A Passive Wheeled Robot with Ability of Tracking Predictable 3D Curved Paths

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***Abstract*— Wheel-based motion is one of the most efficient and simple ways to move on smooth surfaces. Hence, wheeled mobile robots have attracted significant attention in the research field of mobile robots. Designing passive wheeled robots can provide more efficiency for the robot. However, generating predetermined curved path in passive mechanisms is a challenge. In this paper, a very simple wheeled passive robot capable of moving on a curved path. The robot moves on a simple ramp and its motion is driven by gravity force. The mechanism of robot allows predicting and determining its motion on 3D curved paths. The motion of the robot is dependent to its configuration, thus the relationship between the configuration and the robot's path is obtained. The performed analysis results are verified by simulations in ADAMS.**

***Index Term*— Passive Mechanism, Mobile Robot, Kinematics,**

I. Introduction

THERE are some different mechanisms in nature for moving: walking, flying, crawling, swimming etc. One of the mostly used mechanisms is rolling. One may consider this motion mechanism as inspiration of invention of wheel. In fact we can consider the wheeled motion as an optimized way of motion by rolling. Mobilization by means of wheeled mechanisms takes significant advantages which have made wheeled mechanism to be frequently used in different applications. In smooth surfaces, the performance of the wheeled robots is very good in comparison with the robots with other motion mechanisms. Moreover, other mobile robots (ex, legged, flying …) have more degrees of freedom in comparison with wheeled ones, and hence they have more complexity. In addition, stability and balance problem of wheeled mobile robots is a well-studied problem [1].

Nevertheless, some difficulties, inefficiencies and restrictions exist when working with wheeled robots. In this paper we consider energy efficiency problem. However, our approach is not taking strategies for decreasing of energy consumption rate, but we are up to introduce and design a passive wheeled robot with no actuator to such that the robot can move in curved calculable paths. It is obvious that there would be no energy consumption in the mechanism and this is the most ideal condition from the energy-efficiency point of view.

The idea of using passive mechanisms in robotics has been probably initiated by works of McGeer where he inspired from rotation of rimless wagon wheel to design his passive dynamic walkers [2]. Since then a lot of works has been reported in the field of passive locomotion. One can find some examples in [3]-[9]. The idea of passive manipulation, however, was firstly introduced in [10] where the concept of Passive Dynamic Object Manipulation (PDOM) was posed. The four major characteristics of passive systems were listed and three examples of proposed method were described. The passive manipulation of the specific object on predictable curved path was presented in [11], [12]. The mechanism proposed in this works consists of two components. The first component is the manipulated object and the second one is a platform wherein the object is manipulated. The platform is in dynamic interaction with the object and their geometry and dynamics determine the motion parameters of the object.

As we said before, our main goal is extension and development the idea of passive mechanisms in wheeled robots. The most important task of actuators in robotics (and in wheeled robots) is to produce required torques and forces to generate motion and to determine configurations of mobility and departure. In our mechanism, that there is not any actuator or active controllers, the robot only uses gravity force to move and it can travel down a simple ramp along a predetermined curved paths. The path is dependent to the robot's configuration. This dependence is one of the most inherent principals and will be discussed after presenting the mechanism of the robot.

II. Structure of the Robot

Passive Wheeled Robot (PWR) is a robot with no actuator or active controllers to generate the motion or control it through its path. This robot only uses gravity force to move. In fact when it is placed on a simple slope surface its weight makes it move downwards. PWR has a simple structure. There is a specific part in the robot that provides structural passive intelligence in the mechanism and facilitates determination of the path. We will later introduce this part and its application in the mechanism.

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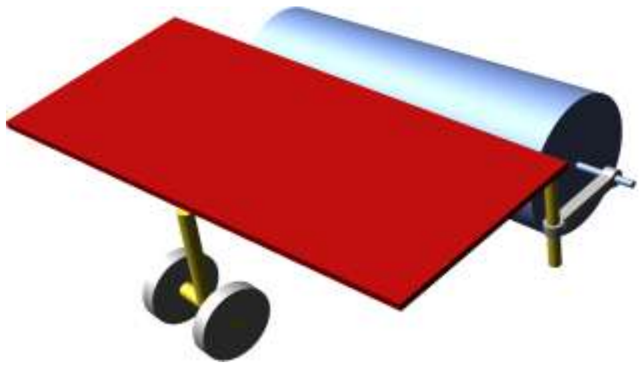

Fig. 1. Schematic diagram of the introduced Passive Wheeled Robot (PWR)

PWR, shown in Fig. 1, is formed of six main parts including: back wheel, connector links, fix bars, body, front wheels and coupling of front wheels. In the following we describe these parts and explain how they are connected to make the whole robot.

A. *The rear wheel*

The rear wheel is the unconventional part of PWR. As it is shown in Fig. 2, the rear wheel is a frustum that the radiuses of the top and bottom circles are assumed to be r_t and r_b respectively.

The vertical distance between the bottom and top surfaces of this object is l_f. The slant height and its tilt angle are shown as s and α respectively such that:

$$\cos\alpha = \frac{l_f}{\sqrt{(r_b - r_t)^2 + l_f^{\,2}}} \tag{1}$$

Mass of the frustum is assumed to be m_f. The center of mass of the rear wheel is shown with G and is located on axis of symmetry n. The vertical distance between the point G and the bottom surface is considered to be l_G and we have:

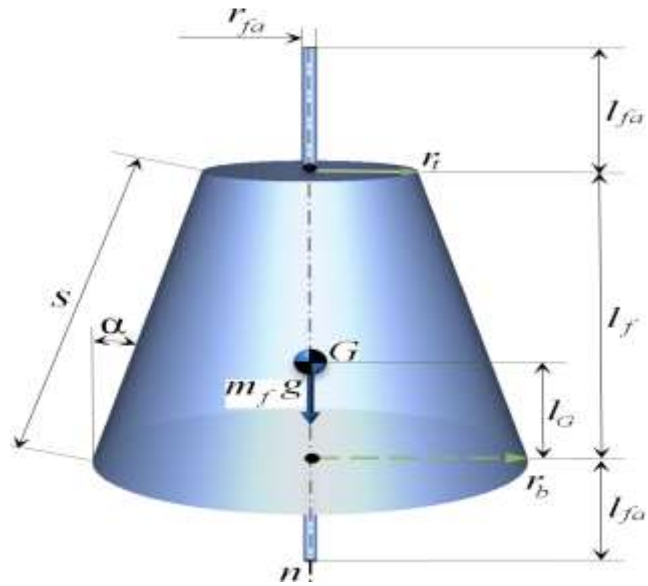

Fig. 2. Dimensions of the rear wheel of the Passive Wheeled Robot.

$$l_G = \frac{l_f\,(r_b^{\,2} + 2r_b r_t + 3r_t^{\,2})}{4(r_b^{\,2} + r_b r_t + r_t^{\,2})} \tag{2}$$

Two thin and equal bars with radius r_{fa} and length l_{fa} are perpendicularly attached to the top and bottom surfaces of the wheel. The function of these bars, those are called as rear wheel axle, is making backrest for connecting the body (connector links) and the rear wheel.

B. *Body*

The second part of PWR is its body which is a slim rectangular cube with dimensions $d_{cu} \times \underline{w}_{cu} \times h_{cu}$. A frame O*xyz* is attached to one of the vertices of the body as it is shown in Fig. 3. This frame is used for describing the position of different parts of mechanism. Two similar cylindrical bars with length L_{co} and radius r_{co} are perpendicularly attached to

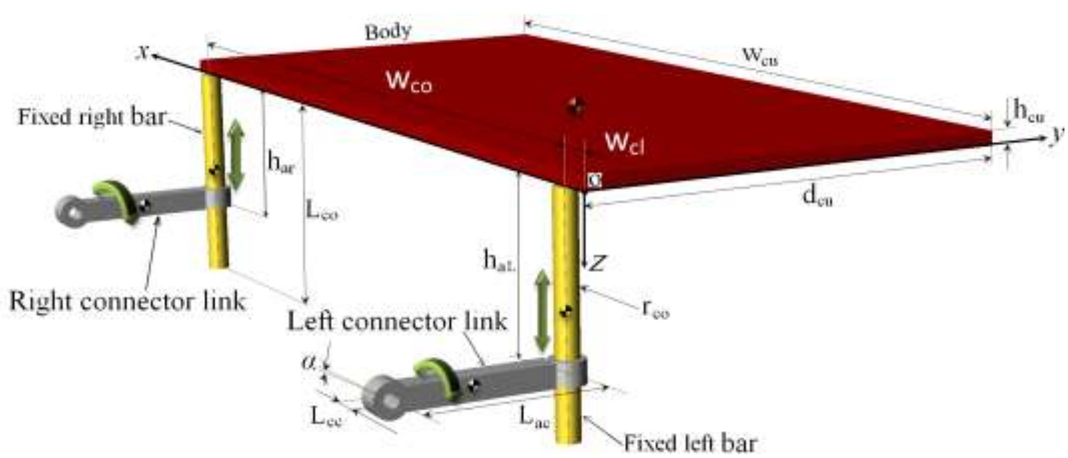

Fig. 3 .The body of the robot and connections of the body and the other parts.

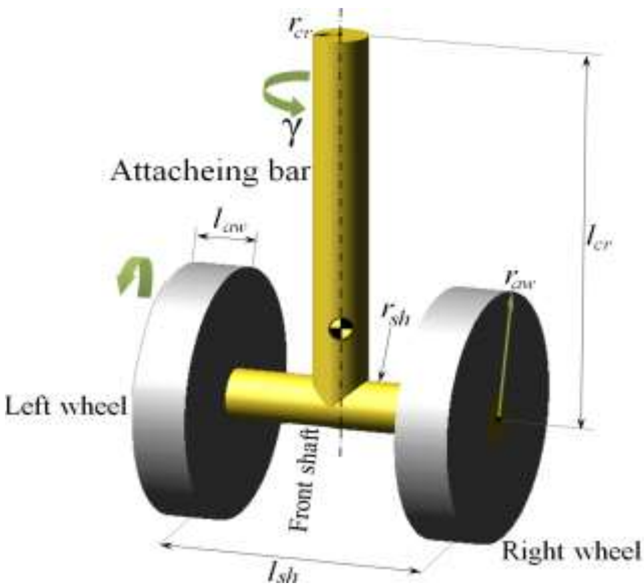

Fig. 4. The front wheel and its coupling.

the lower surface of the body. These bars are previously mentioned fixed bars and one of them is called *left fix bar* and the other one is called as *right fix bar*.

As it is shown in Fig. 3, the distance between two fixed bars is w_{co} and their positions in O_{xyz} are respectively (W_{CL}, 0, 0) , (W_{CL} + W_{Co}, 0, 0). The function of these bars is providing backrest for connector links. The connector links are two similar links with radius r_{ac} and length L_{ac} each connected to one of the fix bars and we call them left and right connector links. The connector links are mounted on the corresponding fixed bars is such a way that the connector link is located along -Y axis of the O_{xyz} frame. Each connection and attachment of this form generates 2 degrees of freedom for the mechanism. Links can move linearly along the bars and also they can rotate around their own axis. It is noteworthy that we can arbitrarily choose intersections of fixed bars and connector links. The other end of the links is the end which is supposed to be connected to rear wheel axis. The connection between any connector link with each corresponding rear wheel axis, is a one degree of freedom connection, and this connection is made by a part with a length (connection width) L_{cc}. This connection allows the rear wheel and its axis to rotate around themselves. It is obvious that in order to having a good and stable connection, we have to let connector links rotate around their axis for the angle α and get fixed and stable on their position.

C. Front wheel

The coupling of front wheels is a T-Shaped part that is made by two perpendicular rods (see Fig. 4). One of these rods is the front wheel's shaft that is call front shaft and the other rod is front attaching bar and its function is to attach the front shaft to the body. Front shaft is r_{sh} in radius and l_{sh} in length and it is fixed on its central point by the end of front attaching bar with radius r_{cr} and length l_{cr} those are perpendicularly attached. The other end of front attaching bar is perpendicularly attached to the lower surface of body with a one degree of freedom. In fact front wheel coupling can rotate with angle γ around front attaching bar axis. In two ends of front shaft we have locations to attach two wheels with radius r_{aw} and width l_{aw} with one degree of freedom. Wheels can rotate around their own axis.

We must consider some conditions about rear wheel dimensions. It is noteworthy that L_{lf} is the distance between left connector link (in connection point to the rear wheel) and the central point of top surface of rear wheel. Also the L_{rf} is the distance between right link to the bottom and it must be: $L_{lf} = L_{rf} = L_{ff}$. The said conditions are:

$$l_f \cos\alpha < \mathrm{w_{co}} - 2\mathrm{L_{CC}} \tag{3}$$

$$(r_b + \mathrm{L}_{ff} \tan\alpha)\cos\alpha < l_{cr} + r_{aw} \tag{4}$$

We have to move connector links to positions on corresponding bars and then fix them for each determined rear wheel. The position for the right link will be named as h_{ar} and for the left one as h_{aL} (see Fig. 3). These positions in O_{xyz} frame is obtained as:

$$\mathrm{h_{ar}} = (l_{cr} + r_{aw}) - (r_b + \mathrm{L}_{ff} \tan\alpha)\cos\alpha \tag{5}$$

$$\mathrm{h_{aL}} = (l_{cr} + r_{aw}) - (r_t - \mathrm{L}_{ff} \tan\alpha)\cos\alpha \tag{6}$$

According to the equations (5), (6) the PWR's body will always be parallel to the platform that the robot is moving on it. As it was discussed, we can summarize advantages of PWR in the following points:

1. It is ideal from the energy consumption viewpoint (zero energy).
2. Utilizing a simple mechanism and with low expenditures for maintenance and repair.
3. Creating a kind of passive intelligence with some changes in mechanisms and conventional structures in wheeled devices.

III. Kinematical Analysis and Determination of Path Math

The parts of PWR will obviously move together and the motions of each part has effect on the motions of other parts according to kinematic and dynamic rules. Our main goal is to determine the path of passive PWR on a simple slope. Here, the rear wheel is a kind of unconventional structure and its passive motion is not along a straight line. Obviously its motion imposes the motion of the robot. Therefore, before we study the motion of the robot, we focus on the rear wheel as a single object and study its motion on a simple slope. After that, its effect on the robot's paths will be tested and measured.

Without loss of generality, it is assumed that in initial configuration, the symmetry plane of the rear wheel is located

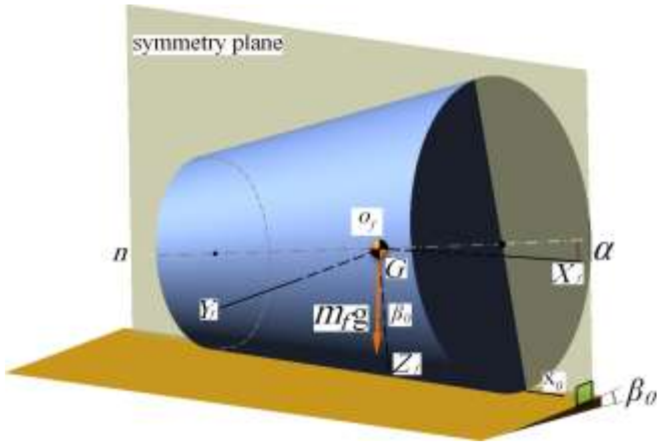

Fig. 5. Initial conditions of the rear wheel on the simple ramp.

perpendicular to the gradient of the surfaces (see Fig. 5).

It means that the initial conditions of PWR must be determined in accordance with mentioned initial conditions of rear wheel. It should be noted that the rear wheel motion is assumed to be a pure rolling. To study motion of the object, we considered right hand coordinates frame $O_{f\ X_f\ Y_f\ Z_f}$ for the object in such a way that its origin O*f* is located in the object Center of Gravity (Fig. 5), X_f axis is parallel with the projection of the axis of symmetry of the object on the platforms and Z_f axis is normal to the surfaces. This frame, which is called "*path-based frame*" in this paper, moves with the object and X axis always remains parallel to the platforms.

In addition, we change view direction to normal direction of the surface of the platform. Thus, without changing the original problem, the wheel motion is changed to a problem of motion on plan in terms of kinematic (figure 6). In figure 6, X_0 axis is projection of the axis of symmetry of the frustum on the platform. We show the angle of path that is passed by frustum with Θ. This angle is measured from the X_0 axis. The range of wheel motion will be assumed to be $0 \le \theta \le \frac{\pi}{2}$ and ω_{x0} is angular velocity about x_0 axis.

Linear velocities of centers of the top and the bottom surfaces of the frustum that are shown by v_t and v_b in y-direction are given as:

$$v_t = \omega_{x0} r_t \cos\alpha \tag{7}$$

$$v_b = \omega_{x0} r_b \cos\alpha \tag{8}$$

The rotation axis Z_0 is a normal axis to surface that passes through wheel's rotation center (P). In figure 6 the distance from center of the top circle of frustum to the point P, signifies the curved path radius and is shown by R_t. Also we can measure angular velocity of wheels around Z_0 in terms of linear velocity of center points of top and bottom circles of

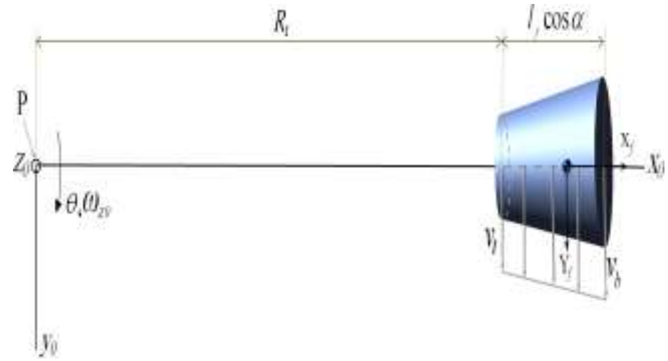

Fig. 6. Display of the rear wheel motion parameters from the normal point of view of the surface.

frustum as:

$$\omega_{z_0} = \frac{v_b}{R_t + l_f \cos\alpha} = \frac{v_t}{R_t} \tag{9}$$

Now we can combine the equations (1), (7), (8) and (9) and calculate curve radius of motion path of center of the top circle of the rear wheel in terms of dimensions of real wheel as following:

$$R_t = \frac{{l_f}^2 r_t}{(r_b - r_t)\sqrt{(r_b - r_t)^2 + {l_f}^2}} \tag{10}$$

We have now understood that how the radius of path of the rear wheel depends on it dimensions. Consequently for each predetermined wheel we have a constant curve radius for all path length. So the path for rear wheel will be a circular path on a simple slope with r_t as radius (for the central point of top

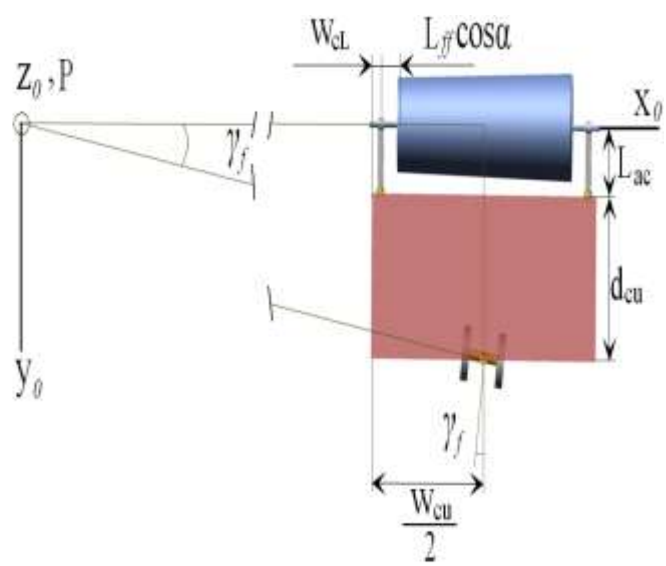

Fig. 7. Display of the PWR from the normal point of view of the surface.

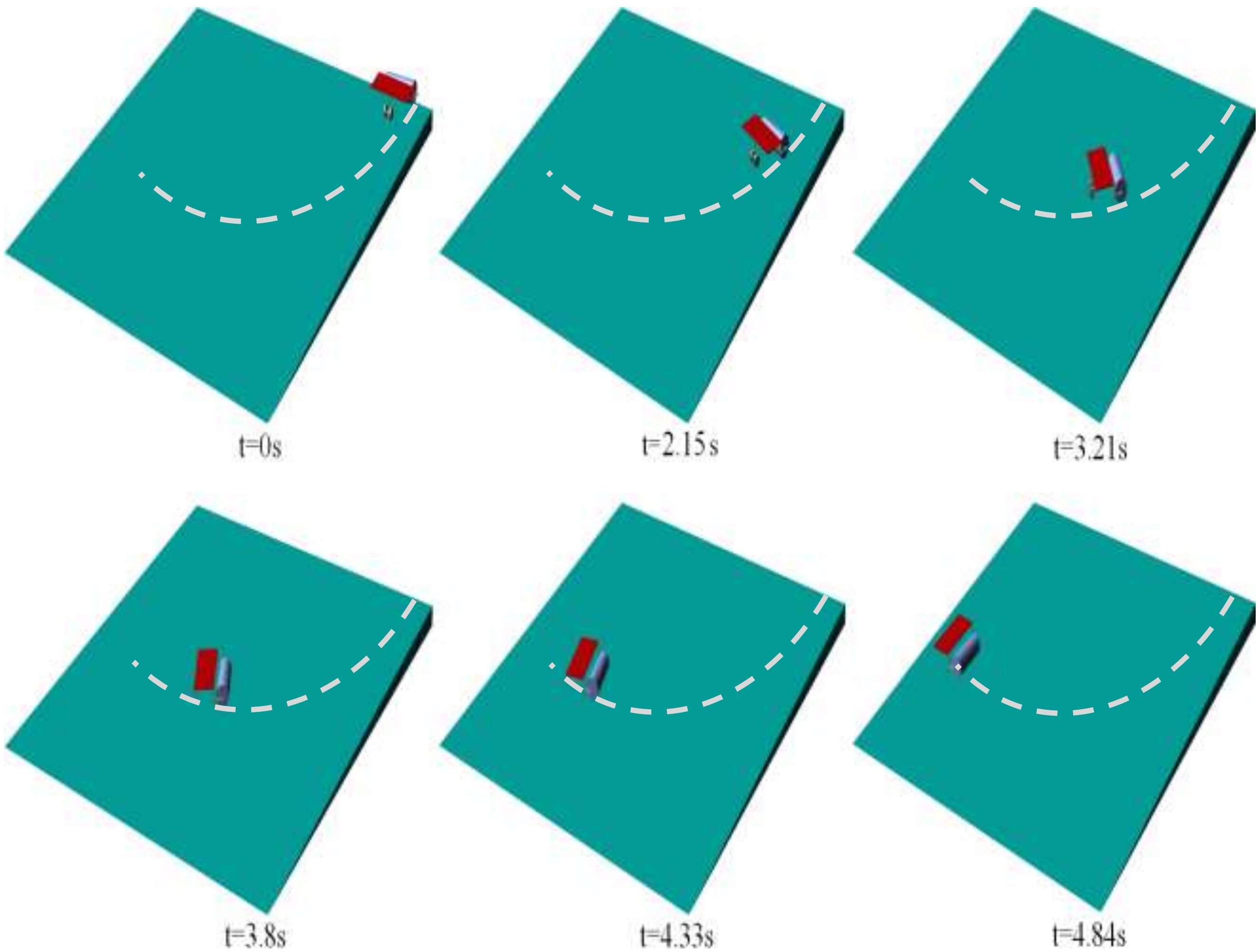

Fig. 8. Six snapshots of the simulations in ADAMS. Predicted path by equation (10) is shown by gray line.

circle).

Coming back to the PWR, it is obvious that all parts of the system move together and they have the same path. In fact the rear wheel directs the robot and controls the robot to move on its own way.

The best condition of motion happens when the front wheels move without any side slip. In this situation there will be a pure rolling motion. To permanently guarantee this pure rolling; it's necessary that the coupling of the front wheels rotate around itself as much as the angle γ_f and then return to its place before getting started to move. The angle γ_f must be in such a way that the connecting line between the rotation center point (P) and center of front wheels are perpendicular on side surface of those wheels.

According figure 7 the angle γ_f can obtained as:

$$\tan\gamma_f = \frac{d_{cu} + L_{ac}}{R_t + \frac{w_{cu}}{2} - w_{cL} - L_{ff}\cos\alpha} \qquad (11)$$

IV. Simulations

The aim of simulations is to verify performance of the introduced mechanism and equations obtained in previous sections. To perform simulations, we considered a PWR with rear wheel as: r_t=43mm ،r_b=49mm ،l_f=248mm, r_{fa}=2.5mm and l_{fa}=40mm. The body is a cube with h_{cu}=5mm, w_{cu}=320mm and d_{cu}=150mm. The fixed bars have radius and length r_{co}=4mm and L_{co}=80mm and connector links length is L_{co}=60mm. These links must be deviated as angle α=1.385^0 and then fix on the attaching position on the rear wheel. The position of the left and right fixed bars are w_{cL}=12mm and $w_{cL}+w_{co}$=308mm respectively. The front attaching bar has radius and length l_{cr}=75mm , r_{cr}=5mm and radius and length of the front wheels shaft are r_{as}=5mm and l_{as}=60mm. The front wheels are with r_{aw}=25mm and l_{aw}=10mm. According discussed characteristic it should be h_{aL}=57.498mm and h_{ar}=50.338mm. Finally front wheels coupling will be located according to equation (11) with angle γ_f =6.318^0 orientation. Using these values, according to (10), the radius of the path is obtained as R_t=1.78m. The slope of the platform is considered to be $\beta_0 = 2.7^0$. The model was built in CATIA and for dynamical analysis it was exported to MSC. ADAMS. In initial configuration, the symmetry plane of the rear wheel is perpendicular to gradient of slope direction. We simulated the system for 4.84 seconds in ADAMS. Figure 8 illustrates six snapshots of the simulation. Predicted path (a circle with radius R_t=1.78m) is shown by dashed gray line.

V. Conclusions

In this paper we elaborated the idea of passive mechanisms to design and introduce a passive wheeled mobile robots field. The robot is able to move through straight or calculable curved paths down a slope. In this robot we have no actuator to drive the robot and make it to move. The only force is gravity force and the robot descents down the slope thanks to its weight. The motion path is dependent to the robot's configuration, thus the relationship between the configuration and the robot's path is obtained and verified by simulations in ADAMS. The robot is interesting from the energy saving point of view as it does not need any external actuation. Ability of tracking a curved path is one of the most advantages of the robot as most of passive mechanisms are only able to move along straight paths.

The introduced robot can be replaced by any of manipulation mechanisms in industries to achieve energy saving manipulation mechanisms. Among these manipulation mechanisms one can refer to a set of conveyers carry a part from one configuration to another; wagons in mines move articles and a robotic arm changes position and orientation of an object.

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