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# Window Cleaning System with Water Circulation for Building Façade Maintenance Robot and Its Efficiency Analysis

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*Most maintenance works on building exterior walls are carried out by human labor and a cable-driven system (gondola). This approach involves a safety problem, motivating many recent studies of exterior wall automated maintenance methods. However, the conventional studies have been concentrated only on moving mechanism and the studies on cleaning method and processing of cleaning materials are insufficient. In addition, most conventional automated systems are composed of a roll-brush and injection nozzle. These systems generate problems such as the scattering and dripping of used water resulting contamination of surrounding areas. In order to solve these problems, a new cleaning tool system with water circulation function is developed to improve cleaning efficiency and reduce water usage in this paper. Using the cleaning tool system with the water circulation (injection-squeeze-suction-collection-filtering-recharge) and Pulse Width Modulation (PWM) flow control, the scattering and dripping was removed and the water usage was reduced about 20%. Also, this cleaning tool system was compared to manual work by human experts as well as previously developed automated (or semi-automated) cleaning robots through statistical analysis.*

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## 1. Introduction

Recently, most of buildings have been constructed with façade systems such as a curtain glass wall rather than with concrete as a traditional way. The contemporary high-rise buildings with the glass facades require periodic maintenance, especially window cleaning, due to excessive dust and pollution in the city.[1] Conventional maintenance usually relies on human labors and a gondola that is suspended by cable-driven system. However, these methods require experienced labors, are inherently danger, and sometimes cause emergency situations when occurring wind gust or earthquake.

For these reasons, many studies have been conducted on the subject of automating window cleaning work of high-rise buildings. Since the building walls are always vertical and are in the direction of gravity, the ability of locomotion on the vertical surface has been important issues.[2,3] Thus, there have been many studies regarding how to generate the holding force against the gravity, such as magnetic force,[4,5] suction force,[6-10] suspended cable,[11-20] guide rail built-in the building wall facade,[21-24] and biomimetic adhesion force.[25-27] However, only the suspended cable and built-in guide rail based systems have been applied to real buildings, since others are not reliable enough yet.

SkyPro[11] that is a very recent commercial building cleaning system uses a crane system installed on the building roof. This system requires two operators, with one operator on the roof and the other operator on the ground to help move and rig the unit from one cleaning section to another. In addition, this system performs the cleaning operation by adhering to the building wall by a suction fan. Qian et al.[12,13] carried out research with a similar moving method using a crane system on the roof. Unlike the conventional methods, they developed a new adhesive method utilizing non-actuated dual suction cups on the exterior wall of a high-rise building. This system avoids a prominent frame of the exterior wall using photo-electric sensor and perpendicular motion based on linear motor. Similarly, Elkmann et al.[14,15] developed the SIRIUS_c that was basically hoisted by a crane system installed on the roof. In addition to this moving method, this system was equipped with an additional mechanism, named 'advanced sliding frame mechanism,' which performs vertical-horizontal motion in a relatively small local region for cleaning work.

As can be seen above, the most existing research on building maintenance automation has focused only on the moving mechanism and the cleaning method and material handling that are practically important have not been addressed in a systematic as well as scientific way. The roll-brush method, often used in the conventional systems, has an advantage on cleaning efficiency but requires large amount of water. This excessive use of water causes additional environmental pollution due to scattering and dripping of contaminated water in the surrounding area.

In this paper, a new cleaning tool system is developed to improve the cleaning efficiency. In particular, this system uses fine mist water spray by two-phase injection nozzles and Pulse Width Modulation (PWM) flow control. The water usage is further minimized by using a water circulation system (injection-squeeze-suction-collection-filtering-recharge) instead of simple water injection and cleaning. These methods greatly reduce environmental pollution due to the dripping and scattering of contaminated water. In addition, the proposed tool system was verified through experimental tests and statistical analysis of their results, in which the amount of water usage and cleaning efficiency was measured and compared with existing cleaning methods.

## 2. Building Façade Maintenance Robot

The first rail guided exterior wall robot was developed in 1985 for painting application and applied in 1988 to the Shinjuku Center Building in Tokyo by Taisei Corporation. Also, the first vertical-horizontal cleaning robot (Oyako Robot) has been applied by Nihon Bisoh in 1993 to the Landmark Tower in Yokohama. Both systems were inspired by the notion of Robot Oriented Design (ROD) by Bock.[22] However, they were semi-automated system and the first fully automated robot was developed by Moon et al..[23,24]

Fig. 1 shows an overview of the Building Façade Maintenance Robot (BFMR) that was developed by Moon et al.. It consists both of horizontal and vertical robots. The horizontal robot carries out window cleaning work while moving along a horizontal rail. The vertical robot transports the horizontal one to another up/down level also along with a vertical rail. The guide rails are built into building façade frames, that is, horizontal transom and vertical mullion. The mullion rail safely holds the vertical robot and guides its vertical motion, using a winch wire system installed on the roof. The transom rail helps the horizontal motion using the driving wheels fixed on the top of BFMR body, while the passive wheels in the bottom rail simply guide the robot.

The vertical robot is equipped with separate piece of horizontal rails that has same cross section and vertical interval to the transom rails, so that the horizontal robot can slide and completely dock into the vertical robot to be transported to another level. For the inter-floor circulation, the vertical robot system has additional mechanisms, that is, rail brakes and rail extensors as shown in Fig. 2. The rail brakes securely hold the vertical robot when the horizontal one docks into, which greatly improves system safety. The rail extensors are protruded during the docking process to fill the gap between the transom rail and the horizontal rail piece that is installed in the vertical robot. The gap is necessary to ensure motion safety margin when the vertical robot

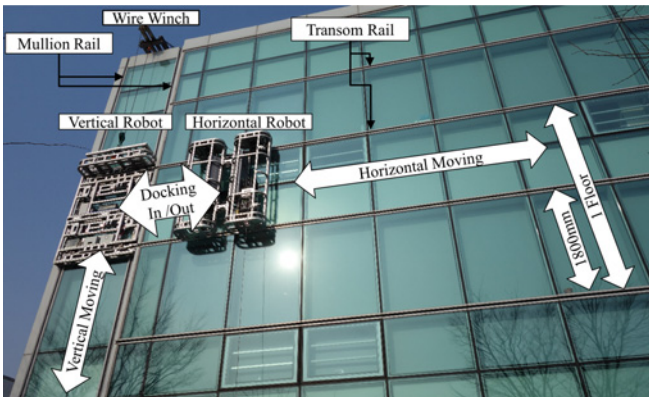


Fig. 1 System overview of building façade maintenance robot[23,24]

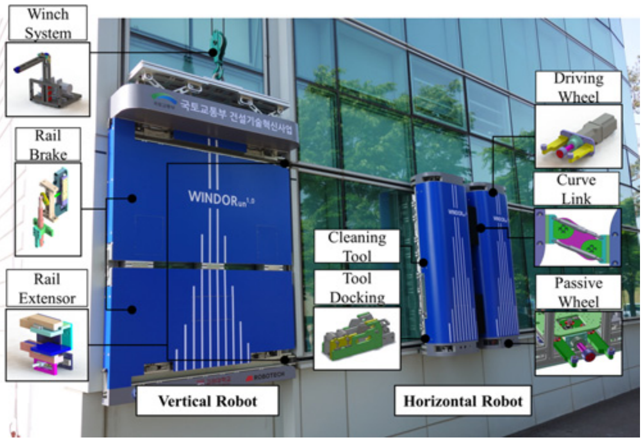


Fig. 2 Components of building façade maintenance robot

moves along the mullion rails.

The horizontal robot is composed of two symmetric units that are tightly linked together with spring-damper loaded hinges. This is to ensure smooth movement even for the façade that has curved shape in top view. The horizontal robot also has tool docking devices that can quickly snap-in and out a maintenance tool. The maintenance tool could include cleaning, inspection, painting, etc., while this paper only deals with a cleaning tool.

## 3. Window Cleaning Tool System

The window cleaning process consists of four consecutive steps: water spraying, squeezing, suctioning, and recycling. Accordingly, the tool system has four different modules corresponding to the steps. The squeezing module is made to ensure continual contact to the glass with a consistent contact angle between the squeezing rubber blade and the glass surface. The continual contact as well as the angle is maintained by two active joints as shown in Fig. 3. One is a prismatic joint that moves perpendicular to the glass and the other is a rotary joint that can adjust the contact angle to the glass surface.

The suction module is somewhat coupled with the squeezing module. That is, the suction holes are located right behind the squeezing blade as shown in Fig. 3, so that the water sprayed on the glass can be effectively retrieved right after squeezing without dripping. The water spray module has four injection nozzles and each

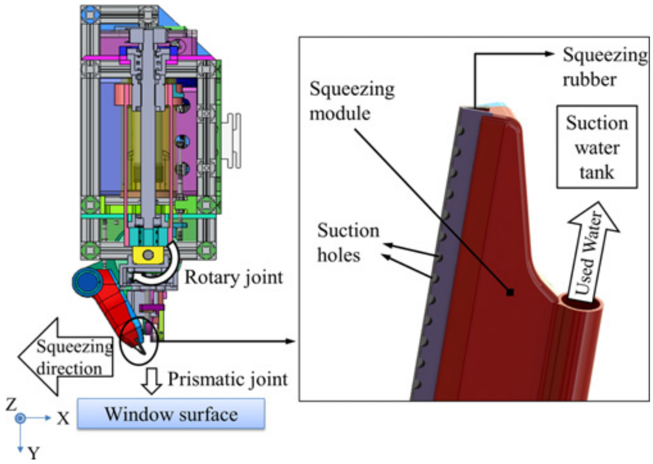


Fig. 3 Squeezing module with suction holes

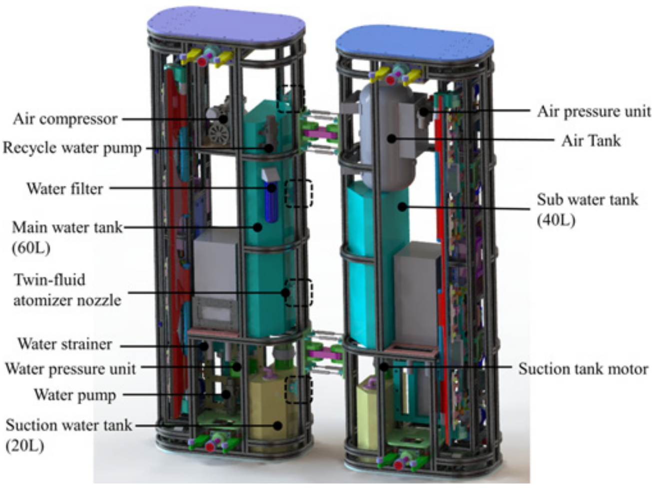


Fig. 4 Configuration of injection and recycle unit

nozzle covers 450 mm of cleaning area of 1800 mm. Thus, the cleaning water can be sprayed on entire vertical area at once. The water is mixed with compressed air and sprayed out in a fine mist form. At this time, the water is supplied from main water tank of 100 L and the compressed air from air tank. The used water is recovered to the main water tank by the water pump after filtering process in the recycle system.

Fig. 4 shows the configuration of the injection and recycle unit. Each part of the cleaning tool system consists of an independent control board and communicates with each other through CAN protocol for integrated control.

Fig. 5 represents the whole process of cleaning and recycling for window cleaning tool system.

## 4. Prevention of Water Dripping and Scattering

Most of conventional systems require excessive water and a large amount of water is rebounded and scattered when sprayed directly on the window surface.[28,29] In particular, splashing of used water will result in complaints from pedestrians and car owners around the building. Also, the environment around the building is contaminated by the used water that is scattered in the air. Because of these issues,

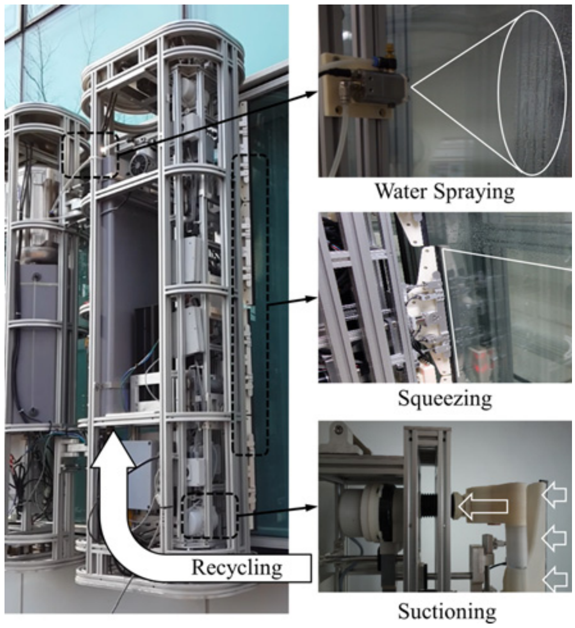


Fig. 5 Whole process of cleaning and recycling

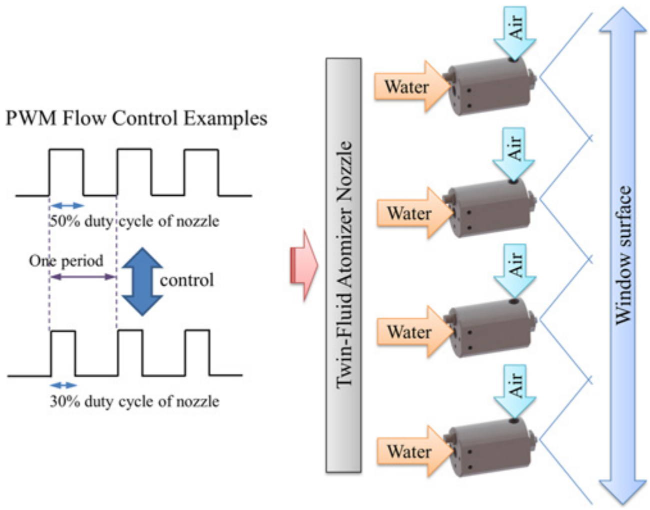


Fig. 6 PWM flow control for the water usage minimization

substantial restrictions are in general in the building cleaning regulations. In order to solve these problems, two important issues need to be addressed: minimization of water usage and prevention of water dripping and scattering.

Firstly, in order to reduce the excessive water usage in the cleaning operation, a PWM flow control was applied to the injection nozzles shown in Fig. 6. Also, the cleaning water can be injected uniformly on the glass with less water by applying a twin-fluid atomizer method which uses a mixture of water and air. When the PWM flow control (which enables an open-and-close control of a nozzle at 10,000 times per minute) is applied to the water spraying process, the amount of water required to cover the same area can be reduced considerably compared to existing injection system.

In the proposed cleaning tool system, the distance between the nozzles and the window surface can change instantaneously when the robot moves on a curved part of the exterior building wall, because the nozzles are eccentric in the center position of the horizontal robot. In

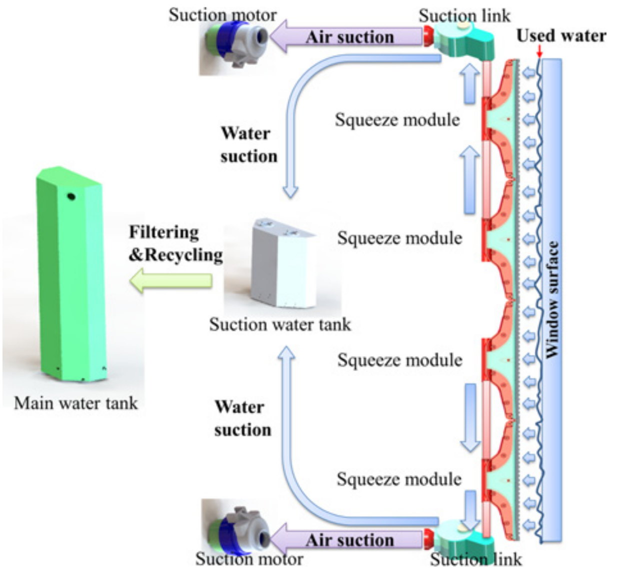


Fig. 7 Scattering and dripping prevention process with water circulation system


Fig. 8 Cleaning process by human labor

these circumstances, the water injected at curved surface is not evenly distributed and scattered in the air. So, the injection control unit is needed to adjust the amount of water spray in accordance with the moving speed and position of the horizontal robot. That is, by controlling the injection of water in the curved part, water spray can be uniformly distributed on the window surface.

The specially designed rubber blade that features with the suction holes right behind the squeezing edge enables simultaneous squeezing and suction of water. This prevents water dripping while squeezing the water and residual stain by eliminating the time to dry out the water on the glass surface. The used water collected by the suction module is temporarily stored in the suction water tank. When a predetermined amount of used water is collected in the suction water tank, this water is again retrieved to the main water tank after filtering process. The scattering and dripping water prevention process using the water circulation system is presented in Fig. 7.

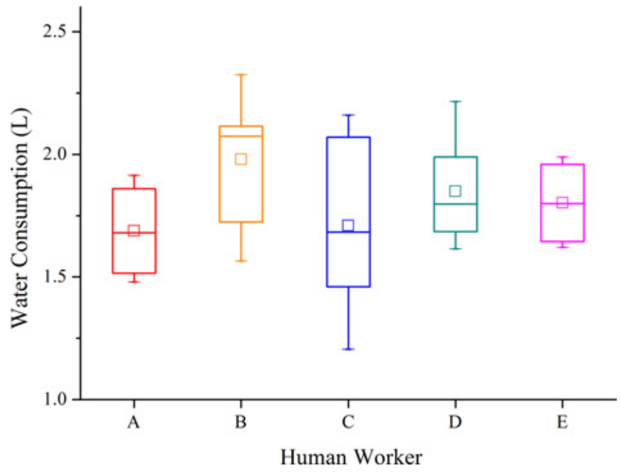


Fig. 9 Box plot for water usage by five workers

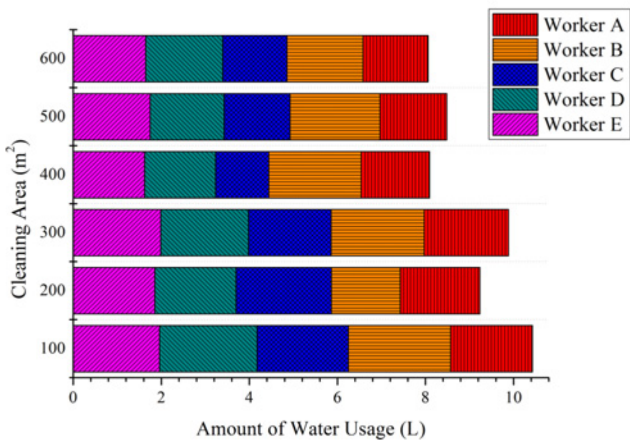


Fig. 10 Water usage per cleaning area by human labor

The series of these two complementary processes enhances the efficiency of the cleaning operation compared to that of the conventional cleaning methods. In the following chapters, the advantages of the BFMR system with the water circulation system will be evaluated through a more systematic analysis method.

## 5. Analysis of Water Usage of Existing Cleaning Methods

In order to validate the feasibility of the proposed system, the efficiency of the existing cleaning methods are investigated, which includes manual cleaning work by human labor and autonomous (or semi-autonomous) cleaning robots announced previously.

In case of the manual cleaning by human labor, real cleaning work was conducted by five experienced operators on a ten-story building and the water consumption and working time were measured in detail. The manual cleaning work consists of four consecutive steps: preparation of cleaning supplies, wire rope knotting, hanging sown the rope, and cleaning window as shown in Fig. 8. Before starting the window cleaning, all cleaning supplies are transported to the roof and all necessary ropes are knotted and hung down from the roof.

The manual cleaning work was conducted on a ten-story building and the water consumption was measured by a precise weighing scale.

Table 1 Specification of building façade robot system

| Building Façade Maintenance Robot system (BFMR) | |
|---|---|
| Dimension | 1600 × 1970 × 545 |
| Weight | 300 Kg |
| Cleaning velocity | 4.2 m/min |
| Cleaning width | 1.6 m |
| Cleaning efficiency | 403.2 m$^2$/hour |

Table 2 Cleaning time per water replacement cycle by five worker

| Water replacement cycle | Worker | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 1 cycle | 30m 51s | 32m 24s | 28m 43s | 33m 12s | 29m 36s |
| 2 cycle | 23m 17s | 21m 46s | 19m 57s | 24m 21s | 22m 45s |
| 3 cycle | 18m 32s | 19m 44s | 15m 39s | 17m 59s | 18m 13s |
| 4 cycle | 13m 28s | 15m 37s | 16m 43s | 14m 12s | 16m 23s |
| 5 cycle | 20m 02s | 18m 36s | 19m 45s | 21m 44s | 18m 49s |
| 6 cycle | 14m 42s | 16m 27s | 18m 33s | 15m 03s | 19m 11s |

Five operators were employed for the cleaning operation and the cleaning water was replaced six times during the entire cleaning area of 626.4 m$^2$ of the ten-story building. At this time, the water replacement cycle is defined to clean for a constant area of about 20 m$^2$ per individual worker. Table 2 represents that spending time per one cycle by human labor. This time includes the preparation time and the intermission time. The total cleaning time by the five workers for the ten-story building was spent approximately two hours. In Fig. 9, a box-plot graph shows the water consumption during the cleaning operation by an individual worker. Fig. 10 shows that 54 L of water is consumed to clean of the ten-story building by five operators. This data is verified that the individual worker used to about ten liters of water for total cleaning area during 2 hours.

In case of the existing cleaning robots, each individual system was surveyed through literatures and their water consumption and cleaning efficiency (cleaning area per hour) are listed in Table 3. Many of them use water spray and roll-brush cleaning method. In this case, these robots spend a large amount of water, sometimes more than 100 L per hour, depending on its body size.

However, the other robot systems spend small amount of water since they use different cleaning methods. WINDORO system developed by Ilshim Global, for example, is operated in tandem with two robots located on the inside and outside of the window glass.[5] The inside robot works as a navigation system for the outside robot and the outside robot performs the cleaning work using spinning microfiber pads with an exclusive detergent. This system does not use water for the cleaning operation but it has the disadvantages that is adequate only for small cleaning area and requires human intervention to move other window area.

The SIRIUSc façade cleaning robot by Fraunhofer was developed for high-rise buildings.[14,15] Unlike other conventional systems, this system has low cleaning efficiency (80 m$^2$ per hour) because it was made up of small cleaning tools using steam evaporation. Thus, it consumes only a small amount of water, 1.5 L per hour, for cleaning operation. However, this system is difficult to apply a wide cleaning area, and the tool system using steam evaporation is not easy to apply in general robot systems.

Table 3 Water consumption and cleaning efficiency of existing robot systems

| Manufacturer | Robot Type | Water Consumption (L/hour) | Cleaning efficiency (m$^2$/hour) |
|---|---|---|---|
| Sky Pro[11] | Single Skydrowasher | 792 | 446-580 |
| | Dual Skydrowasher | 1770 | 893-1160 |
| | 1.8M SkyPro Brush Machine | 408 | 1186 |
| | 2.4M SkyPro Brush Machine | 546 | 1580 |
| | 3.7M SkyPro Brush Machine | 816 | 2437 |
| | Mini | 114 | 402-622 |
| | Mini Sprayer | 545 | 430-664 |
| Jiaotong University[12,13] | Dual suction cups | 50 | 200 |
| Fraunhofer[14,15] | SIRIUS_c | 1.5 (steam evaporation) | 80 |
| Hamburg University[17] | Sky Cleaner 1 | 50 | 37.5 |
| | Sky Cleaner 2 | 50 | 75 |
| | Sky Cleaner 3 | 50 | 125 |
| IPC Eagle[18] | HighRise202 | 228 | 1200 |
| | HighRise303 | 342 | 1800 |
| | HighRise404 | 456 | 2400 |
| | HighRise505 | 570 | 3000 |
| Manntech[19] | Façade Cleaning | 150 | 500 |
| Beihang University[20] | SkyBoy | 30 | 95 |
| Ilshim[5] | WINDORO | 0.04 (only detergent) | 62 |
| RoboSoft[8] | robuGLASS | 4 (water + product) | 800 |
| Serobot[9] | Gekko Façade | 30-90 | 645 |
| Ecovacs[10] | WinBot | 0.1 (only detergent) | 125 |
| Korea University[23,24] | BFMR | 8.7-10.8 | 403.2 |

The RoboSoft, was developed to clean the glass roof of the Pyramide du Louvre in Paris every 3 weeks.[8] This system performs the cleaning operation for the sloped glass, and is connected to a truck which provides power to run the system. This robot moves using a set of tracks and suction cups to adhere to the surface. 4 L per hour of cleaning water is consumed by the cleaning system which is made of a roll-brush and a drying blade. Unfortunately, this system has a disadvantage that it is not possible to apply on the exterior wall of perpendicular angle.

## 6. Water Usage Analysis of BFMR System

Human labors usually apply cleaning water using sponge device to the glass surface. After that, the applied water is quickly removed by using squeezing rubber blade before drying it out and its cleaning quality is determined through visual observation. Nowadays, they only use water because detergent can cause environmental pollution and

(a) Before cleaning

(b) After cleaning

Fig. 11 Cleaning result comparison by BFMR

corrosion of window frame.

The cleaning process by the BFMR is similar to that by the human labors. That is, the cleaning water is evenly sprayed to the glass surface using the water spray module. The applied water is removed by using squeezing module. The squeezing module of BFMR is similar to the existing rubber blade by human labors. As such, the cleaning quality by both methods were analogous based on heuristic evaluation, which was previously reported by Shin and Moon et al..[24] In Fig. 11, window status is shown before and after cleaning by the BFMR.

Based on these results, the cleaning operation by the BFMR system was analyzed under the same condition as that by human labor. Table 1 represents the specification of the BFMR system. The cleaning operation of BFMR system is performed the speed of 4.2 m/min. In this case, the cleaning efficiency is 403.2 $m^2$/hour.

For more precise analysis, the t-test was used. Firstly, the water usage was compared by average verification (95% confidence interval) between the manual work and the BFMR without the Water Circulation System (WCS) using independent t-test. Depending on the cleaning time in Table 2, the evaluation was conducted with 6 samples in each case. The data sample for the water usage is presented in Table 4. On the mean values, the mean of the water usage by human labor is 9031 mL, and the standard deviation is 986 mL. By contrast, the

Table 4 Data sample of the amount of water usage by human labor and the BFMR system according to cleaning time

| Water replacement cycle | Water usage by human labor | Water usage by BFMR system |
|---|---|---|
| 1 cycle | 10430 mL | 5544 mL |
| 2 cycle | 9236 mL | 4118 mL |
| 3 cycle | 9885 mL | 3221 mL |
| 4 cycle | 8090 mL | 2327 mL |
| 5 cycle | 8484 mL | 3579 mL |
| 6 cycle | 8060 mL | 2686 mL |

Table 5 Independent t-test statistics between human labor and BFMR without water circulation system

| | Sample N | Mean (mL) | Std. Deciation | dof | t value |
|---|---|---|---|---|---|
| Human labor | 6 | 9031 | 986 | 10 | 8.8* |
| BFMR without WCS | 6 | 3579 | 1153 | | |

*$p < 0.001$

average of water usage by the BFMR is 3579 mL and the standard deviation is 1153 mL. These results show that the water usage has a range of mean difference between the minimum of 4072 mL and the maximum of 6831 mL during six water replacement cycles in confidence intervals of 95%.

As shown in Table 5, this is recognized statistically by the comparison between human labor and BFMR without the WCS. T-value is 8.8 and the significant probability $p$ has a value lower than 0.001 ($p < 0.001$). Thus, the mean of water usage has statistically significant difference between two cases. These results represent that the water usage by the BFMR without the WCS is meaningfully less than that by the human labor.

Similarly, the water usage was compared between the BFMR with and without the WCS. The water consumption was measured at the interval of four-minutes over 20 samples as shown in Table 6. At that time, the amount of water was precisely regulated with the developed Pulse Width Modulation (PWM) nozzle flow control.

Table 7 shows the paired t-test statistics for this case. The mean of the water usage by the BFMR with the WCS is 578 mL and its standard deviation is 2.1 mL. By contrast, the mean by the BFMR without the WCS is 714 mL and the standard deviation is 5.3 mL. Thereby, these results show that the water usage has a range of mean difference between the minimum of 133.7 mL and the maximum of 139.2 mL in confidence intervals of 95%. In this case, t-value is 103.6 and the significant probability $p$ has a value lower than 0.001 ($p < 0.001$). Thus, the mean of the water usage has statistically significant difference between presence/absence of the WCS.

The statistical comparison for both cases showed that the water consumption is reduced by about 20% with the water circulation method. This is because most of water is rebounded from the glass surface and dried out into the air when sprayed. 20% of reduction is not big but certainly helps to increase cleaning area with one loading of water on the robot, which greatly affects the design of a compact and light-weight robot. Also, note that the main advantage of the WCS is

Table 6 Data sample of the amount of water usage with/without water circulation system at intervals of four-minutes

| Amount of water usage with water circulation system | | | |
|---|---|---|---|
| Count | Water (mL) | Count | Water (mL) |
| 1 | 582 | 11 | 578 |
| 2 | 575 | 12 | 577 |
| 3 | 573 | 13 | 570 |
| 4 | 576 | 14 | 574 |
| 5 | 579 | 15 | 570 |
| 6 | 585 | 16 | 581 |
| 7 | 589 | 17 | 579 |
| 8 | 583 | 18 | 584 |
| 9 | 577 | 19 | 576 |
| 10 | 569 | 20 | 580 |
| Amount of water usage without water circulation system | | | |
| Count | Water (mL) | Count | Water (mL) |
| 1 | 712 | 11 | 711 |
| 2 | 714 | 12 | 716 |
| 3 | 711 | 13 | 715 |
| 4 | 715 | 14 | 719 |
| 5 | 713 | 15 | 715 |
| 6 | 718 | 16 | 713 |
| 7 | 714 | 17 | 714 |
| 8 | 712 | 18 | 713 |
| 9 | 716 | 19 | 714 |
| 10 | 714 | 20 | 717 |

Table 7 Paired t-test statistics of the BFMR with/without water circulation system

| | Sample N | Mean (mL) | Std. Deciation | dof | t value |
|---|---|---|---|---|---|
| BFMR without WCS | 20 | 714 | 2.1 | 19 | 103.6** |
| BFMR without WCS | 20 | 578 | 5.3 | | |

$^{**}p < 0.001$

to prevent water dripping and scattering, so that there is no contamination around the building.

## 7. Conclusions

A new cleaning tool system with a water circulation function was introduced in this study. Together with the building façade maintenance robot, the new cleaning tool certainly reduces water usage compared to manual cleaning by human labor and conventional automated building cleaning machines. Especially, the water circulation system solves the problem of scattering and dripping of used water by applying suction and recycle processes, thus preventing the contamination of workplace and surrounding areas. This study validates the effectiveness of the proposed system by using a t-test and comparing water usage to the conventional methods. Although the water reduction by the proposed system was not big (about 20%), it certainly helps to increase cleaning area with one loading of water on the robot, which greatly affects the design of a compact and light-weight robot.

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