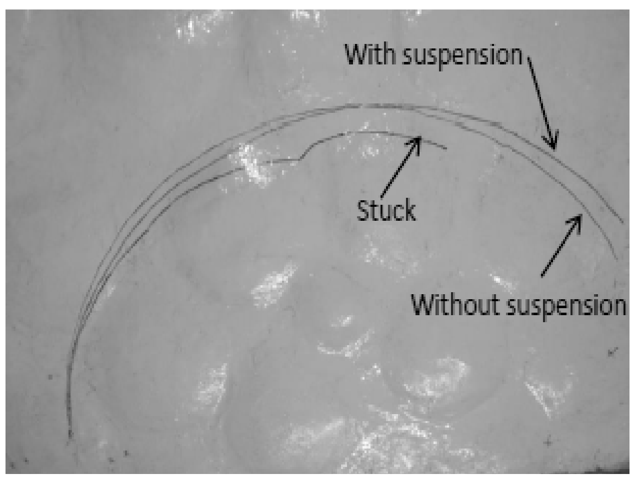

Figure 19: Path traced by CM for circular trajectory

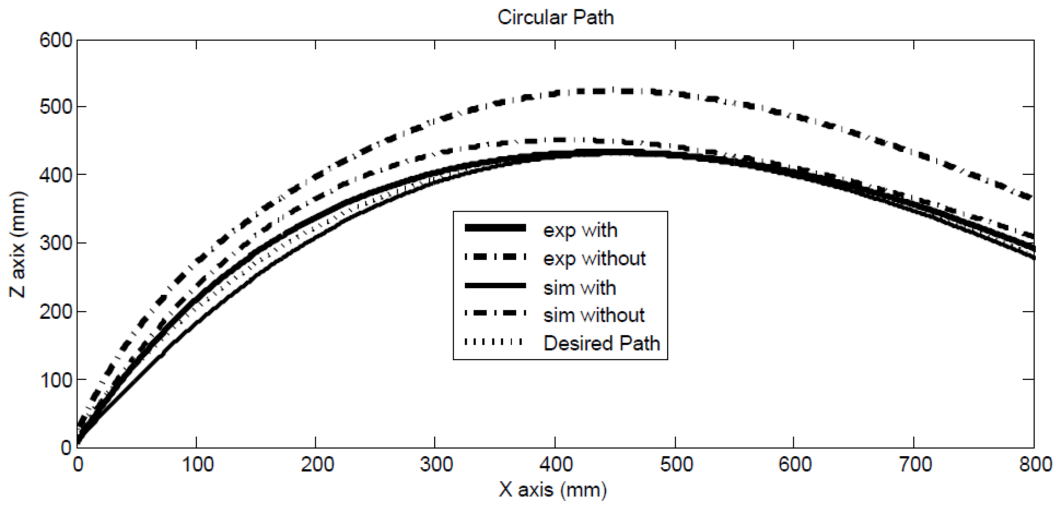

Figure 20: Path of CM in circular motion

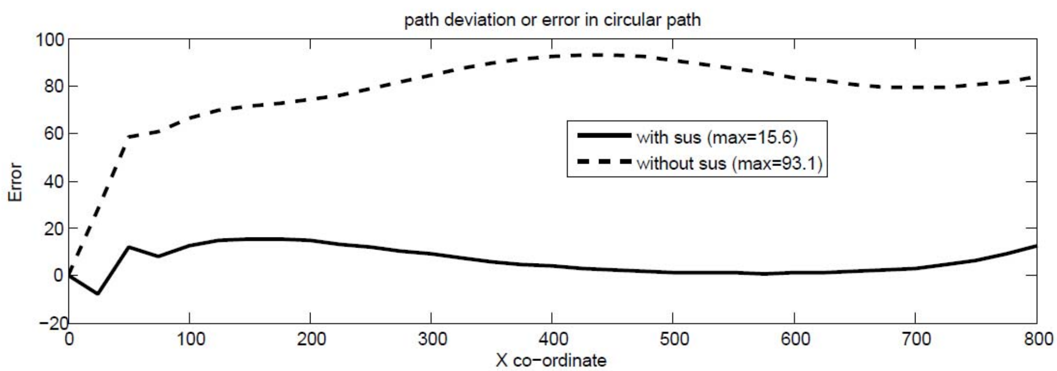

Figure 21: Error plot in straight line motion (experimental values)

5.3 Lane change motion

A third representative experimentation carried out was a lane change maneuver. Unlike zero steering input in straight line motion and fixed steering input in circular motion, in this case the steering input continuously changes to navigate in a lane change path. The two rear wheels connected to port B and C are given 20sec run time with power input as 75. Port A for steering is connected in parallel to port B and C. The run time of motor A is (0 deg)-(30 deg)-(-30 deg)-(0 deg) pattern with wait time as 5sec in between the operation with power input of 50units. Experimentation was performed with and without suspension. The simulated and experimental paths followed by robot, with SFTA suspension on uneven surface, in lane change is shown in figure 22. Path deviation error with and without suspension is shown in figure 23 and the maximum path deviation error is measured to be about 53 mm and 77 mm with and without suspension, respectively. Although the deviation is quite large, it is clear that deviation and error is larger when the suspension is not used. This implies more slip when suspension is not used and the wheels are not allowed to tilt laterally. As in the circular motion case, on one occasion the WMR got stuck at a place and could not complete the desired motion.

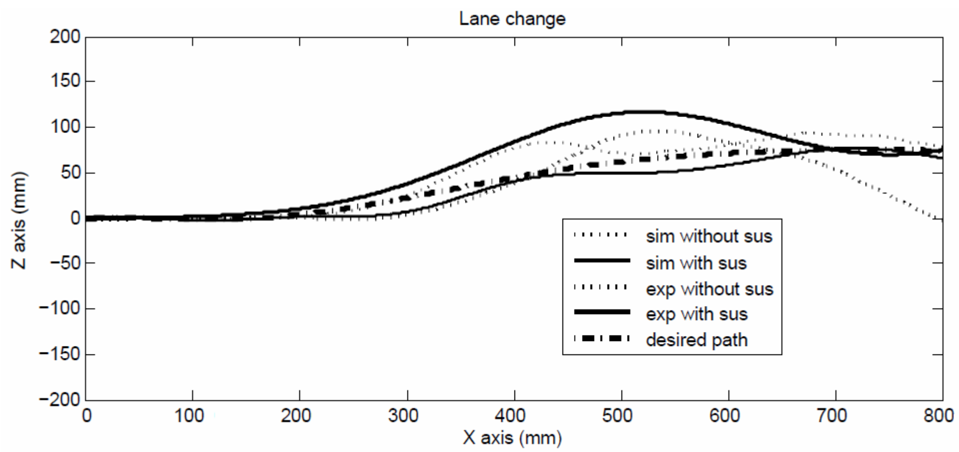

Figure 22: Path of CM in lane change motion

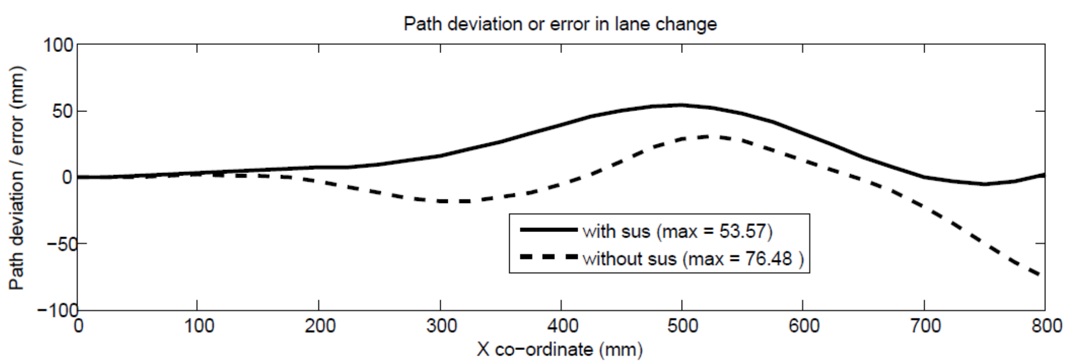

Figure 23: Error plot in lane change motion (experimental values)

6 Conclusions

In this paper, we have presented a two degree-of-freedom suspension mechanism, called the split and fit trailing arm (SFTA) suspension, derived from the well known trailing arm suspension mechanism. This two degree-of-freedom suspension allows lateral tilting of the wheels and is used on a three-wheeled mobile robot to traverse uneven terrains with less slip. Numerical simulations, done using ADAMS /View, show that the mobile robot will exhibit less slip when the SFTA suspension is used while it slips much more when the suspensions is not used (and the wheels are not allowed lateral tilting) on uneven terrains. Based on the design considerations, this suspension mechanism was designed and prototyped. Using a few parts of a LEGO kit and fabricated components, a three-wheeled mobile robot was built and experimented on an uneven terrain. Experimentation was done for three motions, namely a straight line motion, a circular motion and a lane motion. Experiments clearly show that the deviation from desired trajectories and path deviation error are much less when the SFTA suspension is used and the torus shaped wheels are allowed to tilt laterally. The motion is also much smoother and the mobile robot does not get stuck on the uneven terrain when the suspension is used. Future work will focus on the development of a more refined three-wheeled mobile robot and more extensive experimentation to validate the slip free capability of a wheeled mobile robot, traversing an uneven terrain, when the wheels are allowed to tilt laterally.

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