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Air Conditioning Ducts Inspection and Cleaning Using Telerobotics

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Abstract

This paper focuses on the importance of having clean air conditioning duct and its influence on our lifestyle. Firstly, we study health norms and memorandums that emphasize on the hygiene factors and metrics in certain building and habitats then we analyze the possibility of using telerobotic solution in order to improve the cleaning process of the air ducts by automating the cleaning process, removing debris and dust. The telerobotic solution consists of a mobile robot based on BioVac systems, armed with manipulator and spray guns. The positioning of the BioVac robot is controlled using fuzzy logic algorithm.

Keywords: duct cleaning, site management, telerobotics.

1. Introduction

Air and water quality are one of the major elements directly affecting human being. Therefore, historically, most conflicts sparkled in order to acquire healthy and fertile lands. The evolution of the humanity imposed changes to life styles and habitations. With population growth, lands have become luxurious and rare resources. In parallel, importing enough water and services to habitats such as building drainage, water supplies and roads became traditional social and technical problems to deal with.

Many technologies were founded to improve services and making them reachable to human being. For instance, to fight the heat, earlier Arab constructors have designed ducts on top of the roof infiltrating the ceiling of the building, allowing continuous air circulations inside particular rooms (Figure.1.).

Figure 1. Ventilation ducts - traditional Arabic architectural signs

Nowadays, buildings are designed to accommodate centralized air conditioning and heating systems. Taking hospitals as an example, operating theaters and recovery rooms are totally dependent on the air supply unit being designed, as it affects the pressure rate and the air curtain created above the patient. The quality of air supplied is very important. Therefore, recently ultraviolet lamps are installed in the air duct to kill germs. Heath and Safety engineers did not exaggerate while adopting the statement "*what is in your duct is what in your lung*".

Duct cleaning is performed manually by accessing pre-identified areas. Some air supply systems can be purged, so the enclosed air inside the ducts is sucked out to filtering station. Intelligent solutions are also present with telerobotics. This approach consists basically of a telescopic snake robot or a mobile robot equipped with spraying guns or

Looping back to old supply ducts systems, the purging solution cannot be used, while manual method consumes lots of time. The telerobotic solution seems to be the optimal choice [5]. Additionally, this approach can be used frequently, essentially for buildings occupied by citizens with special needs (i.e. in-house ventilated patients).

In this paper we discuss the telerobotic solution for duct cleaning for newly built and old structures. In addition, we highlight setup requirements, implementation constraints and possible improvements.

2. Case study

In this paragraph, we present case study on the influence of the air conditioning ducts on hygiene factor inside hospitals. The subject of calibrating, testing, commissioning and inspecting of air ducts and laminar air flows (LAF) in Ultra Clean Ventillation (UCV) OR's is dealt with in different publications including HTM [11], ASHRAE and ISO14644 documentation. In general, the following should be carried out an annual basis for each operating theatre:

a. Particle counting within the area to assure room compliance with ISO5 or ISO7 limits. With this test we used to select 2 significant particle values for compliance, which is normally 0.5μm and 5μm, although the 2015 revision of ISO14644 has removed the 5μm limit from the specification for class 5 [12];
b. Air flow measurement to ensure the correct velocities and air change rates;
c. Filter face scanning involving an upstream injection of smoke / oil drops (DOP) and then systematic scanning of the filter face to measure how much contaminant gets through. This does require an injection point to be designed in upstream of the canopy to the supply ductwork and will shut down the area for the duration of the test.
d. Entrainment test to ensure that particles are not being drawn into the area from outside the air stream (particle counts at perimeters)
e. Microbiological sampling can be used but the above tests are often sufficient.

According to British standard code BS 14065 "Decontamination of linen for health and social care: Guidance for linen processors implementing" used to regulate construction in healthcare premises, soiled and clean areas should be separated physically or functionally. The physical separation consists of building walls between two different areas, while the functional separation undersigns the implementation of treating technologies. For instance, sterilization rooms are both functionally and physically separated. The same applies for the hospital washing room. To avoid cross contamination between different areas, countries has set additional standards to be implemented. For example, In UK, to avoid the influence of the air conditioning, linen has to be washed for three minutes at a temperature of 71℃, or for 10 minutes at 65℃. The same is not applied in Russia and Norway, where the linen is always washed at a temperature of 90℃ and 85℃ respectively. The supplied air does not only affect linen. The total hygiene of the hospital depends on it [1, 10]. The approved norms for hygiene are illustrated in the following diagram (figure.2). Conserving the hygiene factor depends on the Cleaning In Place cycle (CIP), which is divided into four treating procedures: mechanical, chemical, thermal and chronological (refer to figure 3.). The best approach is to increase mechanical procedure with reference to the others. Chemical procedure requires detergents, which may cause side effects. The thermal procedure is directly related to the working atmosphere such as humidity. The air conditioning ducts affects directly the thermal procedure results, as bacteria and germs can survive and multiply easily in such atmosphere.

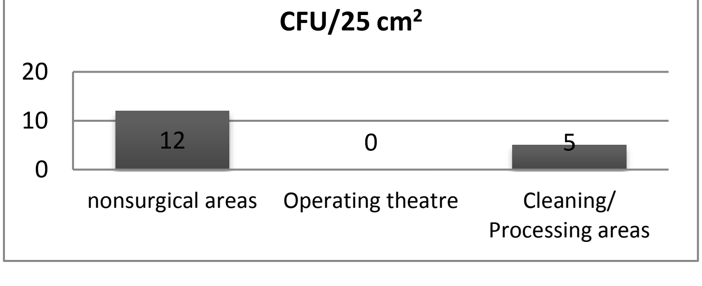

Figure 2. Hygiene factor with reference to room specialty

In addition to side effects, using thermal and chemical procedures are not cost effective and impose indirectly additional financial charges on the habitants or patients.

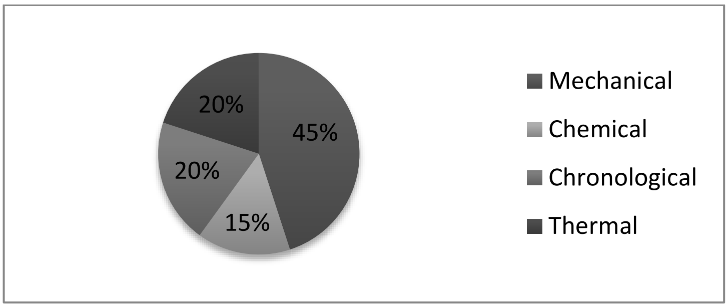

Figure 3. CIP cycle

Ducts are cleaned using ultraviolet lights and manually using vacuum machines but this is not sufficient. As illustrated in figure.4, the ducts can be very dirty between preventive maintenance periods.

Figure 4. Air conditioning duct status A) dirty; B) clean

Subsequently, telerobotic solution can be used to automate long duct cleaning procedures [7,8]. It can be used also to inspect regularly the ducts condition. This solution allows can be integrated with ultraviolet LEDs for old ducts unequipped with special light filters.

3. Telerobotic duct cleaning

From the 2nd paragraph, we can clearly notice that germs and particles affect the airflow and quality. To perform the test (a-e) all equipment to be used should be calibrated annually, which can be an issue for certain countries. In order to avoid such difficulties, hospitals try to select manufacturers with local representation or send their instruments for 2 months just to be calibrated. In the following paragraph, we will describe the robotic concept (Figure.5.), which does not need calibration and it is user-friendly. Hence it does not require special setups and expertise. This can reduce dramatically the maintenance cost and improve the air quality without much hindrance.

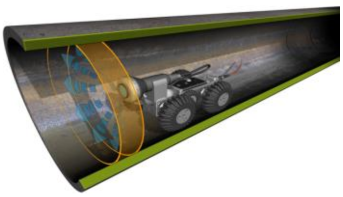

Figure 5. Autonomous/ Telerobotic concept design for air duct cleaning

We will be using articulated robot model since the task is straightforward and does not require sophisticated manipulations. There are several approaches to control the mobile robot. In the literature, most frequently we noticed the implementation of PID regulator due to its simplicity and applicability. On the other hand, with the development in artificial intelligence, adaptive control is used to minimize nonlinear effects such as friction and saturation of the DC motor [4]. Regarding the design of the robotic cleaning procedures, there are different approaches adopting the use of direct dry ice blast cleaning technology as in [2]. Others use intelligent approach to identify the area that needs to be cleaning [3,6].

3.1. *Mobile Robot representation*

The control task consists of tracking the desired metric trajectory. To achieve this goal, it is necessary to model the robotic arm. It is represented as an Elbow manipulator with a base fixation on wheels, body, shoulder, elbow and forearm joints. These mechanisms allow the robot to manipulate three dimensionally to reach difficult corners. Based on Force/Torque relationship, the interaction of the manipulator with the surrounding environment will produce forces and moments on manipulator. We designate F- as the vector of forces and torques identified with the following equation:

$$F = [F_x \quad F_y \quad F_z \quad n_x \quad n_y \quad n_z]^T; \tag{1}$$

where $F_x \quad F_y \quad F_z -$ are the components of the force and $n_x \quad n_y \quad n_z -$ components torques on the grasping tool accordingly. We donate τ for vector of joints torques and δ is the displacement of the end effector caused by the vector F and γ is the corresponding virtual joints displacement. We can write:

$$\delta = J(q) * \gamma; \tag{2}$$

where $J(q) -$ is the Jacobian of the manipulator. The virtual work of the system is given by:

$$\omega = F^T * \gamma - \tau^T * \gamma; \tag{3}$$

By substituting (3) into (2) we obtain:

$$\omega = (F^T * J - \tau^T)\gamma; \tag{4}$$

Since the generalized q is independent, we have the equality

$$\tau = J(q)^T * F; \tag{5}$$

From (5), we obtain the following equality

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \end{bmatrix} = \begin{bmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \end{bmatrix} * \begin{bmatrix} F_x \\ F_y \\ F_z \\ n_x \\ n_y \\ n_z \end{bmatrix}; \tag{6}$$

By obtaining the mathematical model of the controlled manipulator, it is possible to find transfer functions of the compensator. In the following paragraph, we simulate mobile robot with Fuzzy Logic controllers (FLC).

3.2. *FLC Position controller Design*

Positioning of the robot is critical to our case study, as it has to reach difficult corners. In order to design FLC, we should have at least two inputs. We can consider the crisp generated from feedback positioning error and it is deviation in time as inputs for the FLC. The numerical values of the error and its variation in time are obtained while regulating the position using PID controller. The obtained values are segregated as will be represented in form of membership functions MBF. The fuzzy rules are depicted in in figures 6,7 and 8 for “error” input, “deviation” input and “controller output” respectively.

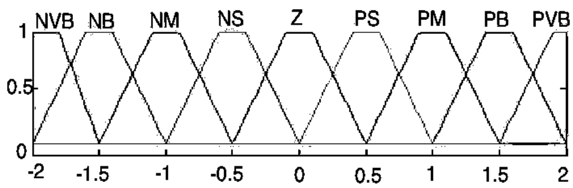

Figure 6. MBF for FLC ERROR input

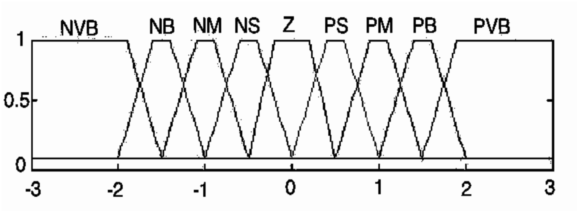

Figure 7. MBF for FLC DEVIATION input

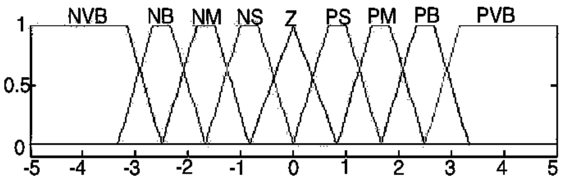

Figure 8. MBF for FLC OUTPUT

In the MBF representation, the following abbreviations are used: NBV- very big negative value, NB- big negative value, NM- medium negative value, NS- small negative value, Z- null value, PS- positive small value, PM- positive medium value, PB- big positive value and PVB- very big positive value. On x-axis, the input/ output variable is represented while on y-axis the degree of membership is identified.

4. Results and discussions

The main control task was to maintain the mobile robot in a certain position in order to achieve collision less maneuverability and safer degree of freedom for the manipulator. This improves the reaching of the spray gun and develops better cleaning results. Figure 9 shows the simulation results for position control.

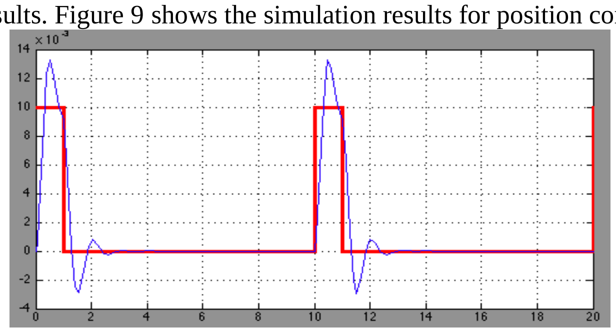

Figure 9. Position control of the mobile robot.

Figure.9 is interpreted as follows: x-axis represents the simulation time (s), y-axis represents the simulation results (position, m). The negative sign indicates the direction. The black pulses designate the control task i.e. the movement coordinates (m); the blue curve is the controlled position of the mobile robot using PID controller (refer to 3.2 Obtaining fuzzy rules and membership functions) while the red curve represents the trajectory of the mobile robot controlled using FLC. The simulation results were obtained based on BioVac Wolverine Robotic systems technical specifications [3], which include the following parameters:

- Robot dimension: 0.4 m x 0.177 m x 0.15 m (High x Length x Width);
- Robot Speed: 1,524 m/s;
- Cable length: 30 meters;
- Weight of the robot: 2.26 Kg.

From the technical specifications, it is assumed that the robot can move into the ducts without hindrance. Albeit the cable length is 30 meters, the diameter of efficiency of the robot can covers large areas up to 2827,43 m^2.
In a related matter, we feel that the need of wireless robotic solution will add value to the mobility factor only as the robot will still be plugged in to water/ detergent supply, which cannot be managed by installing a reservoir on the robot due to payload and dimensions criteria [9].

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