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A Tethered Guiding Vehicle System (TGV) for Façade Window Cleaning

Ramkumar Gandhinathan* **and R Ambigai****

Abstract: Cleaning of façade and skyscrapers are considered one of the most challenging tasks not only because it involves manual labor for cleaning but situations such as weather and wind should be considered. There are many robots developed and under research that climb skyscrapers using different mechanisms like magnetic adhesion, negative pressure, legged or whegged (wheels+legs) kinematics, but each have their own limitations. There are commercially available window cleaning robots such as Winbot or Windoro that clean inner windows of houses or workplaces but are prone to climb heights and clean surfaces of skyscrapers. This paper concentrates on developing a guiding vehicle that would guide Windoro to clean the surfaces of façade and skyscrapers. The guiding robot is designed considering the effect of wind such that the robot doesn't sway while climbing. The design is modelled and analyzed using Pro-E Wildfire 5.0 and the fabricated model is compared with the simulated results.

Index Terms: Climbing; façade; cleaning; robot; sky scraper; domestic; autonomous; guide vehicle; free fall; tethered robots.

1. INTRODUCTION

Window cleaning is one of the most tedious tasks especially when cleaning windows of façades. Tall façades and skyscrapers are prone to air pollution and as a result require frequent cleaning to preserve them. Cleaning windows of façade is generally a manual cleaning process where gondola systems are hung from top of the façades with workers and cleaning apparatus or the worker itself is hung through means of cables and belts. As a result they're more prone to risks of falling or succumbing to physical injuries at times due to swaying of the gondola or cables as a result of wind conditions. Robotization of the window cleaning process is one of the most challenging and exciting fields that is alive and under research. There are many educational institutes concentrating on skyscraper cleaning technologies using robots. Some of the robots under research are currently concentrating on vertical climbing mechanisms using negative pressure [1], suction cups [2], magnetism [3], ropes [4] etc such that they are able to climb tall façades with ease and carry out the cleaning process. Some of the established window cleaning robots are Skscraper –I and Serbot Gekko from Swiss innovations [5]. However these robots have their own advantages and limitations. There are some commercially available window cleaning robots such as Windoro [6] and Winbot that are currently deployed for domestic cleaning purposes. They clean household windows to a certain extent. However they cannot be used to clean windows of skyscrapers as they are not designed to sustain the exterior wind conditions. This paper concentrates on creating a Tethered Guiding Vehicle (TGV) that would help the commercially available cleaning robot to clean windows of tall skyscrapers and façades. The TGV by name is a guiding robot system for cleaning robots such as Windoro or Winbot and is designed to sustain the wind conditions and hence make it compatible to climb vertical surfaces. The TGV uses a rope climbing mechanism to move on the surface of façade because ropes are cost effective and they adhere to any building structure. Hence the TGV guides the cleaning robot to move up and down the façade and the cleaning process is carried out by the window cleaning robot.

* Student, M. Tech Robotics, Department of Mechanical, Engineering, SRM University, Katangulathur, Chennai, India. *Email: ram651991@gmail.com*

** Asst. Professor, Department of Mechanical Engineering, SRM University, Katangulathur, Chennai, India. *Email: ambigai.r@ktr.srmuniv.ac.in*

The paper is organized with the introduction in the beginning followed by explanation of Windoro. Then the mechanism and robot control system are explained with simulation and end results.

2. WINDOW CLEANING ROBOT

The window cleaning robot chosen for this paper is Windoro [6] from Iishim Global Co., Ltd. It is a commercially available window cleaning robot designed suitably for household window cleaning and other large windows or bay in firms. Windoro is shown below in Figure 1.

Figure 1: Windoro

It consists of two robot modules where the one module is placed on the inner surface of the glass to be cleaned and the other on the outer surface. One module consists of cleaning equipment that carries out the cleaning operation and the other module is responsible for holding the cleaning module onto glass and also helps in localization. It is to note that only one side is cleaned at a time. The inner and outer modules are shown below in Figure 2.

Figure 2: Inner and Outer robot modules

3. MECHANISM

The TGV motion is carried out by the use of ropes. They use the phenomenon of friction between two surfaces. Co-efficient of friction varies with different surfaces. Here a ABS wheel with rubber lining and the rope made of nylon is chosen. The co-efficient of friction between rubber and nylon is 0.25. The highest co-efficient is between metal and metal which is above 1. However the design is restricted to use of nylon rope and rubber lining wheels considering time and cost criteria. The rope climbing principle is explained below in Figure 3. The wheels are positioned onto the rope as shown below. The robot kinematics is also shown where *x* and *y* are the translation parameters and □ is the rotation parameter. As per the design shown, the robot would be able to move only in *y* direction. The robot motion is explained in the Table 1 below.

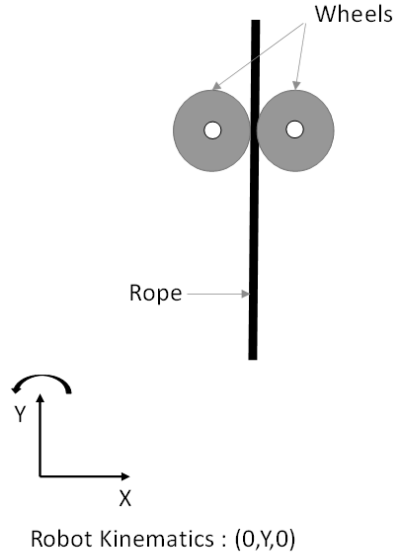


Figure 3: Rope climbing principle

Table 1
Robot Motion.

Left Wheel	*Right Wheel*	*Direction*
0	0	Not Possible
0	1	Downwards
1	0	Upwards
1	1	Not Possible

In the above Table 1 is considered as Clockwise and 0 as Counterclockwise. If the wheels rotate in same direction, then there is no motion possible.

Use of one rope would cause a rotational motion along □ when subjected to wind conditions and hence two parallel ropes are used to eliminate possible motion along □. The comparison is shown below in Figure 4.

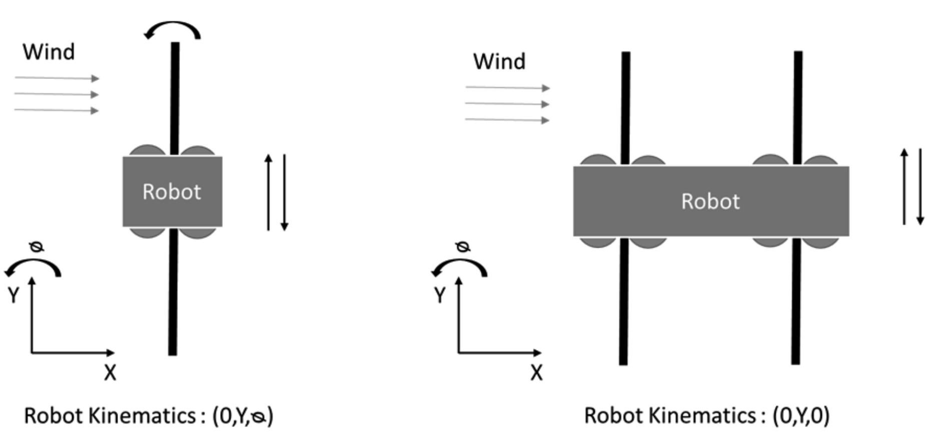


Figure 4: Robot kinematics with wind consideration

4. ROBOT CONTROL SYSTEM

A. Principle of Motion

Unlike other vertical climbing robots that climb using suitable mechanisms [1]-[4] and perform the cleaning operation, free fall concept is used here. This mechanism makes use of gravity itself as one of its actuating parameters along the *y* direction and additionally makes use of a separate actuator to provide braking to the robot at desired positions. Once the robot reaches the ground, the robot is pulled back to the top using a hoist mechanism. As a result, energy consumption is highly reduced. Hence the operating time period for the robot would definitely be high compared to any vertical climbing robot. The robot is made to move in the *x*-direction using railing system on the top and bottom of the building that would be manually controlled. The block diagram that describes the system is shown below in Figure 5.

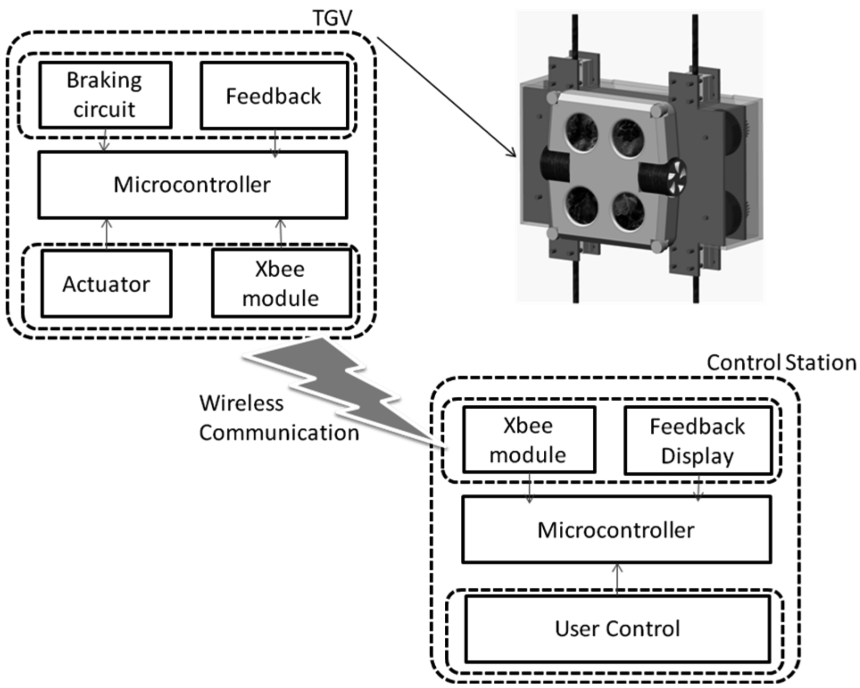


Figure 5: Block Diagram

B. Working

The cleaning robot is attached to the TGV. The TGV is initially place on a railing system on the top of façade or skyscraper. Then the robot is moved down gradually by free fall. The motion is controlled by braking mechanism, which would resemble how PWM control of a motor works, only difference being here is that the motion is due to gravity. The TGV carrying Windoro is shown below in Figure 6.

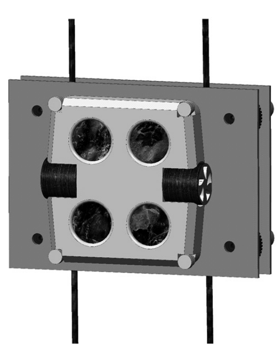


Figure 6: TGV carrying the window cleaning robot

5. MODEL AND SIMULATION

The TGV is a robot-assembly with various components modelled and combined together using a software called Pro-E Wildfire 5.0 as shown below in Figure 7. The bill of materials for the robot is also shown below in Table 2.

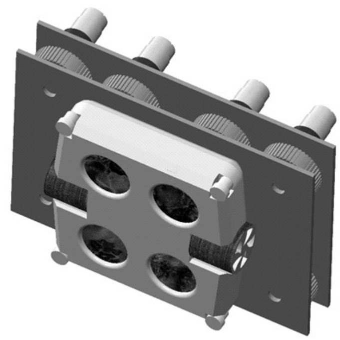


Figure 7: TGV modelled in Pro-E

Table 2
Bill of Materials

S.No	*Component Name*	*Nos req.*
1	Chassis- Acrylic	<weight based>
2	Johnson DC Gear Motor	1
3	Nylon Spur gear	13
4	Linear bearing blocks	4
5	Wheels	8
6	WINDORO robot	1
7	Wheel axle rod	8
8	Bearing block pins	16

An experimental setup is considered to simulate the real time conditions in software. A model of the experimental setup is shown below in Figure 8.

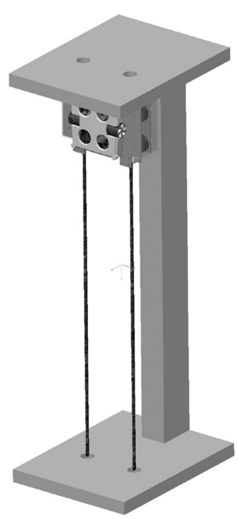
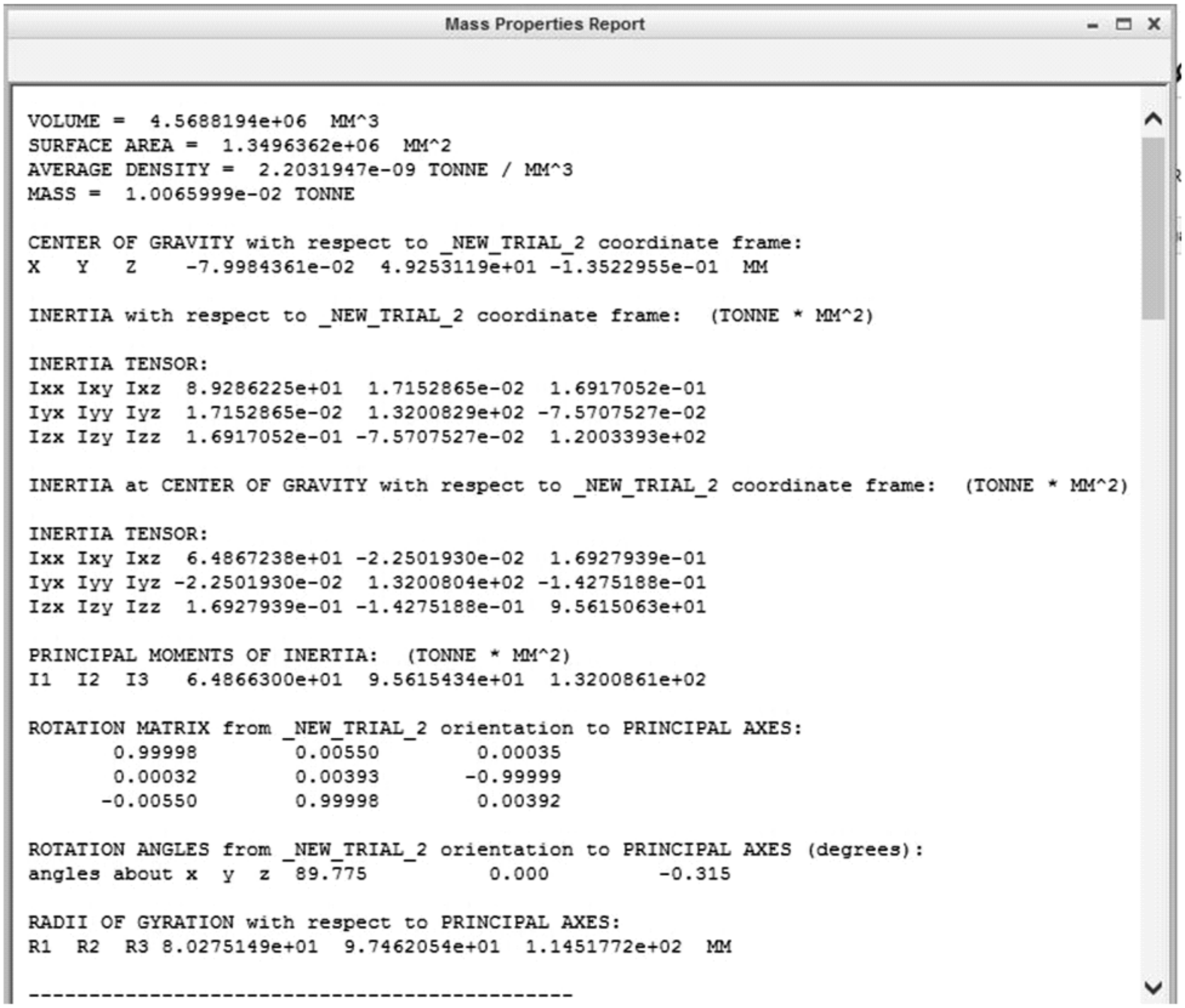


Figure 8: Experimental Setup

The TGV's properties are shown in Figure 9. The simulation was carried out in MDX module of Pro-E Wildfire 5.0. The simulation result acquired is a radar graph and is shown below in Figure 10.



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Mass Properties Report

VOLUME =  4.5688194e+06  MM^3
SURFACE AREA =  1.3496362e+06  MM^2
AVERAGE DENSITY =  2.2031947e-09 TONNE / MM^3
MASS =  1.0065999e-02 TONNE

CENTER OF GRAVITY with respect to _NEW_TRIAL_2 coordinate frame:
X   Y   Z    -7.9984361e-02  4.9253119e+01 -1.3522955e-01  MM

INERTIA with respect to _NEW_TRIAL_2 coordinate frame:  (TONNE * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz  8.9286225e+01  1.7152865e-02  1.6917052e-01
Iyx Iyy Iyz  1.7152865e-02  1.3200829e+02 -7.5707527e-02
Izx Izy Izz  1.6917052e-01 -7.5707527e-02  1.2003393e+02

INERTIA at CENTER OF GRAVITY with respect to _NEW_TRIAL_2 coordinate frame:  (TONNE * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz  6.4867238e+01 -2.2501930e-02  1.6927939e-01
Iyx Iyy Iyz -2.2501930e-02  1.3200804e+02 -1.4275188e-01
Izx Izy Izz  1.6927939e-01 -1.4275188e-01  9.5615063e+01

PRINCIPAL MOMENTS OF INERTIA:  (TONNE * MM^2)
I1  I2  I3    6.4866300e+01  9.5615434e+01  1.3200861e+02

ROTATION MATRIX from _NEW_TRIAL_2 orientation to PRINCIPAL AXES:
       0.99998        0.00550        0.00035
       0.00032        0.00393       -0.99999
      -0.00550        0.99998        0.00392

ROTATION ANGLES from _NEW_TRIAL_2 orientation to PRINCIPAL AXES (degrees):
angles about x  y  z  89.775          0.000         -0.315

RADII OF GYRATION with respect to PRINCIPAL AXES:
R1  R2  R3 8.0275149e+01  9.7462054e+01  1.1451772e+02  MM

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Figure 9: TGV properties

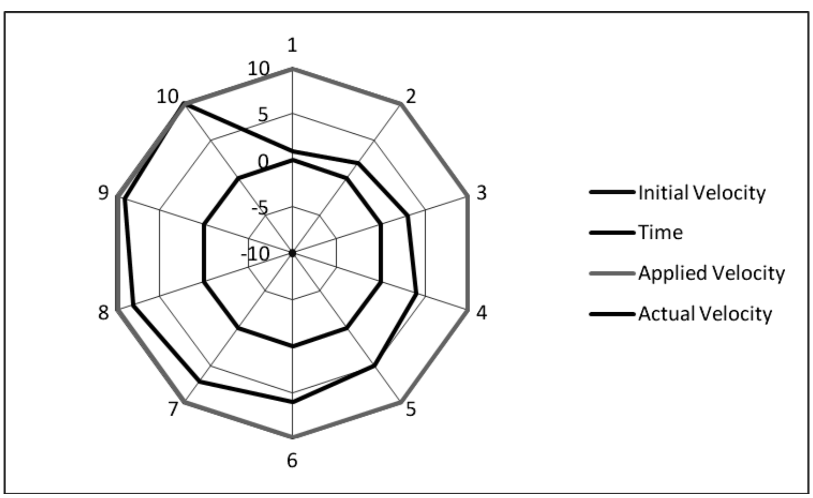

Figure 10: Simulation results

6. CONCLUSION

Window cleaning operation is simplified by means of robotization. Use of already commercially available window cleaning robot is chosen and a guiding vehicle is designed such that it makes the cleaning robot suitable to clean windows of façades and skyscrapers. The TGV is designed considering the wind conditions and rope is chosen as the medium for climbing as they are cheap, easily available and adhere to any building structure. Instead of climbing, a free fall concept is chosen where gravity itself is considered as a suitable actuating parameter and hence the robot operating time is increased. The simulation results show that the actuating velocity is zero and the robot moves with gravitational acceleration in a controlled manner. The TGV is currently semi-autonomous and needs human intervention to control it. Future study is to make the robot completely autonomous and sense the amount of dirt on the windows through Image processing techniques.

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