A Two-Wheeled Mobile Non-Inverted-Pendulum Robot

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Abstract: The two-wheeled mobile non-inverted-pendulum (NIP) robot which is the topic of this paper is a new prototype of a two-wheeled mobile pendulum robot with two internal devices. The pendulum contains the control devices; it is not inverted and free to oscillate. The robot actuation mode is insured by the potential energy of the internal devices. It has two actuators and the free oscillation of the pendulum is mechanically controlled. The robot mechanical structure, the kinematics, the dynamics are given.

Keywords: Pendulum, oscillation, internal device, wheeled mobile robot, wheel.

1. INTRODUCTION

Two-wheeled mobile robots with intermediate body (pendulum) have evoked a lot of interest recently. Actually some prototypes are commercially available. Such vehicles are of interest because they have a small footprint and have good maneuverability.

Most of the presented pendulum robots are called "inverted pendulum robot". Segway [1, 2] Ubot [3, 4], Robovie-IV [5] and. An inverted pendulum robot has its center of gravity above the two wheel common axle. Without an active balancing control system, the robot would just fall over [7, 8]. Other proposed models having the center of gravity below the two wheel common axles have adopted a controlled actuation system to master the oscillation of the intermediate body [9].

This paper deals with a new type of a two-wheeled mobile pendulum robot by solving the problem of instability and nonlinearity of the previous proposed models. The oscillation of the pendulum is mechanically supported the weight of two extra masses mounted on the internal devices. Some previous works had already presented the concept of internal device [10, 11]. But it has been implemented and tested only with unicycle spherical shape mobile robot. This paper shows that it can be used with two wheeled robot and it use avoids the robot's pendulum to be inverted. The weight, size and the power of the new design of wheeled mobile pendulum robot are interesting.

2. DESCRIPTION

The two wheeled mobile non-inverted-pendulum robot consists of two independent driving wheels with a common rotation axle, an encapsulated-driving internal device (ID) for each wheel and an intermediate body (IB). A computer model is represented in Figure **1**. As with the differentially driven mobile robot, this model also has two identical independent driving wheels. They are like a cylindrical shell with an outside and inside diameters (external and internal diameter). The wheeled pendulum mobile robot has two IDs, they are identical and each of them consists of a free wheel of guidance and an actuated wheel. Figure **2** represents a photograph of one the ID. The ID is designed to run inside the cylindrical internal surface of the robot wheel.

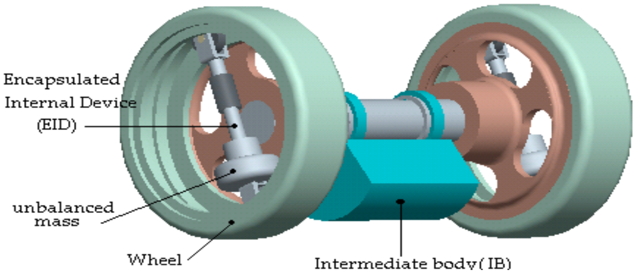

Figure 1: Simplified 3D computer model.

Each ID consists of a free wheel rolling wheel of guidance located at the upper side and an actuated wheel connected to a DC motor by the mean of a gear train. The last cited two wheels have the same radius. The center of mass of the ID is located below the center of the robot wheel by mean of an unbalanced mass situated near the ID driving wheel. Under the effect of gravity, each wheel of the robot turns with respect to its ID position. The shafts of these two wheels are connected by a system of spring to keep

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contact between ID and the internal surface of the robot wheel.

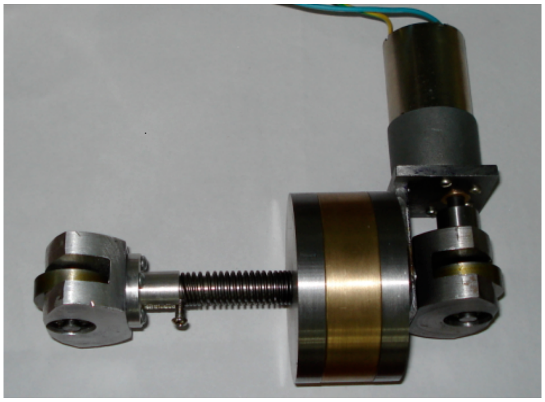

Figure 2: Internal device.

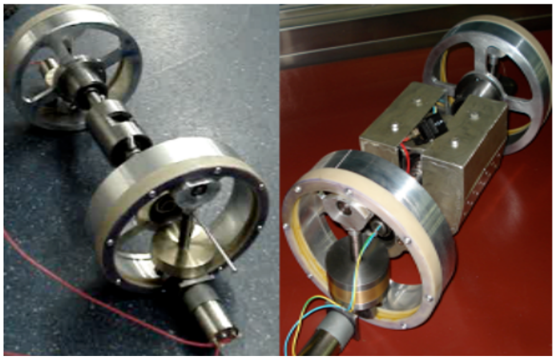

Figure 3: Two-wheeled mobile NIP robot.

The IB is a prismatic case located in between the robot two wheels (Figure **3**- right). The purpose of the IB is to carry out a computer system, sensors and power supply of the control devices. The word “pendulum” is used to qualify this type of robot because the IB is able to rotate about the common axis of the two driving wheels. The IB is designed such a way that its center of mass is located bellow the common axis of the two driving wheels of the wheeled pendulum mobile robot. Two different photographs of the assembling of the two-wheeled mobile pendulum robot with (left) and without (right) the IB are shown in Figure **3**.

3. KINEMATICS

The kinematics of the robot is almost the same as the kinematics of any differential drive. The robot is supposed to move on a horizontal plane.

Some Interpolated experimental results are shown below. Figure **4** represents the robot linear velocities corresponding to the robot different inputs, i.e. the different angular velocities of the ID wheel. Figure **5** represents the variation of the robot angular velocity in rotation about the right wheel with respect to the variation of the left wheel ID wheel angular velocity.

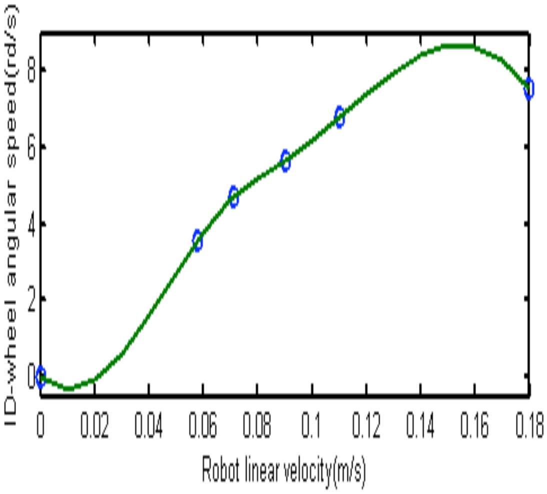

Figure 4: Linear velocity in straight line.

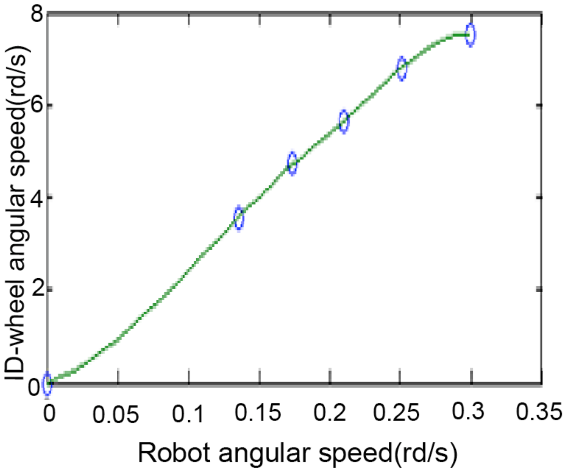

Figure 5: Angular velocity about right wheel.

4. DYNAMICS

To solve the dynamics of the two-wheeled mobile pendulum robot problem, the following equation of Lagrange is used;

$$\frac{d}{dt}\left[\frac{\partial(E)}{\partial \dot{q}_i}\right]-\frac{\partial(E-\Pi)}{\partial q_i}=\tau_i \tag{1}$$

Where E defines the total kinetic energy of the robot, Π defines the total potential energy of the robot, τ_i represents the external generalized forces and q_i ($i=1,...,5$) the generalized coordinates of the system. The total number of generalized coordinates, which are the dynamic variables, is five:

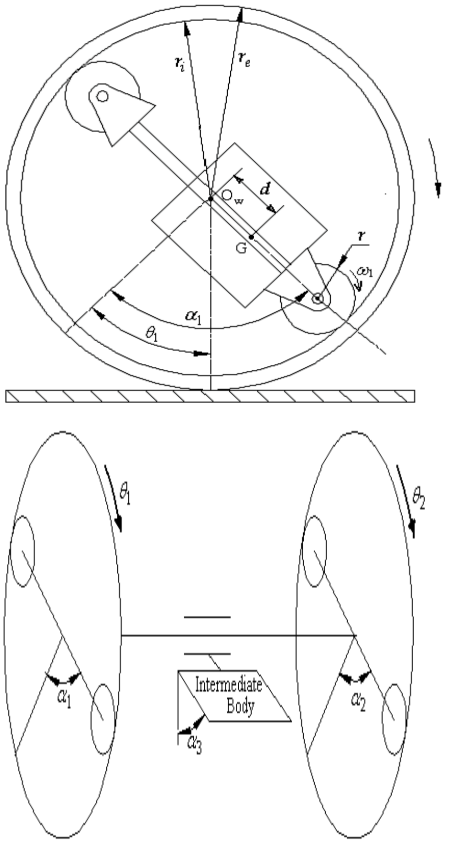

Figure 6: Parameters and generalized coordinates.

$$q_1 = \theta_1 ;\ q_2 = \theta_2 ;\ q_3 = \alpha_1 ;\ q_4 = \alpha_2 ;\ q_5 = \alpha_3$$

Where θ_1 and θ_2 represent the left wheel and right wheel angular velocities of the wheeled mobile pendulum robot, α_1 and α_2 are the ID swing angle, and α_3 represents the instantaneous oscillation angle of intermediate body. The generalized coordinates are represented in Figure **6**-down.

The Robot wheel angular displacements θ_1 and θ_2 are considered as angles measured between the radius through a fixed point on each wheel cylinder and the vertical position (Figure **6**-up). Angles α_1 and α_2 are angles measured between the same radius and each axis of the robot ID.

The Parameters, their definitions and their values are given in the following table.

Table 1: Physical and Geometrical Parameters

Dimension	**r_e =100mm, r_i =89mm, r =15mm, l =380mm, *d*=40mm, *h*=20mm**
Mass	Robot wheel masses *m*=1.5kg ID masses m_i=2kg ID wheel masses m_r=0.1kg IB mass m_b=2kg Robot mass m_r=8.3kg
Other parameters	motor power *P*=5 watts Friction robot wheel/ground μ =0.5, Friction robot wheel/ID μ_2 =0.04, spring compression K=16 N/mm

4.6. Numerical Integration

The integration of the differential equation (1) was performed by the Matlab solver “ode45”, which is based on an explicit Runge-Kutta (4,5 order) formula. During integration a general and two particular motions of the NIP robot have been considered.

The displacements and velocities of the NIP robot wheels, the oscillation angles and velocities of the NIP robot's IB and ID are shown in Figure **7**. Two particular motions have been analyzed: The straight-line motion and the Rotation of the NIP robot about right wheel.

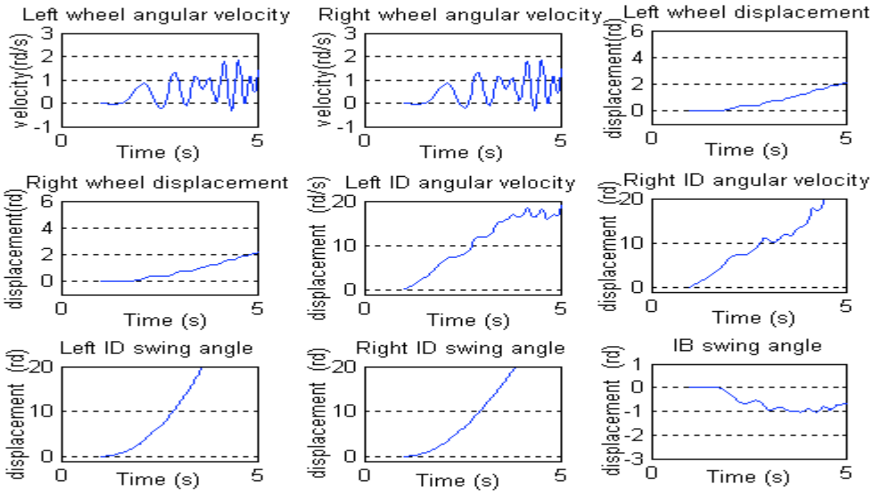

Figure 7: Output of the numerical integration.

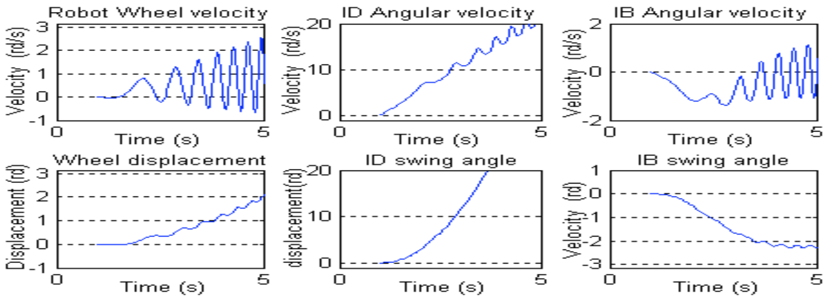

Figure 8: Straight line motion.

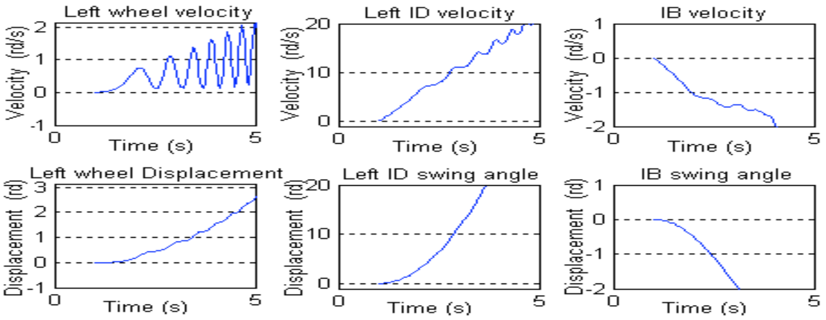

Figure 9: Output of the NIP robot rotation about one of its wheels.

The straight-line motion consists on a pure translation of the NIP robot without rotation. In this situation the two wheels of the robot have the same angular displacement and same angular velocity. The robot's wheel angular displacement, the robot ID's angular displacement, the angular velocity of the IB and the swing angle of the IB are represented in Figure **8**.

In the case of rotation about the robot right wheel there is no translation. The left wheel displacement of the NIP robot and its velocity are equal to zero. The different outputs are represented in Figure **9**.

5. EXPERIMENTAL RESULTS

The internal device of the two-wheeled mobile pendulum robot is a driving device. It rolls inside the robot's wheels. The system wouldn't work properly if an important sliding companies this rolling motion. It was necessary to be sure that the degree of the sliding was low before continuing with the experiments. For this reason different angular velocities have been given to the ID wheel to verify its mobility inside the robot's wheel. Figure **10** represents the variation in the time taken by the internal device to describe an angle of 2π rd with respect to the angular velocity of the ID wheel. The result of this test is satisfactory because the theoretical result and experimental are close to each other. The NIP robot has been also investigated without its IB. Some motions have been experimentally executed such as forward, backward and curved displacements. Different velocities of the robot are obtained with respect to different angular velocities of the ID wheel. Figure **11** represents the theoretical and experimental results of NIP robot in straight-line motion

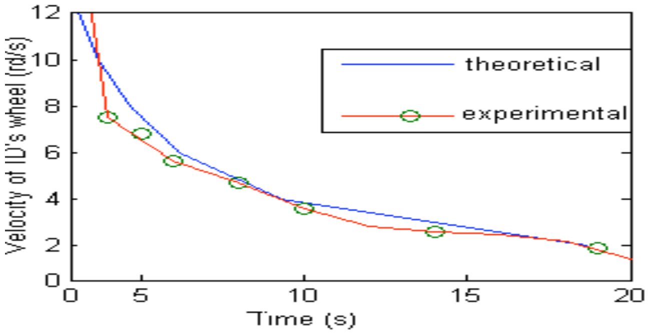

Figure 10: ID rolling motion inside robot's wheel.

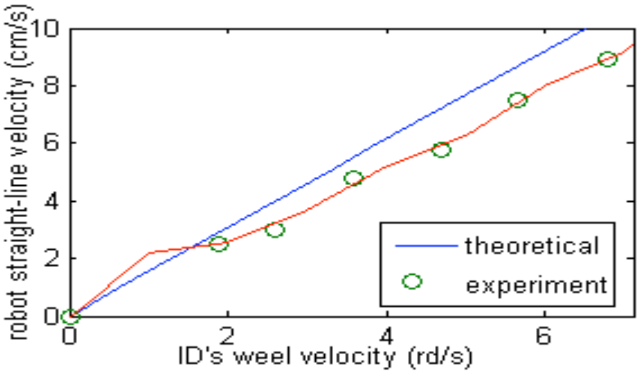

Figure 11: Straight-line motion without IB.

without its IB. The internal frictions and sliding, and the friction between ground and robot's wheel justify the relative difference between the two results.

Some velocity measurements have been done during the experiments of the wheeled mobile pendulum robot. The times corresponding to different voltages in robot straight line (1m) motion and rotation ($2\pi \quad rd$) are reported in Table **2**. It should be noted that when the voltage is low (less than ten volts) or high (more than fourteen volt) the performances of the two-wheeled mobile pendulum robot are not satisfactory.

Table 2: Straight-line and Rotation Measurements with Respect to 1m Distance

	Voltage(V)	**6**	**8**	**10**	**12**	**14**	**16**
Straight Line Motion	Time (s)	20	17	14	11	9	7.5
Rotation about One Wheel		51	46	36	30	25	21
Rotation about Robot Center		28	23	17	13	11	10

The IB (Figure **13**) and its containing devices (battery and control devices) always have some oscillations when the two-wheeled mobile pendulum robot moves. These oscillations react on the movement of the different moving parts without damaging the linear and angular displacements of NIP robot. It should be noted that the mass of the IB represents 25% of the robot mass. The displacement of the two-wheeled mobile pendulum robot is not affected by the IB oscillations in term of covered distance. The experiments have shown that IB oscillation angle varies within the range of –0.2 rd to 0.2 rd. This result verifies the theoretical dynamics as shown in Figure **11**.

Finally robot characteristics and performances can be resumed in Table **3**.

CONCLUSION

During the design one of our aims was to build a two-wheeled mobile pendulum robot with a pendulum that can oscillate freely and to demonstrate theoretically and experimentally that the robot motion can support this oscillation. The result is satisfactory because the two-wheeled mobile pendulum robot has been investigated with and without its intermediate body. The mechanism works properly and some experimental results of the NIP robot have been presented such as the relative mobility of the ID, the degree of the oscillations of IB, the inertial motions of the wheeled mobile pendulum robot, the measurements of different velocities of the two-wheeled mobile pendulum robot and the simulation of the motions.

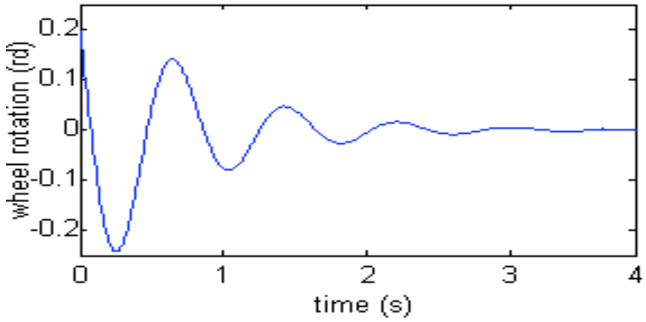

Figure 12: Damped inertial movements.

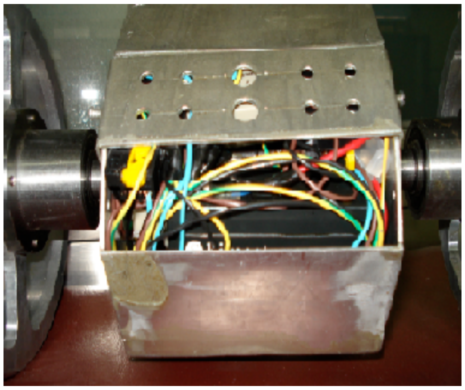

Figure 13: IB and containing devices.

Some coordinated motions have been experimentally executed such as forward, backward and curved displacements. The experiments have shown that it can perform any motion that is required to a differential drive. It should be noted that the different speeds of the robot are non linear but the linearity can be reach by acting on the masses and dimensions of the different parts of the robot.

Table 3: Robot Characteristics and Performances

Power	**Weight**	**Size**	**Speed**	**Pendulum Control**	**Mobility and Maneuverability**	**Load Carrying**
10 watts	8kg	0.2x0.38x0.2m	0.1m/s	Not need	Good ability	Hight

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