Force Control of a Duct Cleaning Robot Brush using a Compliance Device

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Abstract: Conserving clean air and removing contaminants and particular matters accumulated in the ventilation system of the subway stations are key issue for high air quality and green environment. Accumulated various pollutants at inner duct surface can cause secondary air contamination and injure subway passengers' respiratory system and health. In fact, periodic duct cleaning works can improve indoor air quality, but cleaning entire ventilation system takes high cost and manpower. This study proposes a newly developed duct cleaning robot to provide autonomous air duct cleaning. In addition, effective cleaning method with an automated robot device is developed. In particular, the new duct cleaning robot has functionality that cleans four sides of inner duct surface simultaneously with a constant pressure by using a force compliance brush. Control method with the compliant device has also been analysed. The proposed design of autonomous duct cleaning robot is expected to save the operating cost of subway ventilation system and sustain clean indoor air quality by providing easier and faster cleaning tools.

1 INTRODUCTION

The main purpose of the ventilation system and air duct is to supply fresh air into closed spaces such as buildings and subway stations where people work and spend most of their daily hours. The air duct and ventilation system controls various air flows, i.e., outdoor air, supply air, return air, and exhaust air as depicted in Figure 1. The ventilation system also consists of mechanical components such as dampers, fans, filters, and duct terminals. Various particulate matters are initially filtrated with particle filters installed at the side of the supply air duct. The filters commonly used, however, are insufficient to prevent the entrance of all the particulate matters from outdoor air into the duct. Therefore, transported dust and other impurities are accumulated at the duct surface inside the ventilation system. Accumulated dust inside air duct may also originate from the facility construction phase or from ventilation duct installation (Pasanen, 1998).

To provide fresh and clean supply air through the ventilation system into the closed space such as subway stations, eliminating source for the pollutants and contaminants is the most cost effective than cleaning and replacement of the air duct. However, duct cleaning is essential for maintenance after completion of the ventilation system installation. Many countries have existing regulation and guideline for ventilation system cleaning intervals and specific guidelines of ventilation system cleanliness (FiSIAQ, 2001). A few countries do not still provide legal regulation, which makes air quality from the ventilation system severely contaminated.

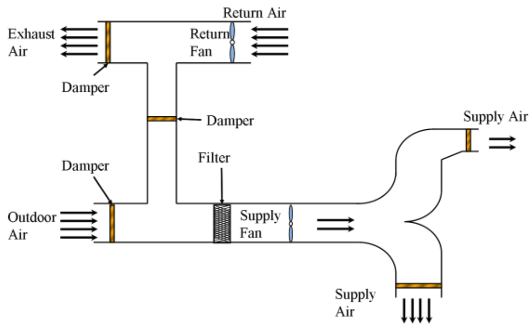

Figure 1: Air duct and ventilation System.

In this paper, various duct cleaning technologies are introduced and types of contaminants are analysed. Based on the mechanical brushing technology, a new autonomous air duct cleaning

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robot has been designed to improve the cleaning efficiency and overcome restrictions of manual duct cleaning. In particular, in order to control constant brush pressure on the duct surface, a simple force compliance device is designed and installed at the brushing arm, which enables consistent cleaning operation despite of irregular duct surface quality.

2 CLEANING TECHNOLOGY

The ventilation system can be contaminated and acted as another source of pollutants, such as microbe, chemical compounds or odours, particulate matters. Accumulated dust and particulate matters inside duct can stick to the inner surface of duct and scatter by air stream of the air duct. Several cleaning technologies can be used to remove the dust and other contaminants effectively from the duct surface.

2.1 Contaminants in Duct

The estimated annual accumulation rate for dust in commercial supply air ducting is normally set at $1 g/m^2$. However, an average accumulation level in supply air ducts of building occupied less than a year was $5.1 g/m^2$ (Pasanen, 1998) while dust level in new constructions was measured as high as $4.9 g/m^2$ (Holopainen et al., 2002). In general, if dust accumulation on an inner duct surface exceeds $2g\sim5g/m^2$ upon the class of ventilation system the duct has to be cleaned. Amount of dust accumulated inside duct is related to the types of facility, complexity of duct and its components and age of building. In addition, dust concentration is affected by factors that interrupt air flow of duct such as surface roughness, air velocity, humidity, number of dampers and diffusers installed.

Accumulation of dust also provides suitable conditions that microbes, bacteria and other microorganism can propagate. In fact, it has been reported that 400 times of penicillium and 9.5 times of aspergillus exists within 1 micro particulate matter (Morey, 1988). In addition, amount of fungi in contaminated indoor air is 10 times higher than that of outdoor air. Many other particulate matters accumulated at a duct terminal may cause secondary infection or contamination of indoor air through the air supply duct.

2.2 Cleaning Technologies

The air duct cleaning methods can be either dry or wet (HVCA, 1998). The most commonly used dry duct cleaning methods are mechanical brushing, compressed air cleaning and vacuuming. Dry cleaning methods use a rotating brush, a powerful air jet or a suction force to detach the dust from the duct surface mechanically. The loose dust is carried out of duct by airflow. Wet cleaning methods include water jet or chemically sterilizing process to eliminate microorganism and bacteria. However, wet cleaning methods are seldom used to clean air ducts because the ductworks are not normally watertight. To remove accumulated dust and oil in duct, mechanical brushing is faster and more effective than compressed air cleaning. Cleaning methods are summarized in Table 1.

Table 1: Summary of duct cleaning techniques.

Cleaning Techniques		Description
Dry method	Mechanical brushing	A brushing or mechanical action is used to dislocate dust from surfaces and transferred to a vacuum collector. The most commonly used is the rotating brushes.
	Compressed air cleaning	Dust is dislodged from surfaces using airflow movement (via air nozzle) and collected using a vacuum collector.
	Vacuuming	Suction and brushing using a brush head to transfer dirt to a collection point.
Wet method	Hand washing	Cleaning components surfaces by hand using tools such as brushes, sponges and a source of water with a cleaning agent.
	Water jet spray	Liquid solutions are sprayed or wet-fogged to adhere, bond, or fibre- fixed particles that were not removed mechanically.
	Chemical disinfection	The use of biocides and sealants to coat and encapsulate duct surfaces. Some duct cleaning contractors introduce ozone as part of the disinfection process.

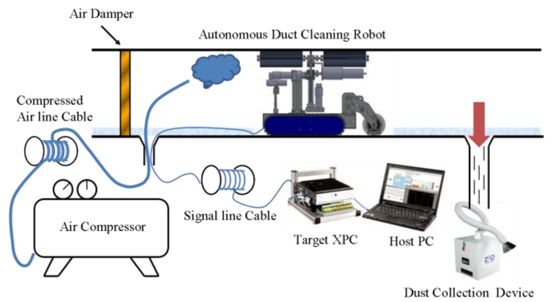

Figure 2: Duct cleaning with mechanical brushing and robot.

In this study, we have focused on mechanical brushing method with autonomous cleaning robot to improve cleaning efficiency for all types of contaminants. As illustrated in Figure 2, the air duct cleaning robot system also utilizes the push-pull technique; the rotating brush removes dust and debris from the inner surface of the duct. The dust is then drawn into a negative collector. Compressed air is often used to push the dust and debris.

3 DESIGN OF A DUCT CLEANING ROBOT

Increased interests in air duct cleaning technology stimulate development of various duct cleaning robots. Most of duct cleaning robots is based on the dry cleaning method with mechanical brush.

As an example, the Articulated Nimble Adaptable Trunk (ANAT) robot has been developed to clean and inspect HVAC ducts. The ANATROLLER ARI-100 duct cleaning robot rolls on tracks or wheels and will continue to operate even if flipped upside down. It is composed of two modules containing the air jet, lighting and camera rotates through 180 degrees, which allows the robot to change its shape to get around or over obstacles (Robotics Design Group). However, the ARI-100 still needs manpower to operate.

The XPW-series duct cleaning robot is of height adjustable rotary brush and rotating camera for inspection and remote control. Its rotary brush mounted at machine bed is oscillatable within a prescribed angle range in a vertical direction (Hanlim Mechatronics Co. Ltd.).

Recently developed cleaning robots can be fitted with spinning brushes, directional air nozzles and whips, sampling devices, and spraying attachments for spraying sanitizing solutions for various coatings.

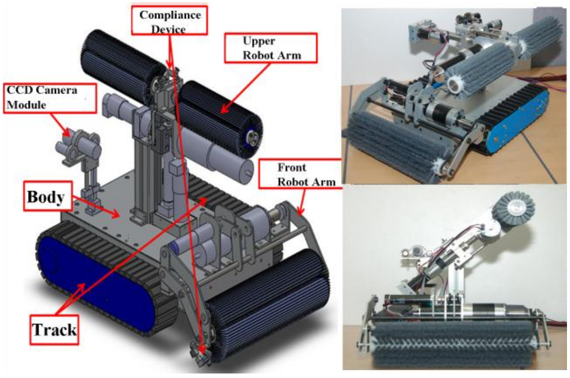

Figure 3: Duct cleaning robot with rotary brush arms.

In this research, the duct cleaning robot designed will be unique in its functionality and usability. The robot has equipped with adjustable brush arms at which rotary brushes are attached to clean four duct surfaces autonomously. In addition, a force compliance device was designed and installed at the end effector of the robot brush arm. Since the compact compliance device can recognize the pressure between brush and duct surface, the robot brushes can clean up the surface as a constant pressure even if the cleaning surface is of irregularity.

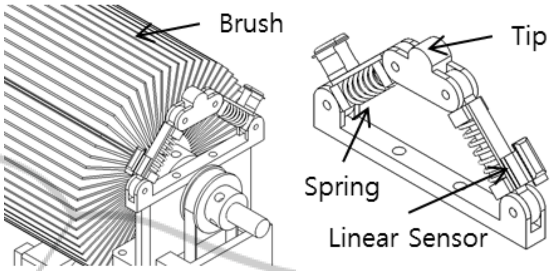

Figure 4: Brush and compliance device.

3.1 Mobile Platform and Arm

A newly developed duct cleaning robot is depicted in Figure 3. The robot consists of a base body, continuous tracked wheels, a camera module, LED light and two brush arms; upper and low arm. Six motors have been used to provide proper torques for ductworks. The rubber-based tracked wheel was selected not only to decrease slippage between driving wheels and duct surface, but also to reduce weight of the robot platform (Wang et al., 2006).

The lower brush arm is attached at the front of platform body and the upper brush is located at the end effector of the upper arm. The upper arm with R-R-P joints is height adjustable for handling various duct sizes.

The compact force compliance device is installed between two cylindrical rotary brushes at the end of the upper arm. The compliance device consists of two springs and linear sensors to read deflection of the spring. The two springs are connected each other at the end point to read two directional force. The brush and compliance device are depicted in Figure 4.

3.2 Force Control with a Compliance Brush

The compliance device attached at the end of the upper arm enable robot arm to detect force between brush and surface of duct, which make it possible to control the constant pressure. Figure 5 presents a model of force compliance brush illustrated in Figure 4. Figure 5(a) represent a model when the brush is contacting only with the upper surface of duct, and Figure 5(b) shows that the brush is contacting at two points, i.e., upper and side surface of duct. During the brush is under pressure, normal force and tangential force are acting on the compliance device.

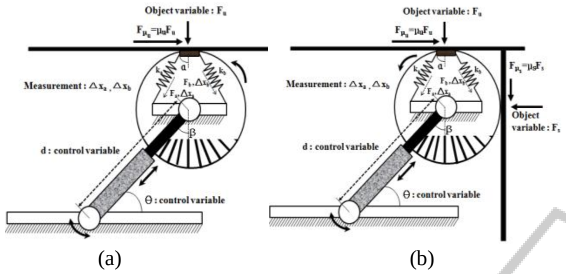

Figure 5: Force compliance brush models; one point contacting model(a) and two points contacting model(b).

The force acting on the compliance device can be simply calculated by using spring constant K, which is given by

$$F_a = K_a \cdot \Delta x_a \, , \tag{1}$$

$$F_b = K_b \cdot \Delta x_b \tag{2}$$

where Δx is a spring deformation and K is a spring constant. The two spring constants are identical when same spring is used. It should be noted that the deformation of spring (Δx) is a nonlinear because the stiffness of brush is, in general, empirically derived and deflection of brush is also affected by many factors such as bristle modulus, the number of tufts, and the trim length of bristles (Rawls et al., 1990). Therefore, value of the Δx has to be found by calculating the stiffness of brush empirically.

Assuming that 2α is the angle between two springs each other, the forces acting on the brush are calculated as

$$F_u = F_a \cos\alpha + F_b \cos\alpha = (F_a + F_b)\cos\alpha \, , \tag{3}$$

$$F_{\mu_u} = F_b \sin\alpha - F_a \sin\alpha = (F_b - F_a)\sin\alpha \tag{4}$$

where F_{μ_u} is a normal force action on the brush from the upper surface. The friction force is written as $F_{\mu_u} = \mu_u F_u$

The dynamic friction coefficient μ_u can be derived from Eq. (3) and (4) and given by

$$\mu_u = \frac{F_{\mu_u}}{F_u} = \frac{(F_b - F_a)\sin\alpha}{(F_a + F_b)\cos\alpha} = \frac{(F_b - F_a)}{(F_a + F_b)}\tan\alpha \tag{5}$$

Therefore, normal force acting the brush can be controlled by using robot arm parameters, i.e., translation length d and rotation angle θ in case of one point contact.

When the rotary brush is contacting at two surfaces as shown in Figure 5(b), the force equilibrium equation from Eq.(3) and (4) can be rewritten as

$$\text{Horizontal:} \quad \mu_u F_u - F_s = (F_b - F_a)\sin\alpha \, , \tag{6}$$

$$\text{Vertical:} \quad F_u + \mu_s F_s = (F_a + F_b)\cos\alpha \, , \tag{7}$$

where F_s is a normal force between the brush and side surface and μ_s is a dynamic friction coefficient at side surface of duct.

Assuming that dynamic friction coefficients are identical, F_u and F_s can be simplified as

$$F_u = \frac{(F_a + F_b)\cos\alpha + (F_b - F_a)\sin\alpha}{1+\mu^2} \, , \tag{8}$$

$$F_u = \frac{\mu^2 (F_a + F_b)\cos\alpha - (F_b - F_a)\sin\alpha}{\mu(1+\mu^2)} \tag{9}$$

where $\mu = \mu_u = \mu_s$.

Consequently, the cleaning pressure of robot brush can be constantly controlled with an actuating arm at both models.

3.3 Control Scheme of Robot System

In addition to control the cleaning pressure of the upper arm brush, it is required to control the driving motion of the mobile platform. The mobile platform can be either controlled by joystick or automatically by using ultrasonic sensors to adjust position and orientation of the robot platform. The overall control scheme is shown in Figure 6.

The CCD camera and LED light enables operators to monitor and control the system manually if needed. Thus, the duct cleaning robot can be controlled automatically or manually through the user interface system.

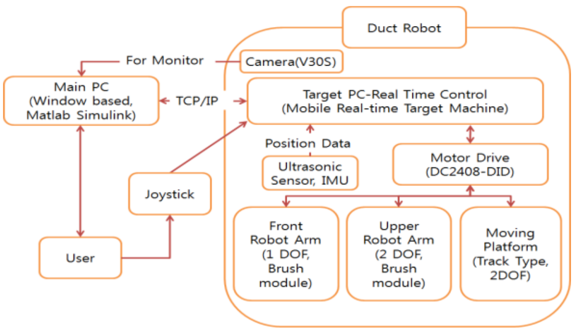

Figure 6: Control scheme of the duct cleaning robot.

4 CONCLUSIONS

In this study, a new type of duct cleaning robot has been designed and prototyped. In particular, the robot has functionality that cleans four sides of inner duct simultaneously with a constant pressure by using a force compliance device. For more dedicated control of brush pressure, the stiffness of brush should be empirically achieved. The adjustable arm brush can make it possible to use in different size of ducts.

However, there are still more room for improvement, especially on the autonomous system. In a real ductwork, there are many components at the inner duct such as dampers, fans, joints and curves that make it difficult to operate the robot consistently and autonomously. Therefore, more intelligent operating system has to be implemented to improve the cleaning process effectively. The developed prototype robot will be continuously upgraded and tested at the test-bed of air duct terminal.

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REFERENCES

Brosseau, L. M., Vesley, D., Kuehn, T. H., Melson, J., Han, H. S. 2000. ‘Duct cleaning: A review of associated health effects and results of company and expert surveys’, *ASHRAE Trans*, 106, 180-187.

Finnish Society of Indoor Air Quality and Climate (FiSIAQ). 2001. Classification of indoor climate 2000, Espoo, Finland.

Foarde, K. K., Menetrez, M. Y. 2002. ‘Evaluating the potential efficacy of three antifungal sealants of duct liner and galvanized steel as used in HVAC systems’, *J Int Microbiol Biotech*, 29, 38 –43.

Hanlim Mechatronics Co. Ltd., XPW-601 Duct Robot, http://www.ductrobot.com, Korea

Holopainen, R., Tuomainen, M., Asikainen, V., Pasanen, P, Säteri, J., Seppänen, O. 2002. ‘The effect of cleanliness control during installation work on the amount of accumulated dust in ducts of new HVAC installations’, *Indoor Air*, 12, 191-197.

Holopainen, R., Asikainen, V., Tuomainen, M., Björkroth, M., Pasanen, P., Seppänen, O. 2003. ‘Effectiveness of duct cleaning methods on newly installed duct surfaces’, *Indoor Air*, 13, 212-222.

HVCA, 1998. Cleanliness of Ventilation System, Guide to Good Practice Cleanliness of Ventilation Systems. Heating and Ventilating Contractors’ Association, London, HVCA Publications.

Jung, Y. H., Ahn, B. W., 2003. “Measurements on Contamination in Air Duct and Air Handling Unit,” *Journal of the Korean Society of Living Environment System*, Vol. 10, No. 1, pp. 41-46.

Morey, P. R. 1988. ‘Experience on the contribution of structure to environmental pollution’. In R. B. Kundisin (ed.), *Architectural design and indoor microbial pollution*. Oxford University Press, New York: 40-79.

Pasanen, P. 1998. ‘Emissions from the filters and hygiene of air ducts in the ventilation systems of office buildings’. Doctoral dissertation, Department of Environmental Sciences, University of Kuopio, Kuopio, Finland.

Robotics Design, ANATROLLER ARI-100, http://www.roboticsdesign.qc.ca/mobile-robots, Canada

Rawls, H. R., Mkwayi-Tulloch, N. J., Krull, M. E., 1990. ‘A mathematical model for predicting toothbrush stiffness’. Dental Materials, Vol. 6(2), pp. 111-117.

Wang, Y., Zhang, J., 2006. ‘Autonomous Air Duct Cleaning Robot System,’ *Proc. of International Midwest Symposium on Circuits And System*, pp. 510-513, 2006