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Design of an Adhesion-Aware Façade Cleaning Robot

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Abstract— **Cleaning requirements of glass façades of high-rise buildings have been significantly increased in recent years due to the growth of the construction industry. The conventional cleaning methods for high-rise buildings require human labor where efficiency, cost, and safety are major concerns. Therefore, robotic systems that can climb and clean glass façades in high-rise buildings have been developed. Capability to attach to a façade surface is one of the critical requirements of a glass façade cleaning robot. Diverse approaches have been proposed for adhesion of cleaning robots to a glass façade. Active vacuum suction mechanisms are widely used for these robots since they provide better controllability to move the robots smartly on the surface. Notably, those are decent for a reconfigurable robot that can transit between window frames. The suction mechanism of a glass façade cleaning robot must provide a reliable suction force to make the robot stay safely and move smartly on a façade. Nevertheless, these suction mechanisms can be failed due to improper fastening between a façade and the mechanism, which may lead to safety and operational issues. Therefore, this paper proposes a novel method to realize the adhesion-awareness of a glass façade cleaning robot. The adhesion-awareness is realized by analyzing The current drawn by the motors attached to the impellers of the vacuum mechanisms. Experiment results validate the capability of the proposed approach in raising the adhesion-awareness of a façade cleaning robot.**

Index Terms— **Adhesion-Awareness, Reconfigurable Mechanism, Façade Cleaning, Active Suction Mechanism**

I. Introduction

The number of high-rise buildings is increased in all most all the urbanized regions of the world due to the growing population and the advancement of the construction industry [1]. Architects attracted to use façades made from glass for these high-rise buildings since glass façades facilitate benefits such as better aesthetic appearance, natural lighting and durability [2]–[4]. Due to that, large glass façade areas can be observed in many modern-day high-rise buildings. Therefore, the maintenance and services requirement of glass façades in the high-rise building has been significantly increased in recent years. Conventional cleaning methods of these glass façades require the involvement of human labor, where efficiency, cost, and safety are major concerns [5], [6].

Based on these concerns, recent technological advancements have facilitated to design and develop robotics architectures which can access these glass façades of high-rise building as well as clean them [7]–[9]. Diverse aspects of glass façade cleaning robots including climbing mechanisms [10], [11], cleaning functions [12], control [13], perception [14], and autonomous operation [15] have been investigated. Capability to climb vertical structures is one of the major requirements of the glass façade cleaning robots since the robots need to operate on vertical surfaces for performing cleaning. In this regard, façade cleanings robots that use the support of external structures such as guide rail mechanisms [16], [17] and cable systems [18], [19] have been developed. The major shortcoming of these approaches is the difficulty of portability for different places without having overhead work for establishing supportive infrastructures. Furthermore, supportive infrastructure for these robots such as the rail mechanism would disrupt the aesthetic appearance which is expected from a glass façade.

Therefore, robotic systems that can climb and operate in façades of a high-rise building with minimal requirements of additional infrastructures are preferred for cleaning of glass façades. To realize this behavior, glass façade cleaning robots should be capable of attaching to façade surfaces. Furthermore, most of the robots climbed with the aid of cables also require adhering to the glass for cleaning. Hence, glass façade cleaning robots require proper adhesive mechanisms, which enables a robot to attach to a vertical glass surface, for reliable and smooth operation. In this regard, various mechanisms that allow a robot to attach to a vertical surface have been designed and developed [10], [11].

Many glass façade cleaning robots that use passive suction cups for attaching to vertical wall surfaces have been developed [20]–[22]. One critical shortcoming of suction cups based mechanism is the loss of negative pressure due to air leaking and subsequently fails to attach a robot to a wall. Approaches have been developed to overcome this [10]. For example, the method proposed in [23] uses a complex mechanical and control functionalities to push a suction cup periodically. However, such mechanisms cause much overhead for robots. Furthermore, glass façade cleaning robots should be capable of manuring within a windows frame as well as transiting from a window frame to another window frame for efficient operation. This kind of transitions and some advanced maneuvering cannot be achieved without performing detaching and attaching of a robot to a wall by controlling the suction cups attached to the robot. For achieving such controllability from a suction cup based mechanism requires complex mechanical designs and controls [20], [22].

In contrast, vacuum pump based adhesive mechanisms have greater flexibility in controlling their suction force. Moreover, vacuum pump based on electrical motor-based

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impeller systems can be easily controlled by varying the electrical signals to the motor. Therefore, vacuum pump based adhesive mechanisms are widely used in glass façade cleaning robots [10], [24], [25]. Furthermore, this mechanism is well suited for reconfigurable robots that can transit through window frames since it provides the ability to control the suction force easily [25]–[27]. Nevertheless, there can be issues in sealing of the mechanism with the wall surface that endangers the safe and reliable stay of a robot on the glass surface. In this regard, the work proposed in [28]–[30] analyzes the suction ability of a propeller based vacuum mechanism including the relationship between the parameters of the vacuum suction mechanism and a robot. Variations of suction force in wet surfaces have also been studied [31]. However, the scope of the work mentioned above was limited for analyzing of the important parameters of the vacuum suction mechanism for the development of a better mechanism for future developments, and the proposed methods are not capable of detecting a deficiency in the vacuum mechanism during the operation of a robot. Moreover, existing glass façade cleaning robots do not possess the adhesion-awareness for reliable and safe operation in glass façades.

Therefore, this paper proposes a novel method to realize the adhesion-awareness of a glass façade cleaning robot. The proposed method was implemented on a reconfigurable glass façade cleaning robot named 'Mantis' [26] for the validation. The proposed method analyzes the current flow of the motors attached to the impellers to establish the adhesion-awareness, which is essential for identifying the deficiencies in sealing between the robot and a glass surface that may hinder the safe operation. The decision of the robot such as the initiation of the reconfiguration can be made by accounting the adhesion-awareness for improving the operation of the robot. A brief description of the dynamics of an impeller based vacuum suction mechanism is given in section II. The proposed method to establish the adhesion-awareness of a façade cleaning robot is explained in section III. Experimental results are analyzed and discussed in section IV. Concluding remarks are given in section V.

II. Vacuum System Fluid Dynamics

Fluid dynamics of the impeller mechanism is very important in identifying the rationale behind the proposed method for establishing the adhesion-awareness. It was observed during the use of the robot that the flow of air inside (see Fig.1) the impeller varied the power consumption of it. Given these circumstances, it was decided to analyze the power consumption to establish the adhesion-awareness of a façade cleaning robot. In the calculation of power consumption, we want to derive the current consumed by impellers by means of applying the Bernoulli equation.

Power consumed by an impeller, W can be obtained from (1), where ρ, g, Q, η, and H are the specific weight of the fluid, gravitational interaction, flow, efficiency, and pumping load respectively.

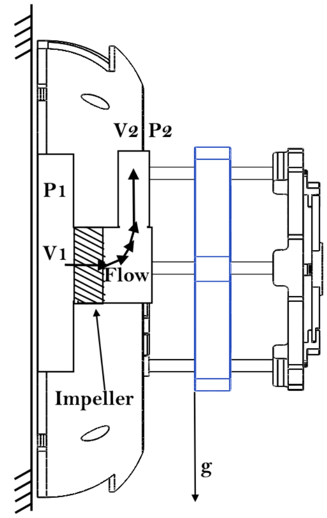

Fig. 1. Free body diagram of impeller fluid dynamic analysis

$$W = \frac{\rho g Q H}{\eta} \tag{1}$$

Pumping load, H can be calculated from (2) since during detached operation $P_1 = P_2$ and the wind speed is the same $v_1 = v_2$.

$$H = Z_2 - Z_1 + \sum_{1}^{2} h_f \tag{2}$$

Z_1 and Z_2 are the initial height and the final height respectively. The frictional loses can be calculated from (3) where the friction factor λ can be determined from (4).

$$\sum_{1}^{2} h_f = \lambda \frac{L}{d} \frac{v^2}{2g} \tag{3}$$

$$\lambda = \frac{64}{Re} \tag{4}$$

Number of Reynolds, Re is calculated as given in (5) knowing the wind speed v, the diameter of the pipe d, the length of the pipe L, the specific weight ρ, and viscosity of μ at temperature of t.

$$R_e = \frac{\rho v d}{\mu} \tag{5}$$

If the power supplied to the robot for its operation is made from a power source, which maintains the supply voltage V constant, then the current drawn (I is varied according to the amount of air flow (Q) in the impeller. Due to the operational conditions, the variables in this application can be reduced as given in (6) (since $W = VI$).

$$I = \frac{\rho g H}{\eta V} Q \tag{6}$$

Voltage V, gravity g, pump load H and efficiency η are constant in this scenario. In this way, the variation of the current (I) has a direct relationship to the air flow (Q) inside of the blower (assuming losses and the no-load current of the motor as zero) for these circumstances.

On the other hand, in attached situations the pressure difference ($P_2 - P_1$) has a inverse relationship with Q. The pressure difference ($P_2 - P_1$) should be maintained above a critical threshold given in (7) to avoid the falling off and overturn conditions [29].

$$P_2 - P_1 \geq \frac{1}{A} max\{\frac{mg}{\mu_g}, \frac{mgC_{g_x}}{R}\} \tag{7}$$

Where A is the area of the vacuum pad, m is the mass of the robot, μ_g is the friction coefficient between the glass and the robot, C_{g_x} is the horizontal distance to center of gravity of the robot, and R is the radius of the vacuum cup.

Therefore, the current drawn by the impeller motor could be used for understanding the air flow through the impeller, and subsequently, it can be used to establish the adhesion-awareness of a façade cleaning robot.

III. Establishing the Adhesion-Awareness

The current drawn by the motor of the impeller mechanism is analyzed by the proposed method to establish the adhesion-awareness. If the vacuum mechanism is completely fastened to the surface, the motor draws the minimum current since it does not need to do work for removing air. In the contrary, the current of the motor maximizes when the vacuum mechanism is fully open state since the motor has to work for blowing the air at its maximum capacity. Moreover, the current drawn by the motor increases with the airflow. This implies that if there is a leakage in the vacuum mechanism tends to increase the current drawn by the impeller mechanism. In addition to this phenomenon, we found out from our experience that high variation of the current of the impeller indicates intermittency of the adhesion forces of a robot. Therefore, the proposed mechanism for establishing the adhesion-awareness analyzes the mean value of current drawn by the impeller and the variation of the mean value within a given period.

Mean of current drawn by the impeller at time t, $I_m(t)$ is obtained as given in (8), where i is the instantaneous current and K is the number of samples considered for calculating the mean.

$$I_m(t) = \frac{\sum_{t-K}^{t} i}{K} \tag{8}$$

Variance of I_m at time t, $I_{var}(t)$ is obtained as given in (9), where N is the number of samples considered and I_{mm} is the mean of I_m. I_{mm} is computed as given in (10).

$$I_{var}(t) = \frac{\sum_{t-N}^{t} (I_m - I_{mm})^2}{N} \tag{9}$$

$$I_{mm}(t) = \frac{\sum_{t-N}^{t} I_m}{N} \tag{10}$$

Due to the vagueness of the interpretation of these two parameters, these two parameters are considered as fuzzy variables, and a Mamdani type fuzzy inference system is used for decision making. The parameter I_m is fuzzified based on the membership function shown in Fig. 2(a) which contains five fuzzy sets. The fuzzy labels are defined as VL: Very Low, L: Low, M: Medium, H: High, and VH: Very High. The second input parameter, I_{var} is fuzzified using the membership function shown in Fig. 2(b) which consists of three fuzzy sets; L: Low, H: High, and VH: Very High. The output of the fuzzy inference system is the uncertainty of the adhesion of the robot to façade. The membership function for the output Y is defined by three triangular fuzzy sets as shown in Fig. 2(c). The fuzzy labels are defined as F: Fine, V: Vigilant, and C: Critical. The input and output fuzzy sets are linked through the rule base given in Table I. This rule-base has been defined based on heuristic expert knowledge. The center of area method is used to defuzzify the output to a crisp value (i.e., defined as Y). This crisp value Y indicates the uncertainty of the adhesion of the robot to a façade due to issues of sealing of vacuum mechanism and other abnormal conditions of the impeller mechanism such as stall conditions. If Y is closer to 1.0 implies that the adhesion has a definite critical issue. In contrast, Y closer to 0.0 suggests that the adhesion is perfectly fine without issues. However, the range of the output Y is theoretically bounded to 0.163 and 0.837 since the center of area method is used for the defuzzification even though the universe of discourse of Y is [0,1].

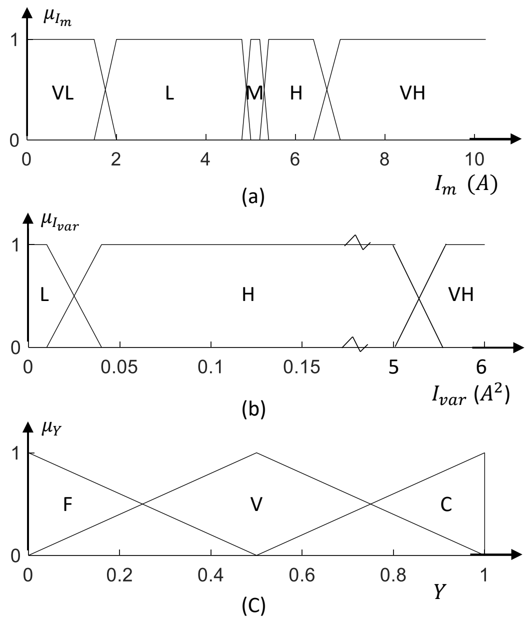

Fig. 2. (a): Membership function for the input I_m. (b): Membership function for the input I_{var}. It should be noted that the input axis is not in a linear scale (c): The output membership function. The ranges of fuzzy sets are defined based on experimental observations.

TABLE I

Rule-base of the fuzzy inference system

I_m		VL	L	M	H	VH
I_{var}	L	C	F	V	C	C
	H	C	V	C	C	C
	VH	C	C	C	C	C

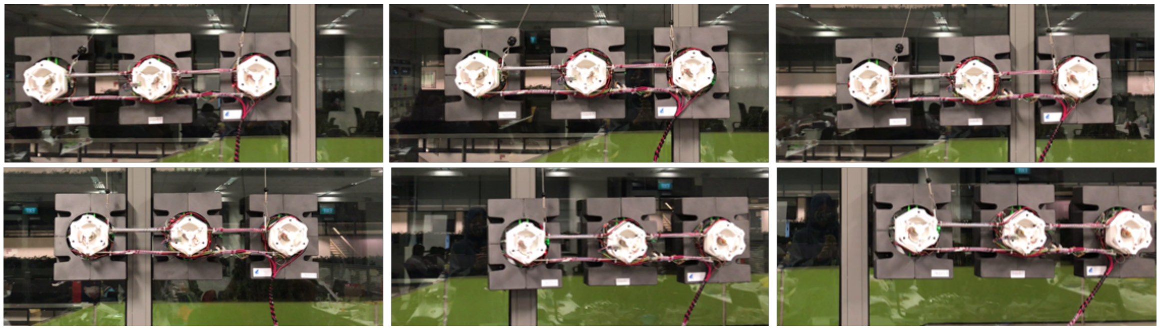

Fig. 3. Mantis making transition avoiding a window frame

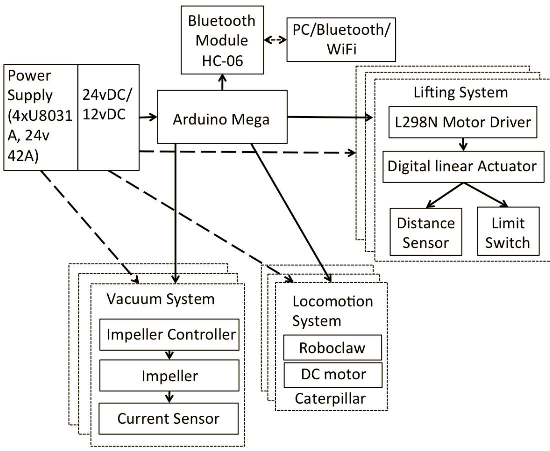

Fig. 4. Mantis Architecture, the figure represents the power flow and data communication

IV. Results and Discussion

A. Experimental setup

The proposed method for establishing the adhesion-awareness was implemented on Mantis [26] robot, and experiments have been conducted inside a laboratory environment by exposing the Mantis robot into different conditions. The number of samples considered for computing I_m and I_{var} were chosen as K = 100 and N = 10 respectively.

Mantis (see Fig.3) is a window climbing robot composed of 3 modules interconnected by parallel longitudinal bars of carbon fiber. Each of the modules is composed of a vacuum system using an impeller based blower. Each of the blowers has a capacity of 8 kPa, which generates vacuum and consequently friction between the microfiber towel adhered to the module and the glass. In the same way, the fabricated cloth is used for dry cleaning.

Mantis can make the transition between one window and another by the avoidance of the frame of the window as explained in Fig. 3. The transition is developed utilizing a linear actuator attached to the pad of each module. The linear actuator separates the pad from the glass for each of the modules respectively, as the modules approach the frame. While one pad is raised, the others remain in the respective position, and at the same time move the robotic platform using the caterpillar band. To maintain the position of the pad with respect to the general structure of the robot, each pad is attached to the top of the module by 3 parallel bars in a triangular position concentric to the assembly of the module.

The functional architecture of Mantis is depicted in Fig. 4. The locomotion is developed using caterpillar wheels, actuated with DC motors, controlled with Roboclaw velocity controller. The system is controlled using Arduino Mega, and a Bluetooth link is used for teleoperation. The module can lift from the glass using a lead-screw linear actuator, using a stepper motor.

During the transition of the robot from one panel to another, the modules are separated from the glass of the window. To know the distance between the module and the glass, Time Of Flight (TOF) distance sensors are used. For the heading angle estimation, an Inertial Measurement Unit (IMU) is used. A current sensor is connected to measure the current flow of each of the blower. ACS715 current sensor from Pololu brand, which has an accuracy level of 0.01 A and a maximum rating of 30 A, is used for this purpose. The sampling frequency is 1.2 ms. The power supply to the impeller motors is kept at 24 V constant.

B. Experiment and Results

The input parameters and the output of the proposed system for establishing the adhesion-awareness were recorded for each of the scenarios for the analysis. The robot was exposed to 7 different conditions, and the data were captured for 12 s for each situation. The variation of the output of the fuzzy inference system Y (i.e., the uncertainty of the adhesion) is plotted in Fig. 6. The variation of mean current (I_m) and variance of mean (I_{var}) during these situations are plotted in Fig. 7 and Fig. 8 respectively.

1) Normal: In this situation, the robot was allowed to clean a glass surface in a normal condition as shown in Fig. 5(a). In this situation, I_m is mostly within 'Low' range in most of the time (I_m is around 4.7 A). I_{var} is mostly within 'Low' range in most of the time (I_{var} is around 0.00 to 0.01). Therefore, the uncertainty of the adhesion (i.e., the output of the proposed fuzzy inference system, Y) is mostly within the 'Fine' category. It varies at around 0.163. Theoretically, 0.163 is the lower bound of the defuzzified output. Furthermore, this situation has the smallest value of Y among other cases. Therefore, this validates that the proposed method is correctly identifying the normal operating condition as a fine

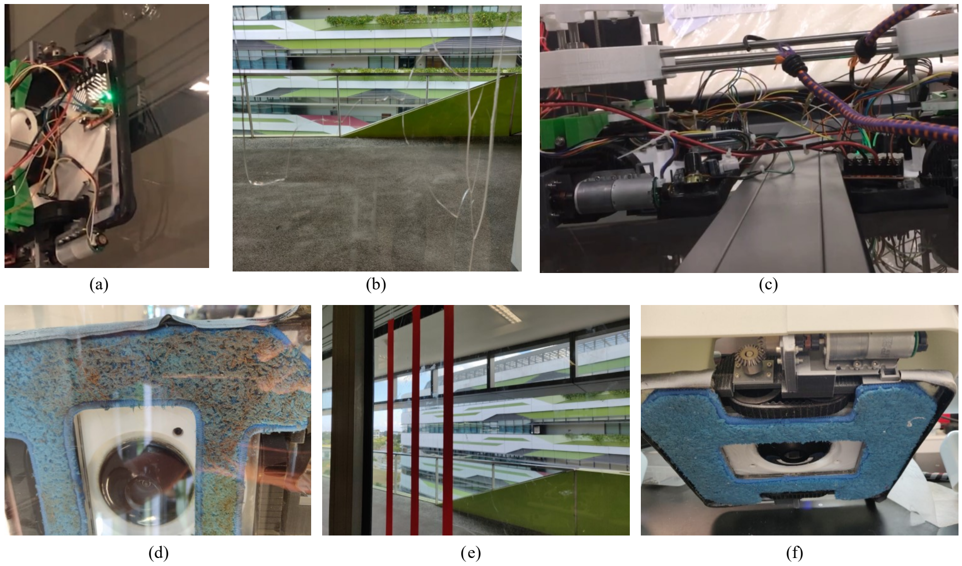

Fig. 5. Testbeds for the different situations; (a): Robot normal operation, (b): Façcades with a crack, (c): Base pad adhesion issue just after a transition, (d): Cleaning towel with more dirt, (e): Façades with stickers, and (f): Base pad peeled off for open condition

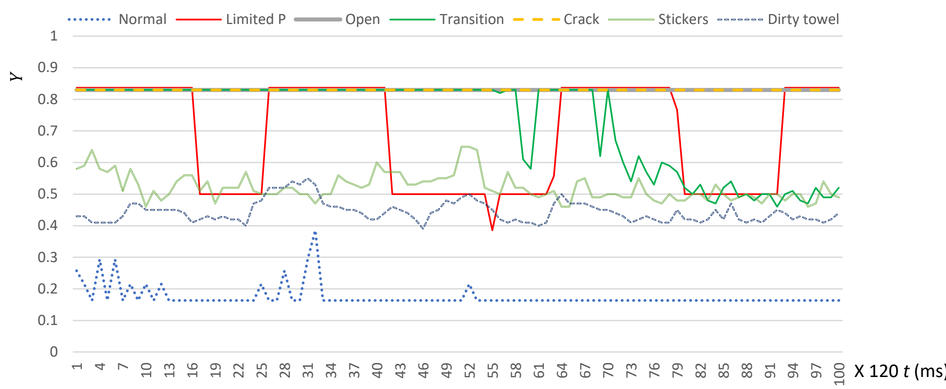

Fig. 6. Variation of the output of the fuzzy inference system Y (i.e., the uncertainty of the adhesion) during different test conditions.

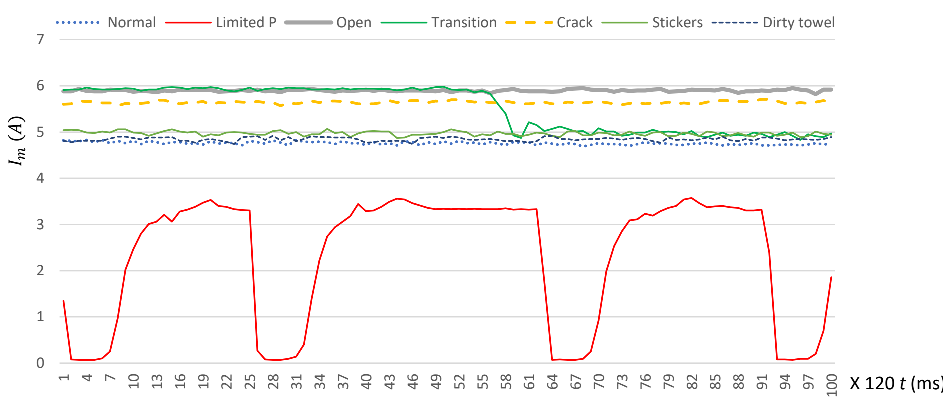

Fig. 7. Variation of the mean current drawn by an impeller motor (i.e., I_m) during different test conditions.

adhesion situation by having a relatively smaller value.

2) Open: The robot's vacuum mechanism was kept fully open in this scenario by keeping it as shown in Fig. 5(f). In this case, the uncertainty of the adhesion (i.e., Y) is at its highest possible value (i.e., 0.837 throughout the considered interval. The reason behind this is the high amount of current drawn by the impeller motor (I_m is around 5.9 A). The intermittency of the adhesion measured through variance of the mean current was low (I_{var} is around 0.00 to 0.01) in this case due to the non-intermittency. The higher value for

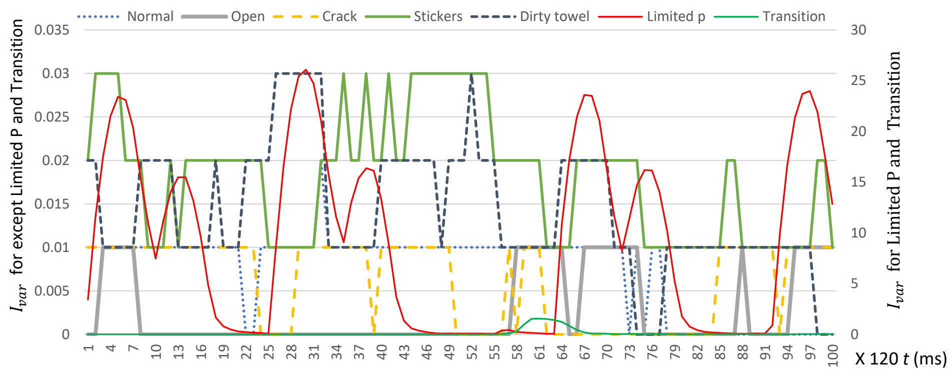

Fig. 8. Variation of variance of I_m (i.e., I_{var}) during different test conditions. It should be noted that the two different scales of Y axis are used here.

the uncertainty of the adhesion indicates the adhesion is not proper. Therefore, this validates that the proposed method can identify such situations.

3) Dirty Towel: In here, the fabric towel of the robot was changed with a towel with dirty particles as shown in Fig. 5 (d). Typically, when the robot cleans glass façades for a quite long time, dirt particles on the glass attach to the towel which acts as the cleaning medium as well as sealing mechanism of the vacuum. In here, we used a fabric towel which was used for a quite long time for cleaning and experimented as similar to the other cases. The mean current drawn by the impeller (I_m) motor was a little bit higher than that of 'normal' operating condition. In addition to that, the intermittency of the current drawn by the impeller motor measured through I_{var} is slightly elevated with respect to 'normal' condition. Therefore, this resulted in a higher uncertainty of the adhesion (Y is around 0.42 to 0.54) which indicates more probability of being 'Vigilant' status. This confirms that the proposed method can recognize the issues of the adhesion aroused due to the attached particles.

4) Limited Power: The power supply of the robot was intentionally limited to provide less power than the amount required by the robot for normal operation, and the robot was allowed to operate on the glass surface as similar to 'normal' condition. In this situation, the mean impeller current has the lowest value among the other cases. It has a cyclic variation as shown in the graph. In some situations, I_m is around 0.08 A, and 3.5 A. If we had merely considered only the mean current, then the adhesion status would have been 'Fine' since the mean current is low in this situation where I_m is around 3.5 A. In contrast, the intermittency of the current drawing was very high (I_{var} is some situations is around 26) resulting criticality of the adhesion. Therefore, the uncertainty of the adhesion was always higher than 0.5, and some situations get moves to the highest possible value (i.e., 0.837) suggesting being 'critical' and 'vigilant' conditions.

5) Stickers on Façades: In here, we pasted some stickers on the glass surface as shown in Fig. 5(e) and the robot was operated on that surface. These stickers create irregularities in the façade surface. Mean current (i.e., I_m) was slightly higher than that of the cases 'Dirty towel' and 'Normal'. In addition to that, I_{var} is also relatively high with respect to 'Dirty towel' and 'Normal' cases. This was due to the intermittency of sealing the vacuum mechanism due to the pasted stickers. Therefore, in this situation, the uncertainty of the adhesion was slightly higher than that of the 'Dirty towel' case. Y is slightly more than 0.5 suggesting a higher probability of being the upper side of 'Vigilant' status. This verifies that the proposed method can identify the danger of the adhesion due to the texture variation caused by the stickers.

6) Crack: In here, the robot was operated to move on a surface that has a crack as shown in Fig. 5(b). Due to the crack, there is air leakage, and this sort of situation might rise to dangerous situations such as falling of the robot due to lack of suction force, further cracking of the glass due to the robot's operation, and sucking of glass particles into the impeller. Therefore, this sort of a dangerous situation should be identified by the proposed method by triggering a higher uncertainty in the adhesion. As expected, the uncertainty of the adhesion determined by the system is around 0.837 which the maximum possible value. This confirms that the proposed system is capable of detecting criticality in this sort of conditions.

7) Transition: In here, a situation where there is a base pad adhesion issue (as shown in Fig. 5(c) just after a transition from a one window frame to another frame was simulated. This sort of situations can be aroused due to the misalignment of the transition mechanism. At the initial stage, the uncertainty of the adhesion status indicates a critical status since Y is at its maximum value. However, after a while, it is decreased to around 0.5 indicating 'Vigilant' conditions. This sudden change is due to the suction force of the robot was capable of attaching to the glass surface to a certain degree than that of initial. Nevertheless, it is not completely fastened, and the condition stays in 'Vigilant'.

In all the seven test conditions underwent, the proposed method is capable of identifying the uncertainty of the adhesion. For example, 'normal' condition has the lowest value with suggesting 'Fine' adhesion. 'Dirty towel' and 'Gap due to stickers' indicate a higher probability of 'Vigilant' status of the adhesion. 'Crack' situation is recognized as 'Critical' by suggesting the maximum possible value for the uncertainty of the adhesion. Therefore, it can be concluded that the proposed method is capable of detecting the adhesion status of a façade cleaning robot by analyzing the current drawn by the impeller. Moreover, the proposed method is capable of establishing the adhesion-awareness of a façade cleaning robot. This adhesion-awareness can be used in the decision-making criterion of the robot's controller to improve its operation. For example, if criticality of the adhesion is detected, the robot's operation could be paused for safety. This integration is proposed for the next stage of the work.

V. Conclusions

This paper proposed a novel method to establish the adhesion-awareness of a glass façade cleaning robot. The adhesion status of a glass façade cleaning robot is one of the crucial factors that ensure the safety and proper operation.

The proposed method uses a fuzzy inference system to analyze the current drawn by the impeller motors of the robot. The fuzzy inference system evaluates the amount of the current drawn and the intermittency for determining the uncertainty of the adhesion, and subsequently to establish the adhesion-awareness.

The proposed method has been integrated into a reconfigurable glass façade cleaning robot 'Mantis' and experiments have been conducted by exposing the robot to different conditions such as normal operation and some possible failure conditions. According to the experimental results, the proposed method is capable of recognizing the uncertainty of the adhesion in each test condition. Moreover, it is capable of establishing the adhesion awareness of a façade cleaning robot. The development of an adhesion-aware decision-making criterion for a robot to improve its overall operation is proposed for future work.

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