Performance Analysis of a Mobile Duct Cleaning Robot

Wootae Jeong[1]
[1]Senior Researcher, Eco-Transport Research Division, Korea Railroad Research Institute,
176 Railroad Museum Road, Uiwang-si, Gyeonggi-do, Korea
[1]wjeong@krri.re.kr

Abstract- Inside air ventilation ducts of the confined space such as subway stations become contaminated by various contaminants and particular matters after long time operation. The accumulated various pollutants at inner duct surface easily transport and cause secondary air contamination and injure subway passengers' respiratory system and health. In fact, only periodic duct cleaning works can improve indoor air quality, but cleaning entire ventilation system takes high cost and manpower. This study proposes an effective duct cleaning method based on the developed autonomous duct cleaning robot. In particular, the new duct cleaning robot equipped with compliance rolling brushes enables to operate robot in a constant cleaning force to the target duct surface. Control method with the compliant device has also been suggested. The mobile robot has been tested with air ventilation duct system in selected subway station.

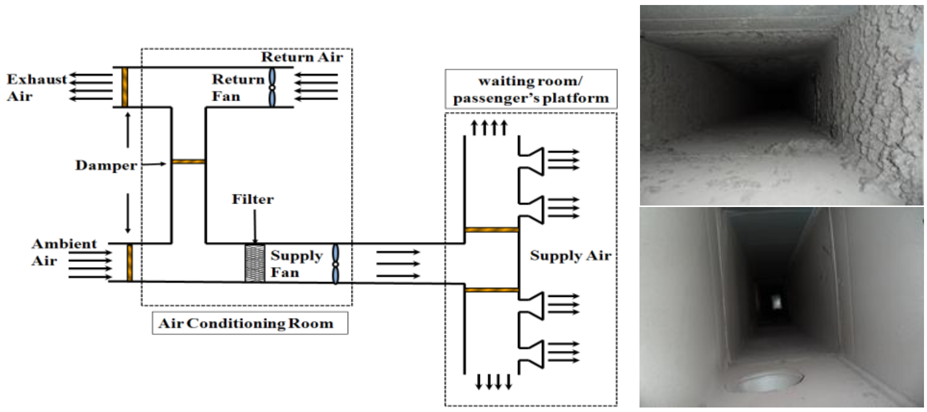
Keywords- Mobile Robot, Service Robot, Duct Cleaning, Air Quality, Air Ventilation

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 P, 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 (Finnish Society of Indoor Air Quality and Climate, 2001). A few countries do not still provide legal regulation, which makes air quality from the ventilation system severely contaminated.

Among various duct cleaning technologies, this paper proposes a new autonomous air duct cleaning robot based on the mechanical brushing method. 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.



(a) (b)

Fig 1- (a)Air flow of air duct ventilation system at subway stations and (b)accumulated dust inside ducts

2. CLEANING METHODOLOGY

The ventilation system can be contaminated and acted as another source of pollutants, such as microbe, chemical compounds or odors, 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 Contamination of duct

The estimated annual accumulation rate for dust in commercial supply air ducting is normally set at $1g/m^2$. However, an average accumulation level in supply air ducts of building occupied less than a year was 5.1 g/m^2 (Pasanen P, 1998) while dust level in new constructions was measured as high as 4.9 g/m^2 (Holopainen R, Tuomainen M, Asikainen V, Pasanen P, Säteri J, and Seppänen O, 2002-2003). 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 R, 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 method.
	Compressed air cleaning	Dust is dislodged from surfaces using airflow movement 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 fiber-fixed particles that were not removed mechanically.
	Chemical disinfection	The use of biocides and sealants to coat and encapsulate duct surfaces.

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 Fig 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.

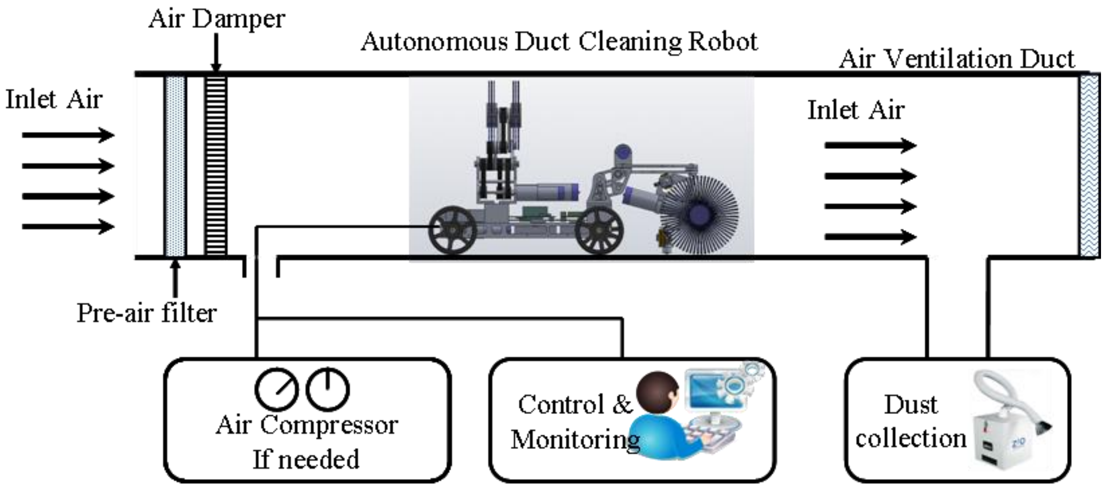


Fig 2-Duct cleaning with a mobile cleaning robot

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, ANATROLLER ARI-100). 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.

The designed duct cleaning robot will be unique in its functionality and usability. Based on the initial prototype model (Jeong W, Jeon S, Park D, and Kwon S, 2012), the robot used in this research has been recently upgraded in its brushes, cleaning power and working mechanism. In addition, three force compliance device with 1 DOF(degree of freedom) were newly 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.

This is wheeled type robtics, it is not suit for more complex duct environment, such as some vertical duct.

Compare to DuCTT, this duct robot have more function that can clean the duct by its brushes.

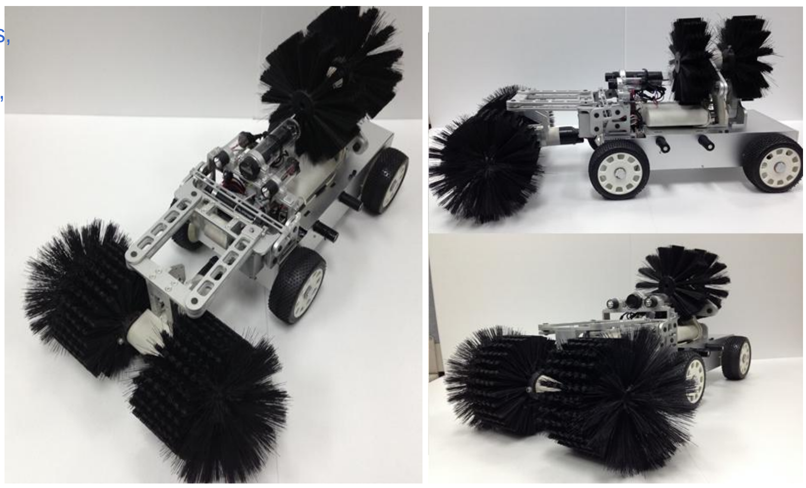


Fig 3- Duct cleaning robot with rotary brush arms

3.1 Autonomous mobile duct cleaning robot

A recently upgraded duct cleaning robot is depicted in Fig 3. The robot consists of a base body, four rubber tire wheels, a camera module, LED light and two brush arms; front and low arm. Seven motors have been used to provide proper torques for ductworks. The continuous tracked wheels of previous model have been exchanged to four tires by considering various obstacles such as screws or pins on duct surface, but also to reduce weight of the robot platform(Jeong W, Jeon S, and Park D, 2013).

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 also shown in Fig 3.

3.2 Robot control and simulation results

The general DC motor dynamic model has been used in simulation with MATLAB® SIMULINK® tool. The model is consisted of linear differential equations of mechanical and electrical system summarized at Eq.(1) and Eq.(2).

$$i_a(t) = \frac{1}{L_a}\int_0^t [V_a(\tau) - R_a i_a(\tau) - e_a(\tau)]d\tau \quad (1)$$

$$w_m(t) = \frac{1}{J_m}\int_0^t [T_e(\tau) - Bw_m(\tau) - T_L(\tau)]d\tau \quad (2)$$

$$e_a = K_b w_m(t) \quad (3)$$

$$T_m = K_t i_a(t) \quad (4)$$

where T_L is motor load, T_e is torque proportional to the current i_a, and e_a is back electro-motive force from the coil of the motor. Jm, B, Kt, Kb, La, Ra are motor constants indicating the rotor inertia, speed/torque gradient, torque constant, speed constant, terminal inductance, and terminal resistance respectively.

The rotation angle of the motor $\theta_m(t) = \theta_2(t)$ is obtained from angular velocity of $w_m(t)$. The load value for the DC motor is also induced from the weight of the robot arm brush. Therefore, the torque generated by the motor Eq.(4) can be calculated as following

$$T_m = \frac{L\sin\theta}{N}(F_1 + 2F_2 - Mg) \quad (5)$$

where T_m is the motor torque, N is the gear reduction ratio, L is the effective length of the link, and M is the mass of the robot arm linkage. In addition, F_1 and F_2 indicate forces applied at each brush of the front arm.

Based on the Hooks Law of the spring-based compliant device (Jeong W, Jeon S, and Park D, 2013), the force of the compliance can be calculated from the deformation generated by the brush(robot arm) moving vertically. The relationship between the position of the brush and deformation of the spring can be expressed as follows

$$\Delta x = l_0 - l = l_0 - \text{Height} + u \quad (6)$$

$$\text{Height} = 0.148 + 0.002\sin(2\pi ft) \quad (7)$$

where l_0 is the initial length of the spring and u is vertical position of the brush.

The Height variable was defined as the length from the top of the duct. The irregularity of duct surface was modelled with sinusoidal function and sensing disturbance was also added to the control model shown in Fig 4. Finally, the Fig 4 illustrates the dynamic model of the force control of the brush with the compliant device.

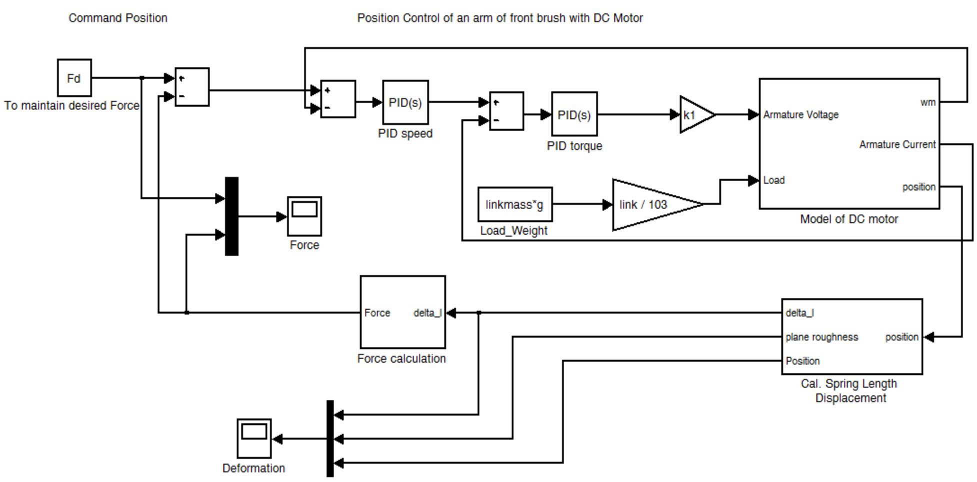
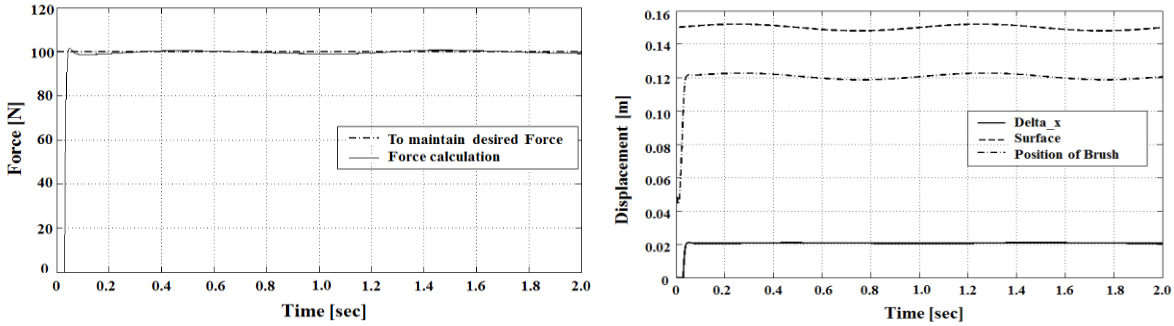


Fig 4- Force control model with deformation feedback

The force control model has been simulated with appropriated PID control gains and simulation results are depicted in Fig 5.

The spring constant (k) of the compliant device used in the simulation is 0.3[N/m], and coefficients for the nonlinear brush stiffness is assumed as values of a=2000[N/m2], and b=4500[N/m], which is expressed in the Eq.(5). It is also considered that the maximum allowable displacement of the spring to the geometry including the diameter of the brush is 100mm and the height of the duct is 150mm. The k is exerted by that of value installed to the prototype robot. However, constants of the nonlinear stiffness brush are decided arbitrary which is relatively higher than that of compliant spring. At first, the simulation results are shown in Fig 5 controlling the force from deformation feedback to satisfy the desired force by moving the brush on the sinusoidal surface.

Fig 5 shows the result of force control that of maximum error is 1% to the objective force and the spring is deformed below the limit (0.05m) of the geometric interference.



(a) (b)

Figure 5: Results of Force Control at 2mm, 1Hz sinusoidal function of Surface. (a) Measured Force, (b) Displacement

3.3 System Control scheme

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 and Simulink mode are shown in Fig 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.

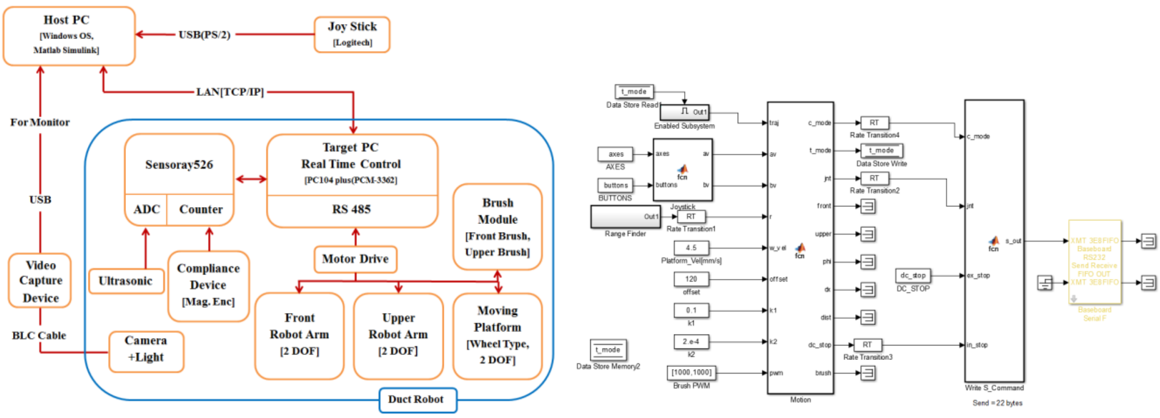


Fig 6- Control scheme and Simulink Model of the duct cleaning robot

3.4 Cleaning performance

The duct cleaning process has been conducted with test-bed ventilation duct system. Deposit Thickness Test(DTT) and vacuum test(VT) have been used to measure the thickness and weight of dust before and after cleaning with the developed robot system.

The thickness of dust has reduced about 50% after cleaning the duct surface. Since the thickness of accumulated dust in this experiment was very thin (< micrometer), the measured thickness was relatively dependent on the measured location of the inner duct surface. Table 2 shows results of dust weight before cleaning and Table 3 summarized the VT results after cleaning with the designed cleaning robot.

Table 2. Vacuum test results at a sampled railway station

Location	*N*	*Vacuum Test (g/m²)*			
		Mean	SD	Range	p-Value
HVAC Room	10	4.59	1.41	1.90-6.81	0.478
Waiting Room	10	5.43	2.57	2.66-11.06	
Platform	8	4.45	1.28	2.94-6.09	

Table 3. Vacuum Test (VT) results

	1st point Measure			2nd point measure		
	Before	After	Rate(%)	Before	After	Rate(%)
Weight(mg)	27.2	2.3	91.5%	25.1	0.1	99.6%
Weight(g/m²)	2.72	0.23	91.5%	2.51	0.01	99.6%

4. CONCLUSIONS

At most of field, ductworks have been conducted manually by human. Converting it to automatic cleaning device requires very sophisticated design of the cleaning device and control. In this study, a new type of duct cleaning robot has been designed and prototyped. In particular, the robot has tested on the test-bed duct facility without manual cleaning process. 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.

There exists more room for improvement, especially on the autonomous cleaning process under real harsh duct system. For examples, many mechanical parts such as dampers, fans, joints make it difficult to operate the robot consistently and autonomously. This research has proved improvement and possibility of using the mobile duct cleaning robot.

5. ACKNOWLEDGEMENTS

This research was carried out as a part of the subway air duct cleaning robot project (Eco-Innovation, No. E211-40002-0003-0) funded by the Ministry of Environment and the subway air quality improvement project from the Ministry of Land, Infrastructure and Transport in Korea.

References

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

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

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

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

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

Jeong W, Jeon S, Park D, Kwon S, Force Control of a Duct Cleaning Robot Brush Using a Compliance Device, In Proceedings of the ICINCO 9th Int. Conference on Informatics in Control, Automation and Robotics; 2012.

Jeong W, Jeon S, Park D, Operational Effect of a Mobile Robot System For Cleaning Ventilation Ducts, PETRA'13; 2013.

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

Pasanen P, 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, 1998.

Rawls R, Mkwayi-Tulloch J, and Krull E, A mathematical model for predicting toothbrush stiffness, Dental Materials, 6(2)(1990)111-117

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