Force Control of Cleaning Tool System for Building Wall Maintenance Robot on Built-in Guide Rail

C.Y. Shin[1], S.M. Moon[1], J.H. Kwon[1], J. Huh[1] and D. Hong[2]

[1]Graduate School of Mechanical Engineering, Korea University, Korea
[2]School of Mechanical Engineering, Korea University, Korea
E-mail: dhhong@korea.ac.kr

Abstract -

In modern days, there has been an increasing trend to build high-rise buildings. Until now, the methods to maintain building wall have relied on human efforts. However, there exist dangers and difficulties caused by height of buildings. Due to this problem, the need for system that can maintain building wall has been increasing and various systems have been developed. On this, the building maintenance robot that is used for built-in guide rail and tool system for cleaning wall of building was developed. Cleaning tool system equipped to building maintenance robot system has squeezing and injection functions. This system operates with spreading the water through injection part and eliminating dust and contaminants using squeezing module. Throughout this process, flow control is needed to spread water evenly on window at the changing velocity of robot. Also, the angle of the squeezing module and the force which is applied to window should be controlled to prevent damage of wall and to remove contaminants completely. This paper suggests algorithms for control of position and force of the squeezing module to implement cleaning building window composed of segmented façade. In addition, flow control algorithm for uniform injection is proposed. After that, the results of experiment in consistent robot velocity and transition of squeezer angle were shown and analyzed.

Keywords –
Force control; Flow control; Building maintenance robot; Façade cleaning

1 Introduction

As the advent of high-rise buildings, managing building wall using conventional methods with human efforts become dangerous and cost. To resolve this, robotic systems for maintaining building wall have been developed [1-4]. One of them is based on built-in guide rail [1]. This system follows the rail horizontally which is already installed in buildings and implements the work. After finishing the work in one floor, it moves to other floor by vertical robot which moves via wire winch system. When robot conducts cleaning process during moving horizontally, it needs tool system for removing contaminants efficiently. Most of the wall of buildings constructed today are made up of windows. Thus, previously developed tool system uses brush and water to clean. However, this method could not remove water perfectly by brush and there remains stain of water in window. To overcome this problem, water and squeezing rubber are used to clean window in this tool system. It is composed of the injection part and the squeezing part. Injection part sprays the water evenly on the wall and squeezing part removes contaminants and water by contacting to wall. During the process, algorithm for flow control of water injection and force control of squeezing part are used.

This paper introduces the structure of tool system and applied algorithms covering flow control, position and force control of squeezing part. Experiment in the interior parallel façade with consistent horizontal robot velocity and specific contact angles between squeezing part and façade is presented and results are shown with graph and analyzed.

2 Injection Part

2.1 Structure

Injection part has 4 PWM nozzles, a water pump, an air tank, and an air compressor. Figure [1] shows the installation of nozzles on robot and magnified picture of a nozzle with tubes connected to air compressor and water pump. Water pump provides water to nozzles through water filter and pressure of water is measured using water pressure gauge. Air compressor injects compressed air to air tank and compressed air is delivered to nozzle when it satisfies the desired air pressure. By using these water and compressed air, injection part spreads out water evenly on the wall based on two-fluid spray process [5].

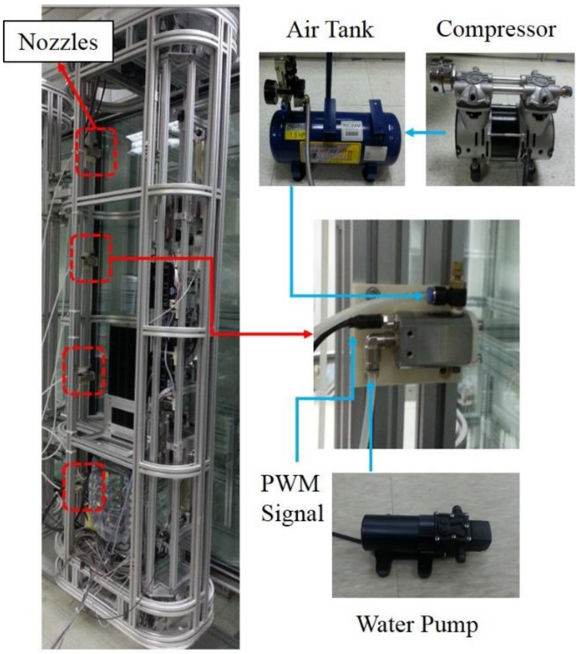


Figure 1. Structure of Injection Part

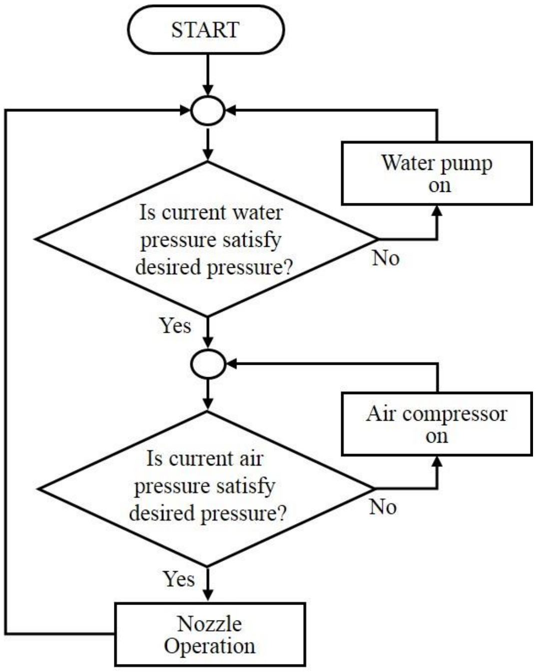


Figure 2. Flow Control Algorithm

2.2 Flow Control Algorithm

Flow control algorithm is presented in Figure [2]. Before operation of injection, pressure of air and water which are used in nozzle needs to be maintained at desired pressure. After process of pressure maintaining, injection should be controlled according to robot's horizontal moving speed. There can exist water overlap region if injection speed is high comparing with robot velocity or dry region on vice versa. Efficiency of cleaning process would be diminished in those cases. Also, water would be wasted and it could not implement cleaning process to wide area because of the lack of water. Thus, by getting robot horizontal speed as input, nozzle regulates the speed of injection.

$$\text{Injection Speed} \propto \text{Frequency} \tag{1}$$

$$\text{Duty ratio} = \frac{T_{ON}}{T_{ON}+T_{OFF}} \tag{2}$$

$$\text{Water Amount} \propto \text{Duty ratio} \tag{3}$$

Frequency of injection and amount of water during one injection period can be handled through PWM signal of nozzle. Figure [3] shows PWM signal of nozzle in one second. Nozzle spreads water during ON-period. Thus, injection frequency is changed with signal frequency, and amount of water used in one cycle relates with time ratio of ON respect to one cycle. Based on this, amount of water used in cleaning process can be minimized and injection frequency is controlled.

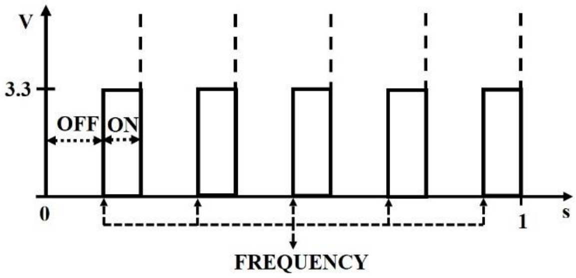


Figure 3. PWM Signal of Injection

3 Squeezing Part

3.1 Structure

Squeezing part is separated into upper and lower parts. Structure of them are equivalent, and it is divided for covering the specific area of wall, which is split, by controlling differently. Each part consists of two motors, a screw structure, 4 load-cells, 3 switch sensors, and 2 squeezing modules. One of motor, named as pressing motor in Figure [4] takes charge of moving forward to wall and pressing force. Another motor named as angle motor rotates the squeezing modules and changes the contact angle between squeezing module and wall. As it can be seen from figure, pressing motor is linked to a screw and this changes the rotating movement of motor to linear movement of squeezing module. Rubber is

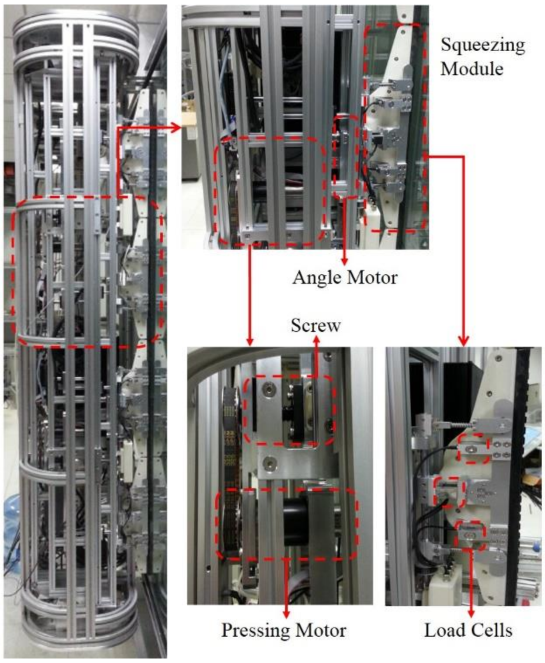


Figure 4. Structure of Squeezing Part

placed on the edge of module to remove water and contaminants. Among four load-cells, two of them are installed in linkage between screw and squeezing module to measure the pressing force which is Fy in the Figure [5] and others are placed between the rotate joint and squeezing module to measure the friction force Fx occurred in the wall. Three of switch sensors are located at each of the beginning and last position of the screw and initialization position of squeezing module. These switches are used for position initialization of squeezing part when it starts and getting reference point during operation.

3.2 Position and Force Control

When cleaning the wall, the angle between the rubber and the wall should be maintained for efficient performance. Also, consistent and sufficient force should be applied to window. It leads to enough friction force to remove contaminants. Contact angle is sustained by position control of angle motor and force applied to wall is controlled by pressing motor using force control. Force control is categorized into impedance control and hybrid control. Predetermined relationship of end-effector force and position is maintained in the impedance control [6]. Explicit and implicit control are used in hybrid control with respect to model. Explicit control needs well analyzed model and applies motor torque directly [7]. Implicit control uses velocity and position of robot without exact model [8]. On the other view, whether reacting to force sensor

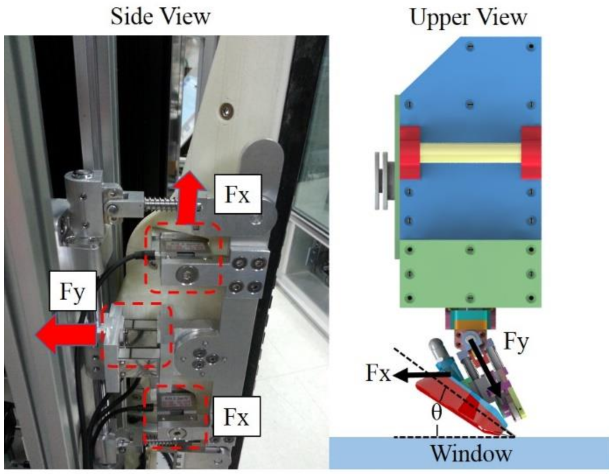


Figure 5. Load cell measurement direction

directly (active compliance) or not (passive compliance) is also issue [9]. This paper uses implicit force control based on velocity and active compliance using force sensor input. Reasons for selecting implicit force control are that model is not needed and approach velocity is limited during no contact and well performance of regulating force during contact. Approach velocity is determined by equation (4). Velocity is proportionate to error between desired force (F_D) and current force sensing data (F_s). Coefficient (K_c) is determined by empirical method in this paper. Environment is assumed as rigid because it is composed of fa çades.

$$\mathrm{v} = K_c * (F_D - F_s) \tag{4}$$

3.3 Control Algorithm

Control algorithm of squeezer module is separated into initialization mode, contact moving mode, force control mode. As shown in Figure [6], in the initialization mode, controller moves the squeezing module to initial point and using that point as reference when controlling position. When controller finds the initial point, it uses switch sensors. At the starting point, if bottom limit switch is pushed, it moves forward until bottom limit switch is off. In the case limit switch is not pushed, it operates with opposite process. These processes locate the robot to edge of limit switch. After that, angle of squeezing module rotates to point where module pushes the limit switch of rotating movement. Before the beginning of force control, difference between desired force and applied force is large because there is space between squeezing module and wall. This space leads to not sufficient contact force. If robot moves horizontally during this situation, area which is covered during start of cleaning will not be cleaned. To

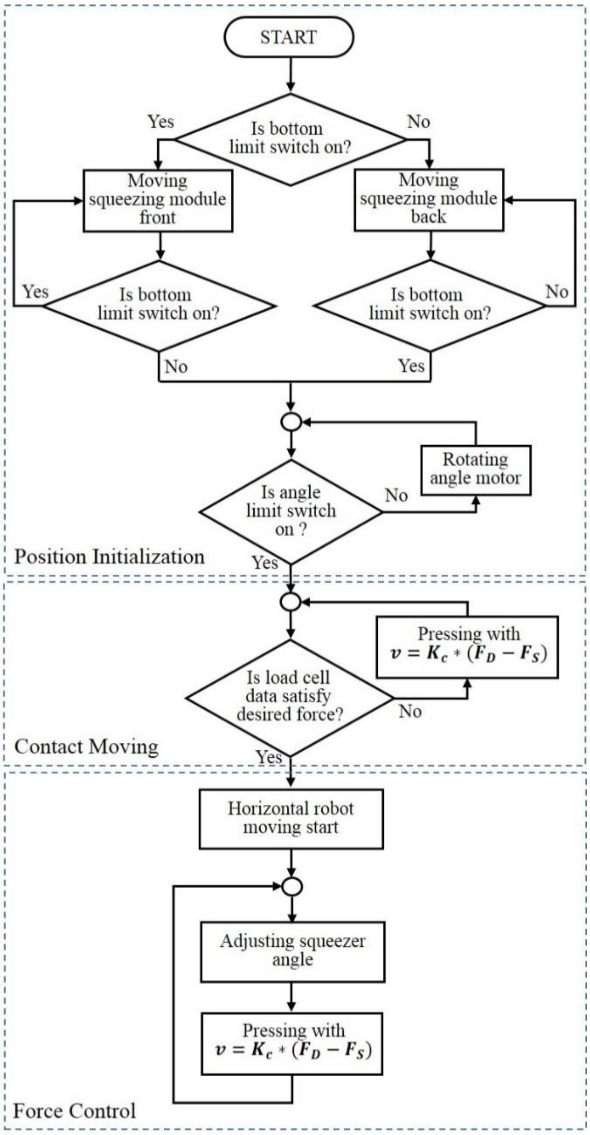


Figure 6. Control Algorithm of Squeezer Module

prevent this, at the beginning, robot waits until desired contact force in the contact moving mode. Next to these processes, controller gets force data from load cells and compares it with desired force. If there is difference, apply the velocity calculated by equation (4) to regulate contact force. This process is repeated until robot reaches the end point.

4 Experiment

4.1 Environment

Experiment environment is shown in Figure [7]. There are 4 fa çades which are 1.8m height and 1.2m width. Two built-in guide rails are placed on top and

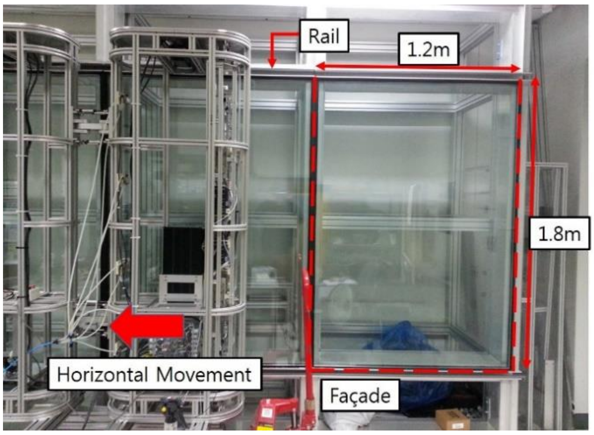
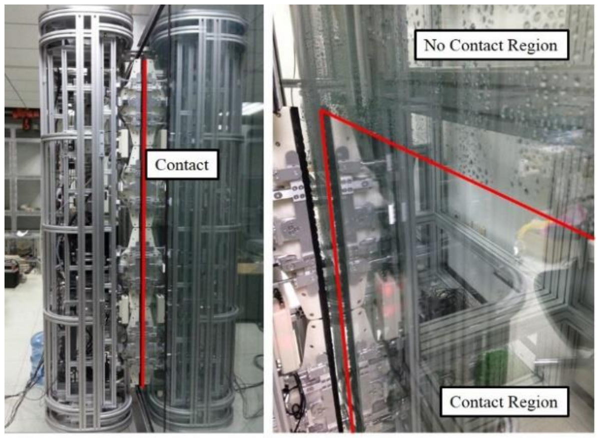


Figure 7. Experiment Environment



During process After process

Figure 8. Experiment Process

bottom of facades. Wheels of robot is fixed to facades and robot moves horizontally with rotating wheels on the top. Horizontal velocity of robot was fixed to 5cm/s and contact was maintained on one fa çade.

4.2 Experiment Strategy

In this experiment, consistent y-axis force which is 2kgf was applied with two angles of squeezing module. Coefficient of equation (4) was 1.25mm/s/kgf. Angles were adjusted to make contact angle between rubber and fa çade 35, 45degrees. Data from load cells were recorded to get the information about friction force and contact force applied to wall. Linear velocity of squeezing module was also recorded to judge how force control algorithm works. Sampling period of data was 120milli seconds. Left picture of Figure [8] shows the process of experiment and right picture presents the difference between contact area and no contact area

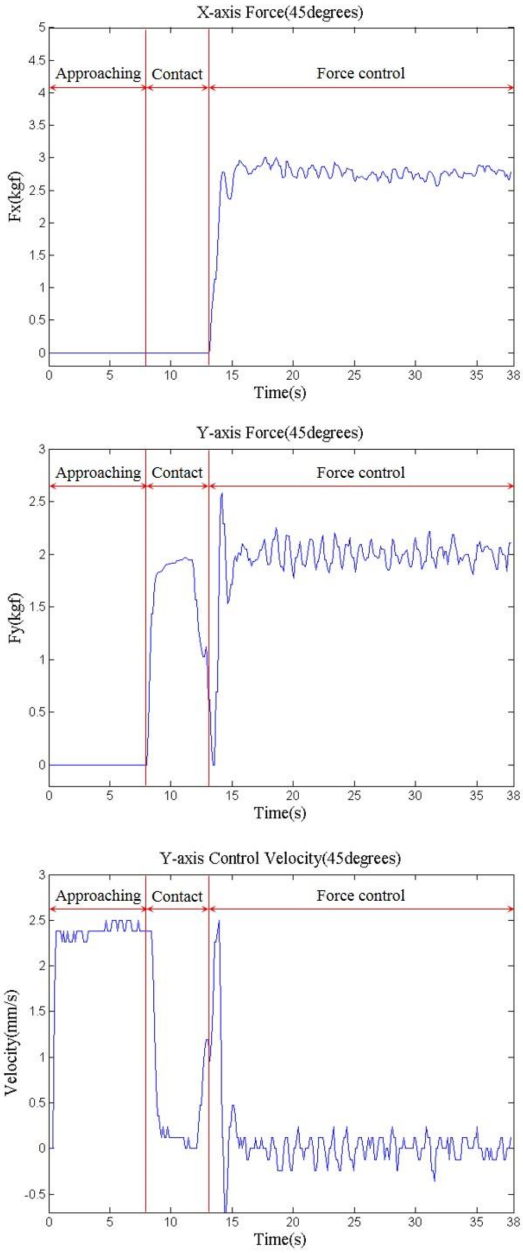


Figure 9. Experiment Results when 45degrees

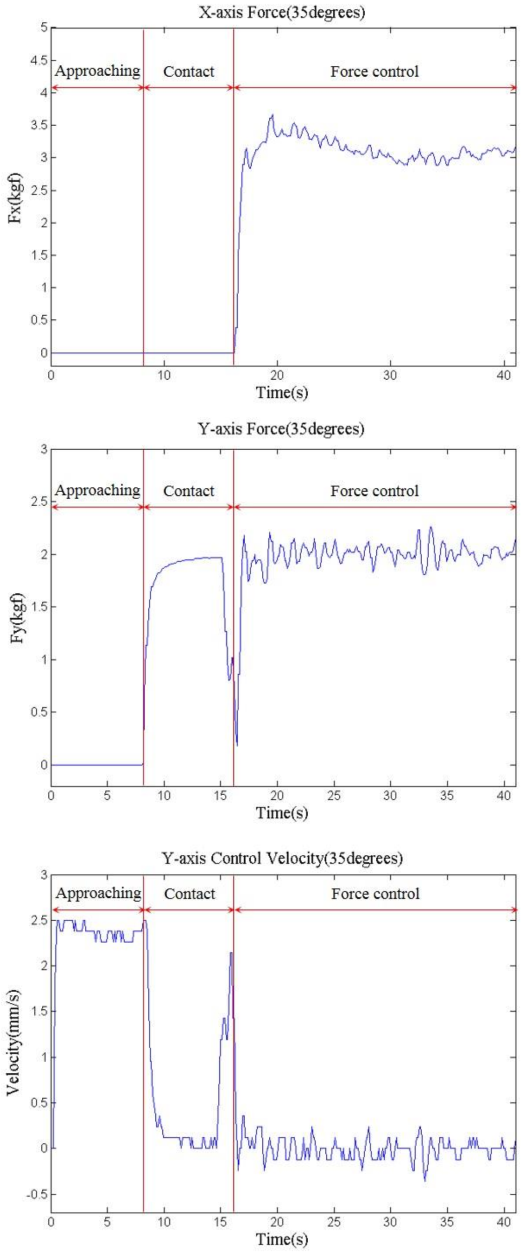


Figure 10. Experiment Results when 35degrees

after process. It can be seen that water was removed well by contact of module.

4.3 Results

Figure [9] presents experiment result data when the contact angle is 45degrees. Sections are separated into three which are approaching, contact, and force control. During the approaching section, squeezing module approaches to façade with limited velocity 2.5mm/s and there is no contact force. After that, contact begins in contact section and y-axis force increases. Horizontal robot does not move in these two sections according to algorithm because there is not enough contact. When y-axis force satisfies 2kgf, robot moves to horizontally and this is the beginning of force control. With slight oscillation, force regulation is well performed for 24 seconds in force control section. However, there is steep decrease of y-axis force at the start of horizontal moving. The reason for this is that friction force pushes squeezing module and it leads to sudden contact angle change. Temporary angle change structurally makes the loss of contact. After contact loss, it can be seen from the data that angle modification and force control algorithm restore the contact force. Average of x-axis force is 2.78kgf. Figure [10] shows the data when contact angle is 35degrees. Flow of force data is similar with 35degrees. There is also steep decrease when robot starts to move horizontally. Y-axis force is well regulated to 2kgf during force control section. However, x-axis force is different with that of 45degrees. Average x-axis force is 3.14kgf and it is higher than that of 45degrees. It is because contact area of rubber and façade increases when angle becomes smaller. Increase of contact area leads to more friction force and x-axis data shows relationship with the friction force and contact angle. This system has independent energy sources. Thus, energy conservation is important to operate longer time. In this respect, 45degrees contact angle has better energy efficiency about 11.5% than 35degrees because that amount of torque is more needed to withstand friction force in 35degrees and results of both cleaning processes are well done which can be seen in Figure [8].

5 Conclusion

This paper deals with structure of tool system of building maintenance, flow control algorithm of water injection and velocity based force control algorithm to control that. Experiment of force control and results are shown and analyzed. Results show that velocity based force control well performs the force regulation between squeezing module and façade. This study will contribute to development of cleaning system of wall with contact.

Further study is convergence control of tool system when robot moves with variable horizontal velocity and irregular surface. Improvement of force control algorithm to solve the steep decrease of contact problem when robot starts to move horizontally will also be studied.

Acknowledgment

The work presented in this paper was funded by BMRC(Building-Façade Maintenance Robot Research Center), supported by Korea Agency for Infrastructure Technology Advancement(KAIA) under the Ministry of Land, Infrastructure and Transport(MOLIT).

This work was supported by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20124010203250)

References

[1] Moon, S.M., Hong, D., Kim, S. W. and Park, S. Building Wall Maintenance Robot based on Built-in Guide Rail. In *Proceedings of the 2012 IEEE International Conference on Industrial Technology*, pages 509-514, Athens, Greece, 2012.

[2] Zhang, H., Zhang, J., Wang, W., Liu, R. and Zong, G. A series of pneumatic glass-wall cleaning robots for high-rise buildings, *Industrial Robot: An International Journal*, 34(2):150 – 160, 2007.

[3] Elkmann, N., Kunst, D., Krueger, T., Lucke, M., Böhme, T., Felsch, T. and Stürze, T. SIRIUSc—Façade cleaning robot for a high-rise building in munich, germany. *Springer Berlin Heidelberg, In Climbing and Walking Robots*:1033-1040, 2005.

[4] Qian, Z.Y., Zhao, Y.Z., Fu, Z. and Cao, Q.X. Design and realization of a non-actuated glass-curtain wall-cleaning robot prototype with dual suction cups. *The International Journal of Advanced Manufacturing Technology*, 30(1-2):147-155, 2006.

[5] Hede, PD., Bach, P. and Jensen, AD. Two-fluid spray atomisation and pneumatic nozzles for fluid bed coating/agglomeration purposes: A review. *Chemical Engineering Science*, 3821-3842, 2008.

[6] Hogan, N. Impedance control: An approach to manipulation: Part III-applications. *Journal of Dynamic Systems, Measurement, and Control*, 107(2), 17-24, 1985.

[7] Yoshikawa, T. Dynamic hybrid position/force control of robot manipulators-description of hand constraints and calculation of joint driving force. *IEEE Journal of Robotics and Automation*, 3(5), 386-392, 1987.

[8] Roy, J. and Whitcomb, LL. Adaptive force control of position/velocity controlled robots: theory and experiment. *Transactions on Robotics and Automation*, 18(2), 121-137, 2002.

[9] De Schutter, J. and Van Brussel, H. Compliant robot motion II. A Control approach based on external control loops. *The International Journal of Robotics Research*, 7(4), 18-33, 1988.