Development of Wall Climbing Robot
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Abstract--- One of the most promising ways to make a robot climb are vacuum pumps and suction cups. Most of the mobile robots now days essentially move in 2D plane without wall climbing capability. Wall climbing robot is one of the special in mobile robots because it moves in vertical plane. This paper present a research on the wall climbing robot with vacuum suction method. An Analysis of various aspects in mechanical design, including locomotion mechanism, adhesion mechanism are discussed. The generalized equation of wall climbing robot's to find velocity and acceleration are derived. Static and Dynamic forces found. Designing two wheeled robot, selection of components. Developed cost effective, small size, simple in construction wall climbing robot.

I. INTRODUCTION
In recent time, there have been strong demands that use of robots for defense, surveillance, and counter terrorism missions. Most of the mobile robots now days essentially move in 2D plane without wall climbing capability. Wall climbing robot is one of the special in mobile robots because it moves in vertical plane. Wall climbing robot needs not only special locomotion system but also required adhesion system. One of the most challenging tasks in climbing robot design is to develop a proper adhesion mechanism to ensure that the robot sticks to the wall surfaces without sacrificing mobility. So far many of researchers developed this type of adhesion technique, Magnetic Adhesion, Elastomer Adhesion, suction-pad adhesion[5].

In this work, mathematical model for wheel velocity, body velocity are obtained by transformation. The torque and acceleration is calculated using Euler-Lagrange Formulation for dynamic analysis. The conceptual model is derived for moving on vertical surface and ceiling. Wheeled locomotion[1] is selected and suction pressure is generated by installing impeller which is run by bldc motor. The mathematical equations are formulated for static and dynamic adhesion on wall and suction pressure is calculated. Collecting right components and developed conceptual model for wall climbing robot.

II. DERIVED MODEL EQUATION FOR TWO WHEELED WALL CLIMBING ROBOT
For two wheeled robot design[3] the derivation of equation for position, velocity and angular acceleration for vertical surfaces.

Steps for deriving model equation:
- Derive kinematic and dynamic equations for robot chassis
- Apply Euler-Lagrange formulation for robot chassis
- Equations for wheel dynamics
- Formulate combined chassis and wheel model equation
- Total energy of the system
- Apply Euler-Lagrange formulation for the whole system for the dynamics

Fig.1 shows co-ordinates of robot body. Where, x(t), y(t) are robot position in x and y coordinates and \( \nu(t) \), \( \omega(t) \) Robot linear and angular velocity with respect to body fixed frame.

Total kinetic energy of the whole body is the sum of kinetic energy of the robot chassis and kinetic energy of the wheels is,

\[
\frac{1}{2} Mc \nu^2 + \frac{1}{2} Ic \omega^2 + \frac{1}{2} Mw \nu(l)^2 + \frac{1}{2} Mw \nu(r)^2 + \frac{1}{2} Iw \omega(l)^2 + \frac{1}{2} Iw \omega(r)^2
\]

Put the relationship value of the velocities, ...

\[
\left( \frac{1}{2} Ic \frac{Rw^2}{Re^2} + \frac{1}{8} Mc Rw^2 + \frac{1}{2} Mw Rw^2 + \frac{1}{2} Iw \omega(l)^2 \right) \nu(l)^2 +
\left( \frac{1}{2} Ic \frac{Rw^2}{Re^2} + \frac{1}{8} Mc Rw^2 + \frac{1}{2} Mw Rw^2 + \frac{1}{2} Iw \omega(r)^2 \right) \nu(r)^2 +
\left( \frac{1}{4} Mc Rw^2 - Ic \frac{Rw^2}{Re^2} \right) \omega(l) \omega(r)
\]

Where Mc is robot chassis mass, Mw wheel mass, Rc is chassis radius, Rw is wheel radius, Iw wheel moment of inertia, Ic chassis moment of inertia.

Potential energy of the robot body is Mgy. Apply Euler-Lagrange formulation, total energy becomes,
\[
\left[ \frac{I_c R_w^2}{R_c^2} + \frac{1}{4} McR_w^2 + MwR_w^2 + Iw \right] \phi(l) + \\
\left[ \frac{1}{4} McR_w^2 - \frac{1}{4} I_c R_w^2 \right] \phi(r) - \tau(l) - \frac{1}{2} Mgy
\]
\[
\left[ \frac{I_c R_w^2}{R_c^2} + \frac{1}{4} McR_w^2 + MwR_w^2 + Iw \right] \phi(r) + \\
\left[ \frac{1}{4} McR_w^2 - \frac{1}{4} I_c R_w^2 \right] \phi(l) - \tau(r) - \frac{1}{2} Mgy = [0, 0]
\]

Where \(\tau(l), \tau(r)\) torque for left and right wheel

Left wheel acceleration equation is,
\[
(4IcR_w^2 + McR_w^2R_c^2 + 4MwR_w^2R_c^2 + 4IwR_c^2)\tau(l) + (-McR_w^2R_c^2 + 4IcR_w^2)\tau(r) + \\
(4IcR_w^2 + 2MwR_w^2R_c^2 + 2IwR_c^2)Mgy
\]
\[
\frac{(4Mw^4R_w^2R_c^2 + 4Iw^2R_c^2 + 4McIcR_w^4 + 8MwIcR_w^2 + 8IcIwR_w^2 + 2McMwR_w^2R_c^2 + 2McIwR_w^2R_c^2 + 8MwIwR_w^2R_c^2)}{} \]

Similarly can be derived for \(\omega(r)\)

Linear acceleration, \(\ddot{v}(t) = \frac{1}{2} R_w \dot{\omega}(l) + \frac{1}{2} R_w \dot{\omega}(r) \) \(..(5)\)

Angular acceleration, \(\ddot{\omega}(t) = \frac{R_w \dot{\omega}(l) - R_w \dot{\omega}(r)}{R_c} \) \(..(6)\)

These equations are required velocity and acceleration for two wheeled vertical moving vehicle.

Fig.2 shows the schematic of main components of wall climbing robot, which includes components like Bldc motor, Drive dc motor, Wheels, Foam sheet body, Plastic cover and inside centrifugal impeller. A special BLDC motor is selected for present application which is assembled with centrifugal impeller also known as vacuum impeller.

III. CONCEPTUAL MODEL

BLDC motor is rotating at maximum 50,000 rpm. So impeller rotates at this speed and create enough suction pressure to adhere the robot with wall safely. Which matches the analytical suction pressure requirements, also it is proven by an experiment. Wheels made up of rubber tubes are selected for locomotion system. External body material is PVC foam sheet board which is light weight, easy to cut, enough strength to carry the weight as compare to its size, and best suitable for wall climbing robot.

The distance between robot and wall is minimum 0 mm and maximum 5 mm. Minimum distance is 0 mm because the tail part of the body is directly connected with wall and upper part which is nearer by wheel its distance with wall is 5 mm.
IV. STATIC AND DYNAMIC FORCES

Static and dynamic analysis equations for centrifugal impeller based wall climbing robot are derived by Jun Li, Xuanshan Gao, Ningjun Fan, Kejie Li and Zhihong Jiang[2]. It is force balancing equation which gives how much static and dynamic force required to stick the robot with the wall safely. Application of mentioned set of equations is utilized for force analysis.

**Static analysis:-**

As shown in fig the balancing horizontal and vertical surfaces, get,

\[ Fa = F_s_b + F_s_eb + F_s_d1 + F_s_d \] \hspace{1cm} (7)

\[ G = F_f_d1 + F_f_d2 + F_f_eb \] \hspace{1cm} (8)

Where, \( G \) is gravity force, subscript ‘s’ for supporting force, subscript ‘f’ for friction force, b for body, eb for edge body, d1,2 for driving wheel 1,2.

Taking moment about center point of axle, torque can be found,

\[ Fa*b1 + G*hg = Fs_eb(b1 + b2) + Fs_b \] \hspace{1cm} (9)

Consider only sliding friction of wheel balancing gravity force, neglecting other body force. And solving above equation for minimum adhesion force required to stick the robot on wall at rest is,

\[ F_{a_min} = \left( b1/b2 + 1 \right) \left( G*K_r/\mu_d \right) + G*hg/b2 + Fs_b \] \hspace{1cm} (10)

Where, \( b1, b2 \) is the distance from wheel and center of gravity. \( K_r \) is the adhere safety factor, \( \mu_d \) is friction between wheel and wall, \( hg \) is the distance between wall and center of gravity.

This equations shows that When \( G \) and \( K_r \) is constant, to minimized the required necessary adhesion force, For that the ratio of \( b1/b2 \) small as much as possible, it will cause more driving forces on drive wheel. To achieve same reduction in \( hg \) is also the another option, reduce the distance between wall and center of gravity.

For the sufficient suction reduce supporting body force(\( F_{s_b} \)) as much as possible.

**Dynamic analysis:-**

Apply D’alambert’s principle on forces, the balancing equation in vertical direction. Take gravity force, acceleration force, edge body friction force and body friction force.

\[ 2F_f_d = F_s_b + G + F_f_eb + Ma \] \hspace{1cm} (11)

This equation shows the drive wheel’s friction force, it divides in four components, (1)gravity of the system (2)contact body’s sliding friction (3)edge body’s sliding friction (4)inertia force. The first three components shows the just balancing gravity only when the robots rest on the wall. The forth component shows drive wheel’s dynamic performance, drive wheel must gain sufficient friction to get pre concentrated acceleration. Put the corresponding value of the above components and get \( F_{f_d min} \) Drive wheel’s minimum drive friction force which is fundamentally related with static friction as shown equation.

\[ F_s_d = F_f_d / \mu_d \] \hspace{1cm} (12)

When robot's geometrical parameters are fixed, \( F_s_d \) is determined directly by adhesion force \( Fa \) which can be obtained by solving eq.(7-9).

\[ F_{a_min} = 2F_s_d(1 + b1/b2) + G*hg/b2 + Fs_b \] \hspace{1cm} (13)

This equation provides suction system with necessary minimum adhesion force index for designing.

V. EXPERIMENTAL WORK AND RESULT

Weight of the robot is nearly equal to 1.5 kg(Maximum with pay load). The choosing wheel diameter is 80 mm. The other dimension of the robot is shown in fig.3. Selected motor torque is 0.5726 N.m. By Using equation 4 and 5 ,get linear acceleration of the robot is 0.0972m/sec^2 ages. And power p is 7 watt(for drive wheel) is found. As per applied force diagram selected motor is safe and applicable.

**Force calculation:-**

Horizontal condition:-

When robot rest on ceiling at that time adhesion force is equal to gravity force. Consider robot weight is equal to 1 kg. For that required adhesion force is 9.81 N.

Vertical condition:-

As shown in equation (10) and (13) Adhesion force is dependable on the ratio of \( b1/b2 \). Take two case for different ratio of \( b1/b2 \).

**Case 1:** \( b1/b2 = 0.6875 \)

\[ F_{f_d(min)} = 9.3681 \text{ N} \] is found. Put this value in eq. (12) and using eq.(13), dynamic minimum adhesion force 42.058 N is found.

**Case 2:** \( b1/b2 = 0.143 \)

\[ F_{f_d(min)} = 3.2861 \text{ N} \] is found. Put this value in eq. (12) and using eq.(13), dynamic minimum adhesion force 42.058 N is found.

**Experiment work:-**

Fig.2 shows the conceptual model of the robot and fig.3 shows the drawing of the robot. Experiment is done on different surfaces like on ceiling, plywood and glass. The snapshot is taken and shown below the working of wall climbing robot.
source will be beneficial if the robot is to be moved at too much height like multistory building. The wheeled locomotion will be the best suited locomotion system for glass, plywood and vertical surfaces as on wall or as on ceiling. It can be run with light weight, low cost dc motors. The suction pressure can be easily generated by impeller with backward curved vanes. Such impellers are readily available from market with vacuum cleaner supplier and repairer at low cost. Hence it is concluded that wall climbing robot for civil application can be fabricated considering wheeled locomotion. The suction pressure can be generated by impeller.

VII. FUTURE SCOPE

1. It is desirable to make robot autonomous to use it for specific tasks. Battery powered suction cups are desired.
2. A paper by Brockmann Et Al gave inspiration for developing a passive suction cup for Robot. They showed that with a pulling mechanism it is very easy to release suction cups and that pushing them on a surface takes less energy than continuous pumping. This seemed to suit very much, in terms of energy consumption and the constructive character of the system.

VIII. REFERENCES

[6] Gecko Inspired Surface Climbing Robots Carlo Menon, Michael Murphy, and Metin Sitti, Member, IEEE