Three-Wheel Robot Driven by Inertial Actuator

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Abstract

This paper presents experimental study on a three-wheel robot driven by an inertial actuator. The robot has a front steering wheel and two rear inclined caster wheels. If proper side-to-side sinusoidal force is applied, the robot can move forward without having motors directly driving its wheels. We have designed and constructed a robot prototype in order to study effects of its main parameters on the forward motion. The inertial actuator composes of two eccentric counter-rotating discs driven by a dc motor. In experiment, we studied the effects of the forcing frequency, inclination angle of the rear caster wheel axes, and the mass distribution on the forward speed of the robot. From the test, the inclination angle and the mass distribution were found to have great effect on the forward motion. Furthermore, there exists an optimum operating frequency for the sinusoidal force for each inclination angle.

Keywords: Mobile robot, caster-wheel robot, non-holonomic system

1. Introduction

Scooter and skateboard are a classic example of push-and-go type vehicle. To ride this type of vehicle, rider places one foot on the board and pushes the other foot against road surface in order to move forward. Recently, another type of skate board called the “snake board” (Fig. 1) has been introduced. The snake board can travel without direct propelling force from the rider – the feet of the rider do not touch road surface and can stay on board at all time. It composes of two foot plates each having an axle and two wheels attached to it. The footplates are connected to a middle plate by revolute joint allowing them to rotate. The rider stands on the footplates and, by moving his/her feet in and out in conjunction with the shoulder and hip, is able to propel the board in any direction. The board moves in similar fashion to that of a snake. A number of researchers have given explanation of how the snake board can move (for example see [1]). Some researchers [2] have designed a snake board robot without a rider and studied how to control it.

Fig. 1 Snake Board

Also recently, another type of scooter called the “Razor PowerWing®” (Fig. 2) has been offered as another fun ride for outdoor activity. It is a transporter that offers new way to ride. It has three wheels and the rider can stand stably on board with both feet at all time. To ride it, the rider moves his/her body side-to-side and the Razor PowerWing® will move forward. Similar to the snake board, no pushing action is required. In effect the Razor PowerWing® moves forward by means of *reactive sinusoidal force* generated from the rider. The Razor PowerWing® composes of a front steering wheel and two rear *inclined* caster wheels – the steering axis of the caster is tilted relative to vertical direction. The inclination of the caster wheels and possibly other parameters such as inclination angle of the caster, frequency of the sinusoidal force, mass distribution, etc., play important role for the forward motion but it is not clear how.

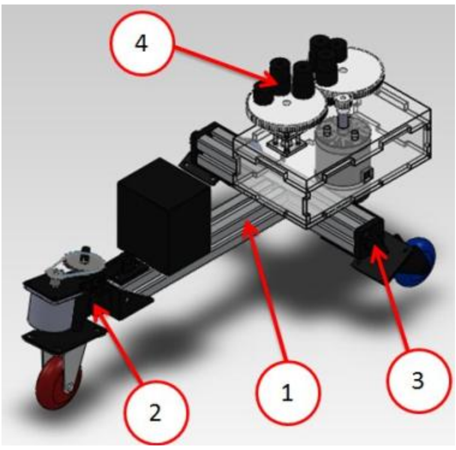
A number of studies have investigated on similar systems, e.g., the Roller-Walker type robot [3]-[5], the RoboTrikke robot [6], the G-Snake robot [7]. The kinematic analysis of these systems are rather straightforward as it involves non-honolomic constraints only in two dimensional space. However, locomotion analysis of the Razor PowerWing® type scooter is not simple. The main difficulty is the non-holonomic nature of the inclined caster wheels which render the kinematic problem to three-dimensional space. As the wheels swivel around their axes, the scooter body can be raised up and lowered down.

This study therefore aims to: 1) primarily understand how this scooter works by means of experiment and 2) test the effects of system's main parameters on the forward motion. A robot prototype was constructed similar to the Razor PowerWing® as explained in the next section.

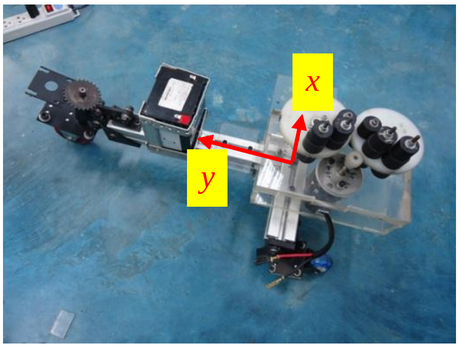
Fig. 2 Razor PowerWing®
(http://www.razor.com)

2. A Three-Wheel Robot Prototype

A robot prototype was designed and constructed (Fig. 3) similar to the Razor PowerWing® design. It is 36 cm. wide, 61 cm. long and weighs 12.5 kg. It consists of: 1) an aluminum frame 2) a front steering wheel 3) two rear inclined caster wheels and 4) an inertial actuator. The distances between the two rear caster wheels is 30 cm the between the front wheel axis and rear wheel axis is 40 cm. The axis of the caster wheels is tilted ϕ degrees from the vertical direction (see Fig. 4). The front steering wheel is driven by a stepper motor which can simulate the hand-turning action of the rider. The robot is driven by the inertial actuator which provides reactive sinusoidal force that simulates the side-to-side motion of the rider. The inertial actuator composes of two counter-rotating discs driven at the same speed by a dc motor. Solid steel block(s) of mass m is placed at distance e from the center of rotation (Fig. 5). As the discs rotate centrifugal forces are generated. The two counter-rotating discs can be arranged such that together as they rotate linear sinusoidal force, $f_x = 2m\omega^2 e\cos\theta$, is produced side-to-side on the robot body while no resultant force exists in the back-to-front direction: $f_y = 0$. The frequency of the inertial force which is equal to the angular velocity ω (rad/s) of the discs, can be adjusted by varying the speed of the driving motor. Note that this inertial force is the only active element in driving the robot forward. There are no motors directly driving the wheels of the robot



a)



b)
Fig. 3 A robot prototype

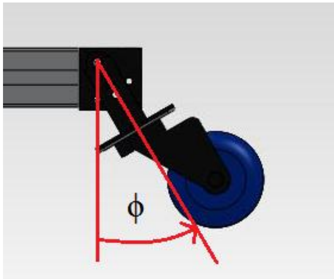


Fig. 4 Inclined caster wheel (rear)

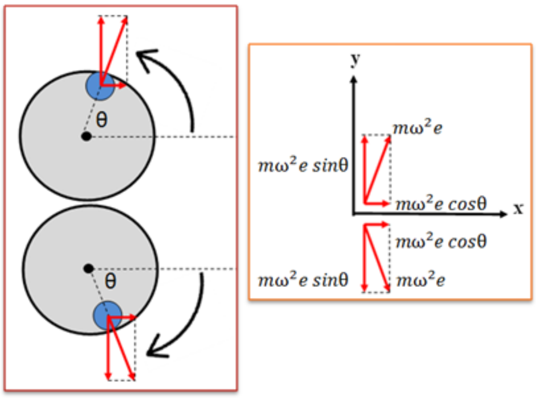


Fig.5 linear sinusoidal force is generated by rotation of two counter-rotating eccentric discs (θ is the rotation angle of eccentric masses)

3. Control Hardware Set-Up

Figure 6 illustrates the hardware set-up for robot control. A remote control composes of a joystick having two potentiometers to provide analog voltages in relation to the steering and motor speed commands. The analog voltages are read by ARM7 microcontroller unit (MCU) which then sends ASCII coded control signals to the robot through wireless transmitter (ET-RF24G 2.4 GHz). Another wireless receiver (ET-RF24G 2.4 GHz), located on the robot receives the control signals and passes them to another ARM7 MCU onboard the robot. The MCU then decodes the signals to separate the steering command and motor speed command. The MCU calculates the control logic based on the steering command and feed it to the stepper motor driver system. The MCU also generates pulse width modulated (PWM) signal based on the motor speed command and sends it to the dc motor driver.

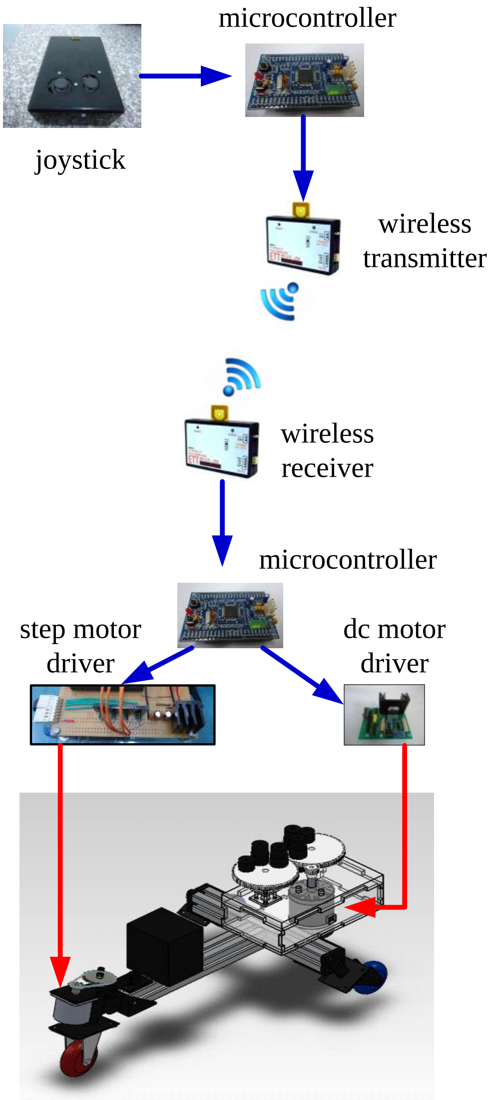


Fig.6 Hardware set-up for robot control

4. Experiment and Results

The experiment was set up to study effects of the forcing frequency, inclination angle of the caster wheel axes and the robot mass distribution on the forward speed of the robot on a horizontal plane. A heavy battery can be placed at the front, middle or back of the robot to vary the mass distribution of the robot. No numerical values of the robot center of mass were measured, however.

The robot was tested on a building floor with a flat and horizontal surface. During the test we tried to ensure that no slippage between the wheels and the floor occurred. However, this was only carried out by observation. It is very difficult to confirm perfect non slippage condition, but the polyurethane wheels certainly help in terms of friction. In each test condition, a number of experiments were performed and the average forward speed of the robot was recorded. The frequency of the sinusoidal force was varied by changing the rotational speed of the eccentric discs. The speed was varied within the range that the robot underwent a forward motion. At low rotational speed, the magnitude of the force may be too low to generate the forward motion. However, for very high rotational speed the robot may not move forward either. This will be shown in the results. Note that the amplitude of sinusoidal force in this set up is squarely proportional to the frequency of the discs. Therefore, the higher the disc speed the higher the amplitude of the inertial force.

4.1 Effect of inclination angle

Figure 7 shows the result of tests for the case where the eccentric mass $m = 1.152$ kg is placed on each disc. The graphs show the relationships between the robot's forward speed and the forcing frequency. In our set-up, for the inclination angle of 20 degrees and lower, the robot did not move forward at any forcing frequency. The results were the same for the inclination angle of 40 degrees and higher. The robot only moved forward when the inclination angle was between 25 and 35 degrees. Subsequently, three values of the inclination angle of the caster wheel axes were tested: 25, 30, 35 degrees. It was found that as the inclination angle was increased from 25 to 35 degrees, higher forward speed was obtained. For our prototype, the highest forward speed was obtained at about 11.2 m/min when the inclination angle was 35 degrees, the forcing frequency was 280 rpm or 4.67 Hz, and the battery was placed in the middle. An important characteristic was found that for each inclination angle, there appears to be an optimal operating frequency as evident in the results.

Figure 8 shows the results for the case where the eccentric mass of the disc is $m = 1.440$ kg. As the mass is increased, at the same frequency the amplitude of the force is higher. With higher force amplitude, the robot seemed to be able to start moving forward at lower rotational speed for the case where $\phi = 25$ degrees but had no effect for $\phi = 30$ and $\phi = 35$ degrees. In most cases, the robot speed increased. We did not attempt to put more eccentric mass on the discs as there was space limitation. The maximum forward speed was obtained at about 14.4 m/min when the inclination angle was 35 degrees, the forcing frequency was 290 rpm and the battery was placed in the back. Similar to the previous case, there exists an optimal operating frequency for each inclination angle.

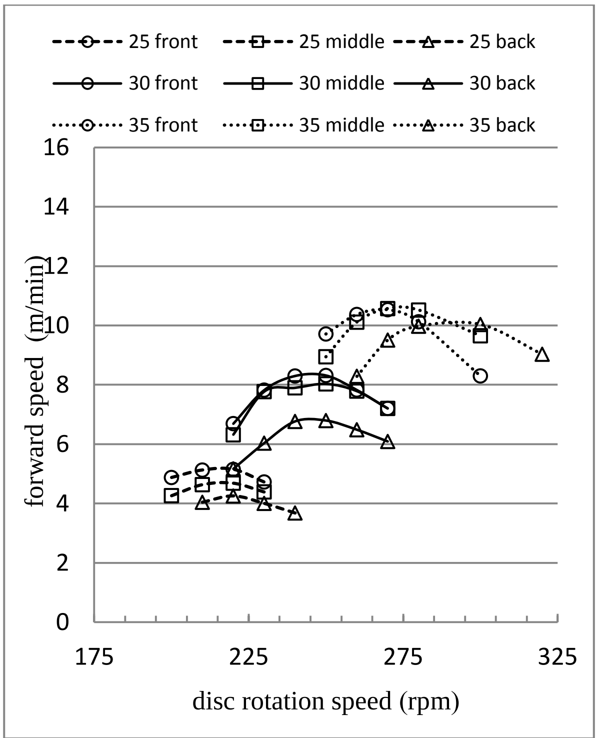


Fig.7 Test results (m=1.152 kg)

4.2 Effect of mass distribution

The mass distribution of the robot can be adjusted by changing the location of the battery. It should be noted, however, that by doing so the center of mass of the robot does not change significantly as the mass of the battery only accounts for about 15% of the robot mass. What may have a significant impact, however, is the local change in the moments of inertia of the system relative to the locations of the wheels and the sinusoidal force. Nevertheless, in this preliminary experiment study, we did not attempt to obtain their numerical values.

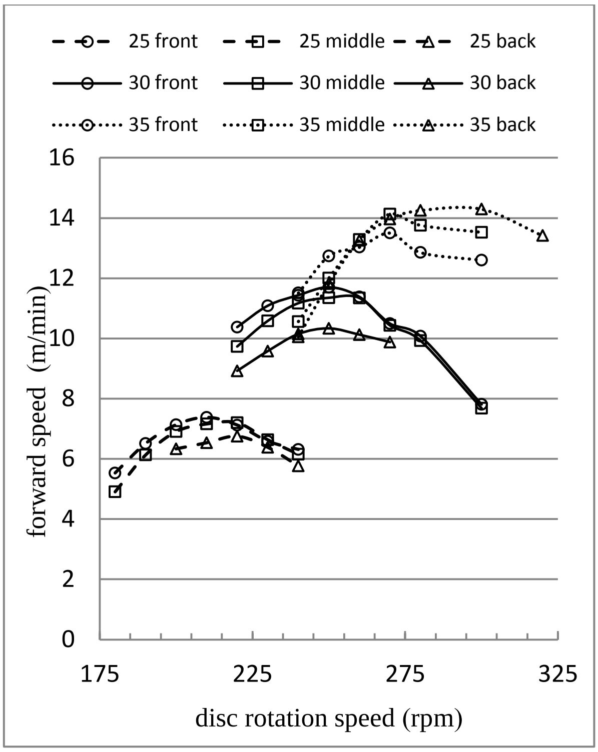


Fig.8 Test results (m=1.44 kg)

The effect of the mass contribution can be observed in both Fig. 7 and Fig.8. By placing the battery further forward, the robot seemed to move forward more quickly for the case where $\phi = 25$ and 30 degrees. However, as ϕ increases to 35 degree, the tendency becomes inconclusive. The robot could move with higher speed when placing the battery at the back in the case where $m = 1.440$ kg. But for $m = 1.152$ kg placing the battery at the front still results in higher speed. Another effect that was clearly observed at $\phi = 35$ degrees is that the frequency at which the robot started moving forward was shifted higher when the battery was placed further back. This is also true for the highest frequency where the robot stopped moving forward.

4.3 Turning

We selected the optimal parameters ($m = 1.440$ kg, $\phi = 35$, running speed 290 rpm, battery at the back) to test the turning radius of the robot. Figure 9 shows the exponential relationship between the turning radius and the steering angle. As expected, similar results were obtained for both left and right turns as the mass distribution is almost axially symmetric. The robot is able to turn with a minimum radius of 50 cm.

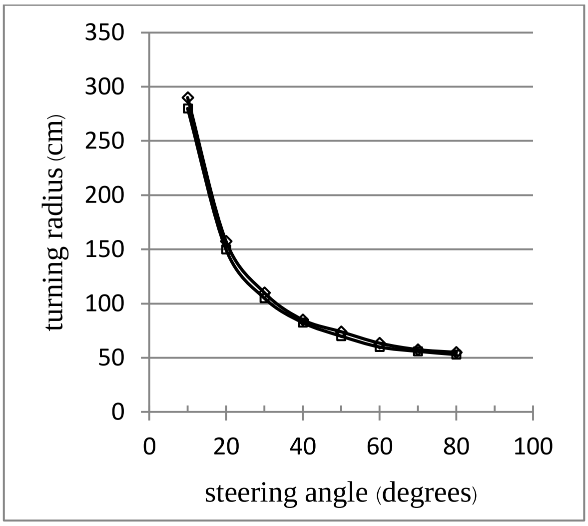


Fig.9 Turning radius (─□─ right, ─Δ─ left)

5. Discussion and Conclusion

We have built and tested a three-wheel robot driven by an inertial actuator to study the locomotion of the Razor PowerWing® scooter. Through our observation, the mechanism for which the robot can move forward may be explained as follows. We believe that the robot moves forward by means of a proper periodic exchange between robot's rotational kinetic energy and its potential energy under three dimensional non-holonimic constraint. As the actuating force is applied to the robot, its body moves side way. The inclined caster wheels then swivel around their axes causing the robot body to raise up slightly hence gaining gravitational potential energy. As the actuating force reverses direction, the robot body moves back toward the other side. The caster wheels swivel back which then lower the robot body. Its potential energy is decreased and transformed to the kinetic energy. As the robot gains kinetic energy from moving down through the non-holonomic constraint, having proper parameters, the robot moves forward. How well the robot moves forward depends on many factors. The frequency of the applied force is one of the most important factors. To obtain the best forward speed, the forcing frequency must be in synchronous with the frequency at which the robot best exchanges kinetic and kinetic energies. This depends on both kinematic parameters such as inclination angle, wheel base, etc., and kinetic parameter such as robot's mass distribution. For each inclination angle, there appears to be an optimal operating frequency that maximum forward speed is achieved.

From the test, it is apparent that the inclination angle has great effect on the forward speed of the robot. Our robot prototype only moved forward for the inclination angles between 25-35 degrees. If the inclination is lower than 25 degrees the robot would not move forward for any operating frequency. This could be due to limitation of our actuator. From other results it is expected that for inclination less than 25 degrees the operating frequency would be in a low range and the actuator can not produce enough force amplitude in that range to drive the robot forward. For high inclination angle, the robot may not move forward either but this is likely due to kinematic limitation. The higher the inclination angle, the more difficult the caster wheels can swivel around their axes. In our robot prototype the maximum inclination angle is at 35 degrees which happens to be the angle that provides the best forward speed.

The mass distribution of the robot also has great effect on the robot forward speed, as moving the location of the battery further forward the robot body, higher forward speed could be obtained. However, this is only true for the inclination angle less than 35 degrees. The mass distribution also affect the minimum and maximum operating speeds at which the robot can move forward.

It should be noted that there is a coupling between the amplitude and the frequency of the force produced in our current inertial actuator design, i.e., the amplitude is squarely proportional to the frequency. It would be ideal if these two variables can be varied independently. This should be exploited in further study.

The experiment results have given us a hint about the effects of robot parameters on the robot motion. However, these results are only preliminary. It is difficult to know exactly the effect of each parameter and to know how the robot can move forward by only observing experimental data as the robot motion involves complex dynamics with three dimensional non-holonomic constraints. In future work, we aim to derive a dynamic model of the system with a complete set of non-holonomic constraints in order to better understand the system.

6. Acknowledgement

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7. References

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