Can Tho University Journal of Science
website: sj.ctu.edu.vn

DOI: 10.22144/ctu.jen.2017.044

Design a model of glass cleaning device

Nguyen Huynh Anh Duy, Nguyen Van Khanh and Nguyen Chi Ngon
College of Engineering Technology, Can Tho University, Vietnam

Article info.

Received 04 Dec 2016
Revised 28 Apr 2017
Accepted 31 Oct 2017

Keywords

Device, glass cleaning, robot, wall climbing

ABSTRACT

Design and create a supportive automatic device for labors working on cleaning vertical glasses on the skyscrapers has been one of the concerned topic in the issue of occupational safety recently. This study will recover briefly the main points of designing mechanical structure with a new idea after referring the previous works in glass cleaning robot. The trapezoidal velocity profile (TVP) method is mentioned in order to control the velocity of the device; and the movement strategy for cleaning glass is considered carefully while manufacturing the model of the device. The experiment has been conducted on a dirty glass with the size of 1.45m x 0.85m, this proved a good initial result which has met the expected requirement for a low-power device.

Cited as: Duy, N.H.A., Khanh, N.V. and Ngon, N.C., 2017. Design a model of glass cleaning device. Can Tho University Journal of Science. 7: 19-26.

1 INTRODUCTION

In Vietnam, the glass cleaning device or robots have been one of the prevalent topic in automatic aspect and mechatronics. There are several studies, in which many good solutions were examined and have been published. For example, the project of lecturers and students from Lac Hong university has presented: "Industrial robot serves in cleaning glasses for skyscrapers" (Dai Hoc Lac Hong, 2015). The robot has four legs including 12 suction cups with the 3D-size of 700x550x350 mm. The productivity of this device can reach 80m^2/h however due to the heavy weight of 12 Kg, the initial set-up stage of the robot on the glass is complex and the energy consumption is large. Another related product was presented by Nguyen Cong Nguyen and Ho Viet Tuan, students of Danang university of technology, the "*Climbing robot can clean glass for skyscraper*" (Luan, 2015). Similar moving solution of using suction cups, this robot can operate freely through the windows edges.

In other developed countries, the climbing robots were applied and commercialized like Winbot 9 of Ecovas (Ecovacs Robotics) from Germany - one small and low-power gadget using as vacuum machine on the vertical glasses. The idea and design for cleaning glass of Winbot 9 is only good for indoor glasses and the limitation of this product derives from its operational power which only clean the light dirt and there is no use of hygiene liquid or water for hard and dirty dust. In addition, some companies in USA using robots to replace human on cleaning skyscrapers as the fast and safe service for both the clients and the owers, e.g. Scotty - the commercial windows cleaner company - has been implemented the crane-like device to control robot and water pipes by cables hanging on the steel frame. The frame is attached on the top of the building and takes the role of supply energy and material for cleaning glasses on any height. In this paper, the final product has been referred the above concepts in order to design and build a model for cleaning device on the vertical glasses with the targets of simple mechanical structure with popular components which suit the current technology in university laboratory.

The structure of the paper is including 5 sections. Sections 2 describes the mechanical structure of the device including analyzing the vacuum chamber and force calculation. Section 3 illustrates the controller and electronic part, the TVP control technique is discussed. Section 4 describes the experiment and the result. Section 5 concludes the paper.

2 MECHANISM STRUCTURE

As popular concept of a climbing robot, it has moving mechanisms called “legs” with small suction cups. This increases the power consumption and the mechanical structure is also complicated. As observing the labors cleaning on the vertical glasses, the horizontal and vertical moving are two main directions for the solution of cleaning flat surfaces like glasses. Moreover, robots which carry pumps, pipes, and liquids for the cleaning procedure while controlling stability and precise position is a complicated task for the controller and requires high-tech components. This research is aiming to design a simple mechanism in order to reduce pressure on the complicated mechanical parts and expensive electronics devices.

Gravity force of the device when working on the vertical glasses is the most concerning factor. Therefore, the concept of hanging the cleaning device vertically with cable is implemented. This type of mechanism is named crane-like model which can locate precise position of the cleaning parts on the glass.

2.1 Horizontal moving mechanism - crane-like model

The horizontal moving part of the device includes two round slidebars (diameter of Φ12 mm), three pulleys and one DC motor (the gearbox with the ratio of 1:90, the maximum angular velocity at 300 rpm). The motor is attached directly on a chainring (with 12 tooth) which helps the motor moving along the chain. The chain is attached in parallel to the slidebars so as to the pulleys rolling on these bars (Figure 1). For vertical moving solution, one more DC motor with high torque (higher ration from gearbox) attached with the similar chainring to pull the cleaning part of the device as a pulley model.

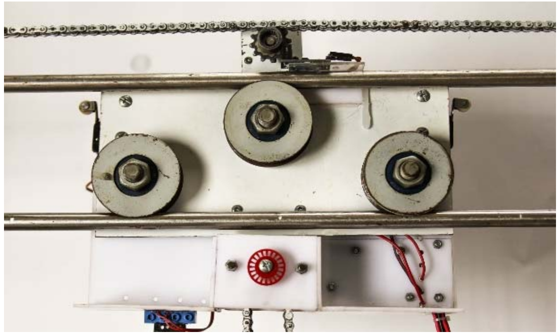

Fig. 1: The mechanical structure for moving

2.2 Cleaning part

This part of the device has the responsibility to control adhesive force and carry water pump to spray hygiene liquid with two rollers for wiping dirt and water on glass. This part is connected to one end of the chain, another end is hanging a weight, the chain moves up and down due to the rotation of the motor on the moving part. The size of this part is 360x280x100 mm with a frame made of metal to create the inertia for the system when moving horizontally. Both ends of the frame are two rollers which are controlled independently by two motors. In the middle, the vacuum chamber takes the role for keeping the constant adhesive force to push the rollers at a proper contact with the glass surface. A 45W vacuum pump is located inside the chamber in order to create the gap of air pressures between the air inside the chamber and the atmosphere. The mechanical design of the moving part has been calculated deliberately in order to make the distance between the chamber to the glass below 10 mm. When the pump operates, the pressure causes the distance decreasing and helps the rollers contacting closer. This increases the friction forces for wiping the dirt easier. There are two reasons for positioning the chamber at the middle of the cleaning part:

- It locates the gravity point being at the middle of the device. This makes the moving control easier and more precise.
- The force from the surface of glass will be systematically delivery on the rollers. This protects the glass and optimizes the cleaning area.

Next section will analyze the pressure drop and forces with several relative calculations to examine the feasibility of the chamber designing for this device.

2.2.1 Vacuum Chamber

Vacuum chamber is designed under the principle of Venturi which illustrated the relationship between pressure and area of the fluid, also the increasing internal of the fluid speed cause the decreasing of the internal pressure. As stated in the Venturi principle, the higher pressure at the smaller area and vice versa. In this project, the chamber is design in a shape of a funnel with the bigger end is at the glass surface side, the smaller end is on the other side.

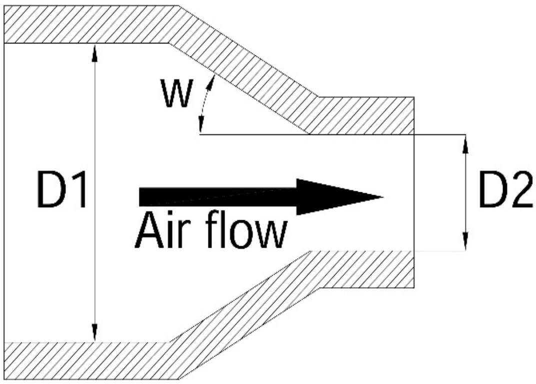

Fig. 2: The vacuum chamber with the shape of funnel

Flow rate measurement:

In order to test the drop of the pressure according to the different flow rates, a sensor is used to measure the volume of air at the output of the chamber in a certain period of time. The flow rate of air going through the chamber at about 1048 L/min (liter/minute) at the maximum power of the pump. This variable dropped to around 550 L/min when the atmosphere pressure is higher than that of inside the chamber. The pressure drop can be calculated from the measured flow rate by the equation of Bernoulli:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2 \quad (1)$$

where:

- p_i: pressure at the area i^{th} (N/m^2)
- ρ: fluid density (kg/m^3)
- v_i: volume of the fluid at area i^{th} (m^3)

During steady state of the vacuum chamber operation, the fluid is assumed as uniformed velocity profile, the continuity equation can be express as (The Engineering Toolbox):

$$q = A_1 v_1 = A_2 v_2 \quad (2)$$

where:

- q: flow rate (m^3/s)
- A_i: area i^{th} (m^2)

From (1) and (2), the equation of pressure drop:

$$q = A_2 . \sqrt{\frac{2(p_1 - p_2)}{\rho[1-(A_2/A_1)^2]}} \quad (3)$$

Equation (3) shows that the change of flow rate proportional to the square root of the pressure difference. Therefore, the flow rate drop leads to decrease of gap of pressures.

Pressure drop calculation:

In order to calculate the pressure drop of the contraction pipe, there is an online tool (Pressure Drop Online Calculator for Mobile and PDA) to examine the properties of fluid in the funnel-like pipe. In this case, the chamber is in the gradual contraction shape which its parameters are presented in Table 1.

Table 1: Specification of vacuum chamber

Diameter of pipe D1	100 mm
Diameter of pipe D2	25 mm
Angle w in degree	55^0
Pipe roughness	0.0015 mm (PVC)
Flow medium	Air
Condition	Gaseous
Volume flow	1100 L/min
Weight density	1.225 Kg/m^3
Dynamic viscosity	$171.4.10^{-6}$ Kg/ms
Pressure (inlet)	~10^5 Pa (1 bar)
Temperature (inlet/outlet)	30^0C

With above necessary parameters, the calculation online tool provides many related information (Figure 3) including the pressure drop of ΔP = 0.08 mbar = 8 N/m^2.

While the area cleaning part is suffered from the atmosphere pressure A = 0.35.0.28 = 0.098 m^2. Attractive force between the cleaning part and the ambient air: F_{att} = ΔP/A= 8/0.098 = 81.63 N. The attractive force is quite big in comparison with the distance between the glass and the vacuum chamber and that is enough to meet the requirement of friction to wipe dirt.

Calculation output

Flow medium:	Air / gaseous
Volume flow:	1100 l/min
Weight density:	1.225 kg/m³
Dynamic Viscosity:	171.4 10-6 kg/ms
Element of pipe:	Gradual contraction
Dimensions of element:	Diameter of pipe D1: 100 mm Diameter of pipe D2: 25 mm Angle w in degree 55
Velocity of flow:	2.33 m/s
Reynolds number:	1668
Velocity of flow 2:	37.35 m/s
Reynolds number 2:	6673
Flow:	laminar
Absolute roughness:	0.0015 mm
Pipe friction number:	
Resistance coefficient:	0.01
Resist.coeff.branching pipe:	-
Press.drop branch.pipe:	-
Pressure drop:	0.08 mbar 0 bar

Fig. 3: The output of calculation from pressure drop calculation online tool

2.2.2 Tensor force and motor torque calculation

As the cleaning part is the most concerning component about forces, the free body diagram with attached forces are illustrated in Figure 4:

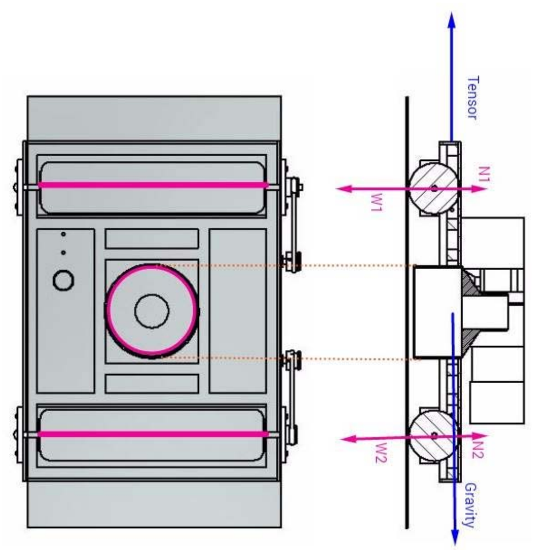

Fig. 4: The free body diagram with forces on the cleaning device

As assume the vacuum chamber as a suction cup, the equation to calculate the tensor force for a suction cup is stated in (AVS group, 2005):

$$F_t = \frac{m}{\mu}.(g + a).S \quad (4)$$

where:

- F_t: tensor force (N)
- m: mass of the cleaning part (Kg)
- μ: coefficient of friction
- (0.2..0.3: wet surface)
- g: gravity acceleration (9.81 m/s²)
- a: acceleration of the cleaning part (m/s²)
- S: safety factor

From the specification in the table 3, the minimum force is calculated from (4):

$$F_{t\_up} = \frac{3.6}{0.25}.(9.81 - \frac{0.055}{25.3}).1 = 141.3N$$

Note: The acceleration rate of the system takes from the values of maximum speed and time for pulling up the cleaning part. The gravity acceleration is also in the opposite direction of the system acceleration. The safety factor is chosen value as S = 1.

The minimum torque of the motor shaft will be:

$$T = F.r \quad (5)$$

where:

- T: torque exerted from the motor shaft (Nm)
- F: tensor force (N)
- r: radius of the motor shaft (m)

The necessary torques of motor to pull and release the cleaning device are calculated from (5):

$$T_{t\_up} = F_{t\_up}.r_{chaincrank} = 141.3.0.012 = 1.695Nm$$

When cleaning part is moving down, the vacuum pump does not operate, the tensor force is also equal to the gravity force:

$$F_{t\_down} = mg = 3.6\ .\ 9.81 = 35.32N$$

$$T_{t\_down} = F_{t\_up}.r_{chaincrank} = 35.32.0.012 = 0.424Nm$$

2.2.3 Pumping and spraying liquid components

On the real model, one low-power hydraulic pump is attached with a small tank (the volume of 0.5 liter) for supplying water in experiment. The pressure of water from the pipes along the rollers is controlled by the speed of the pump. On each pipe, there are small holes (with its diameter below 1mm) for creating pressure to wipe the hard dirt before the rollers take all away from the glass surface. This also benefits to control the amount of water or liquid not to be wasted and to be delivered sufficiently to the glass.

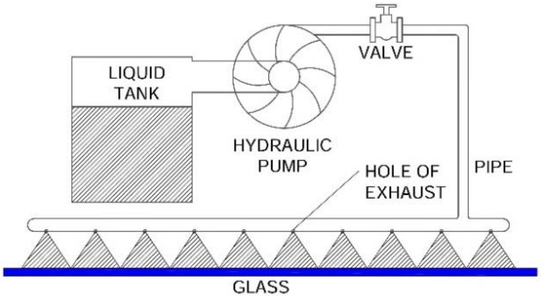

Fig. 5: The design of the pile for spraying liquid

The whole completed mechanical structure with the frame of glass of the device is presented in Figure 9.

3 CONTROLLER

The device is controlled by the Arduino Mega 2560, which receives the signals from sensors (encoders, limited switches and buttons) and calculates PWM values to drive motors and pumps through power circuit boards. In addition, there is one control remote which connects directly to the Arduino board for manual use, this module transmits and receives RF wave under the frequency of 315KHz. The main display on the device is LCD shield board with five buttons for choosing programs as well as testing functions of the system. The whole electronic part is attached on the sliding rail of the model (Figure 6).

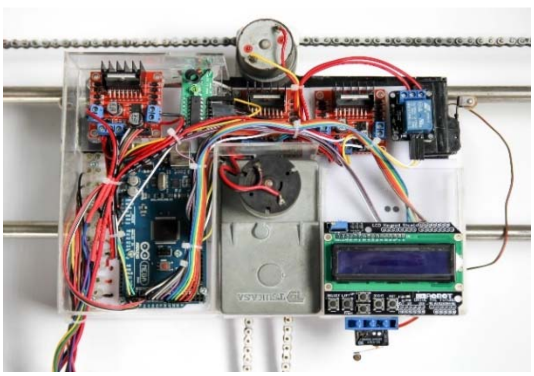

Fig. 6: Electronic controller of the device

3.1 Trapezoidal Velocity Profile (TVP) control technique for the speed of motion

The operational area of the device is only on the glass surface. Therefore, the trajectory of the system is somehow similar to a 2D CNC machine (only on horizontal and vertical motion). For optimizing the speed and position of the system, the control algorithm takes the vital role. The issue of avoiding collision or scratches on the glass is also relied on this important element.

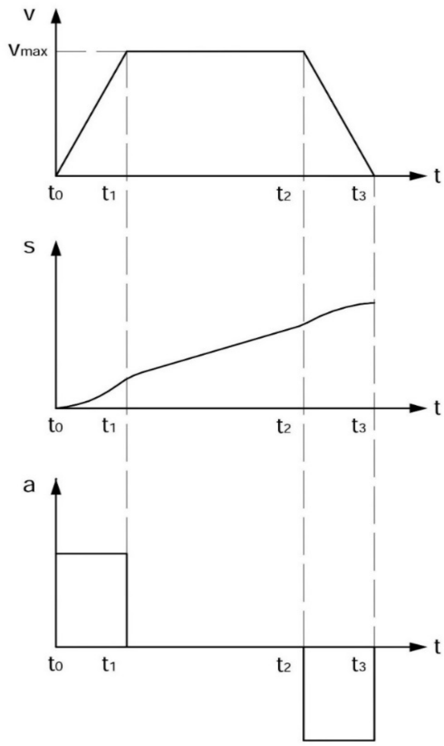

Fig. 7: The TVP profile for velocity, distance and acceleration

The TVP control technique is implemented popularly in industry, especially for the high inertia systems. The presentation for this method with the profile of velocity in trapezoidal shape (Figure 7). Moreover, the distance and acceleration diagram are also depicted in the same figure.

The variables for speed, distance and acceleration are considered into three phases: speed up to maximum, steady at max speed and speed down to stop as mentioned in the table 2.

Table 2: Variable calculation in TVP technique

	Velocity	Distance	Acceleration	Equation
t0 → t1 (*speed up*)	$v_1 = K(t_1 - t_0)$	$s_1 = \int_{t_0}^{t_1} K.tdt = K\frac{(t_1-t_0)^2}{2}$	$a_1 = \frac{d}{dt}K.t = K$	(6) – (8)
t1 → t2 (*steady*)	$v_2 = v_{\max}$	$s_2 = \int_{t_1}^{t_2} v_{\max}dt = v_{\max}(t_2 - t_1)$	$a_2 = \frac{d}{dt}v_{\max} = 0$	(9) – (11)
t2 → t3 (*speed down*)	$v_3 = -K(t_3 - t_2)$	$s_3 = -\int_{t_2}^{t_3} K.tdt = -K\frac{(t_3-t_2)^2}{2}$	$a_3 = -\frac{d}{dt}K.t = -K$	(12) – (14)

The frame of glass has the size of 1.45m x 0.85m for the experiment. In order to control the cleaning part moving on the distance of x-direction (horizontal move) is 0.85 – 0.28 = 0.57 m, and of y-direction (vertical move) is 1.45 - 0.36 =1.090 m. For a detail explanation of how TVP implemented in this model, the total number of links for chain is 90 for the whole length of the x-motion. The chain crank on the motor shaft has 12 teeth. Consequently, the motor shaft has to revolute 7.5 rounds (90/12=7.5) and the maximum speed of the rotor is v_{max} = 56 rpm. We can calculate the controlled variables from v_0 = 0 rpm to v_{max} = 56 rpm.

$$a = \frac{v_{\max}}{t} = \left(56\frac{round}{\min}.\frac{1}{t}\right) = \frac{14}{15t}\left(\frac{round}{s^2}\right)$$

$$s = a.\frac{t^2}{2} = \frac{14}{15t}.\frac{t^2}{2} = \frac{7}{15}t\left(round\right)$$

- the value of s is equivalent to half of rotor revolution or 6.t links of chain (t is amount of time for acceleration).

From the equations above, each motor requires appropriate range value of t. If the value of t is chosen quite large e.g. t = 10 (s), the device will operate slowly and unproductivity. Inversely, the system will be jerked with the small period of time t. In this case, the maximum value of t should be chosen not over the time for acceleration with the isosceles triangle profile of velocity (Figure 8):

$$t = \frac{s}{v_{\max}} = \frac{45}{56}.\frac{1}{rpm}$$

$$= \frac{45}{56}.\frac{round}{12}.\frac{60s}{round} = 4.018s$$

For optimal control of all variables, time to accelerate should be below 4 seconds. For the physical model, the time to complete the whole horizontal move is at most 8s.

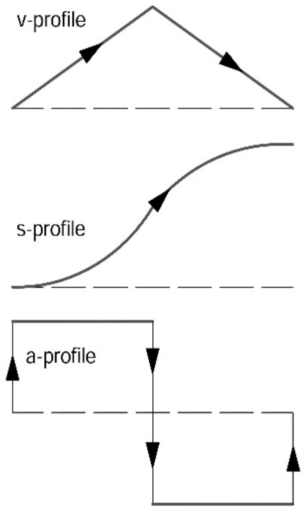

Fig. 8: The isosceles triangle profile of velocity, distance and acceleration

Table 3: Specification of device

Motors	Moving motors (GR37) x1, (TG-85E) x1 Roller motors x2
Pumps	Hydraulic pump x1 Vacuum pump x1
Sensors	Limit switches x4 Encoders (12 pulses) x2 Flow rate x1
Dimensions	360x280x100mm
Weight	3.6kg
Max speed	x-direction: 0.13m/s y-direction: 0.055m/s (up) – 0.087m/s (down)

Due to the symmetry of the TVP profile, the deceleration part is similar to the first one. At the middle state, the system will operate steadily at the maximum speed. For the vertical move (y-direction), the TVP also be implemented as above-mentioned analyze.

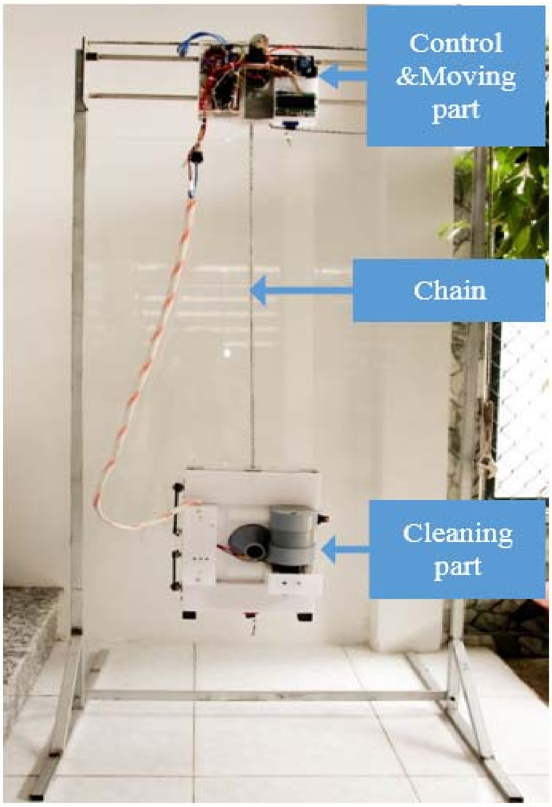

Fig. 9: The frame of glass with the device for experiment

4 EXPERIMENT AND RESULTS

The model is experiment on a vertical glass with the size of frame: 1.45mx0.85m. The dirt of glass is simulated by the white powder for easier visualization as being shown in Figure 10.

The trajectory of motion is described in Figure 11. At any position, the device is programmed to return automatically to the started position at the left top comer of the glass for waiting the command of cleaning operation.

The cleaning operation includes subsequent steps as follows. At the first step (wet route), the cleaning part is moving down and the water pump system starts to spray liquid or water on the glass for softening or dropping out the hard dirt. Next, the device changes the direction of move, the water pump stops and the vacuum pump begins to run for increasing adhesive force between the glass surface and the rollers. The rollers also operate with different rotational directions. The first roller has the responsibility to remove dirt; the second one will absorb the water in order to make glass clean and dry. When the cleaning part reach the upper edge of the glass (recognized by limited switches attached on the top and bottom of the cleaning part), the device moves to the right with the distance of 280 mm (also the width of the cleaning part). Then, this will continue the wet and dry routes as the last stage.

Fig. 10: The white dirt on glass for experiment

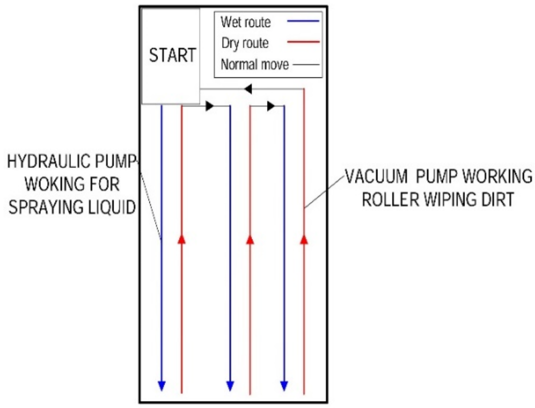

Fig. 11: The trajectory of motion of the device on the experiment frame

Table 4 presents the measured values for velocities of the cleaning part for both up and down directions, the horizontal velocity of the horizontal moving mechanism as well as the average time of motion for each variable. The experiment conducted six times to examine the stability of the system. The average values of up and down speed are 0.55 and 0.088 m/s respectively and there is small variation of those speeds, while the device moves with relatively 0.125 m/s on the horizontal motion. The total time for finishing cleaning all the glass frame (1.45 m x 0.85 m) is about 137 seconds or 2 minutes 16 seconds for the area of 1.23 m^2.

Table 4: Experiment statistic table for speed and time of motion of the device

Time	Vertical Speed (Up) (m/s)	Average time (s)	Vertical Speed (Down) (m/s)	Average time (s)	Horizontal Speed (m/s)	Average time (s)
1	0.0553	25.3	0.0882	16.1	0.132	6.5
2	0.0541		0.0877		0.127	
3	0.0561		0.0880		0.123	
4	0.0551		0.0866		0.123	
5	0.0582		0.0881		0.130	
6	0.0563		0.0883		0.125	

After all stages, the experiment results show that the research objective is satisfied (cleaning all dirt and water completely - Figure 12). The mechanical and control systems work stably and compatibly with each other.

Fig. 12: The final stage of cleaning

5 CONCLUSIONS

The real model of the glass cleaning device has been completed as the design and simulation. All the functions of separated parts and the whole system are examined and verified on the glass frame with real condition of dirt. The experiment result has shown the feasibility of the concept which applied the simple TVP control method for moving on the wet and vertical glass in comparison with robots with legs and multiple small suction cups. One highlight for this model is the vacuum chamber that generates adhere force to increase the friction of the rollers with glass for wiping dirt and water efficiently. However, there are many conditions which should be concerned in the future including: the cleaning practice with different kinds of dirt, the influence of ambient disturbances (wind, temperature, optimized speed), the experiment on higher and larger area of glass and so all. This model can be the fundamental platform to develop similar kinds of robot which provide to university students the means of research and applied knowledge as well as practical applications.

REFERENCES

AVS group, 2005. Example of Vacuum calculation, accessed on 12 September 2016. Available from www.avs-yhtiot.fi/sites/default/files/pdf/7.01.05_alipaine_ohje.pdf.

Dai Hoc Lac Hong, 2015. Cleaning glass for skyscrapers by…robot, accessed on 05 July 2016. Available from https://lhu.edu.vn/407/202/.

Ecovacs Robotics, WINBOT 930 – The window cleaning robot, accessed on 03 July 2016. Available from http://www.ecovacs.co.uk/window-cleaning-robots/winbot-9/.

Engineering Toolbox, Orifice, Nozzle and Venturi Flow Rate Meters, accessed on 07 September 2016. Available from http://www.engineeringtoolbox.com/orifice-nozzle-venturi-d_590.html.

Miyake, T., Ishihara, H., Shoji, R., and Yoshida, S., 2006. Development of small-size window cleaning robot by wall climbing mechanism. In Proceedings of the 23rd International Symposium on Automation and Robotics in Construction, pp. 215-220.

Nishi, A., 1996. Development of wall-climbing robots. Computers & Electrical Engineering. 22(2): 123-149.

Pressure Drop Online Calculator for Mobile and PDA, accessed on 07 September 2016. Available from http://www.pressure-drop.mobi/0304.html.

Van Luan, 2015. Create the wall climbing robot for skyscrapers, accessed on 03 July 2016. Available from http://cand.com.vn/Kham-pha-Chuyen-la/Sang-tao-robot-leo-tuong-lau-kinh-tu-dong-cho-nha-cao-tang-364277/.

Zhang, H., Zhang, J., and Zong, G., 2004, August. Requirements of glass cleaning and development of climbing robot systems. In Intelligent Mechatronics and Automation, 2004. Proceedings. 2004 International Conference on., IEEE., pp. 101-106.