Design and Fabrication of a Window Washer Prototype for High-Rise Buildings

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Abstract

Window cleaning or window washing is the task that involves exterior cleaning of glass used for structural, lighting, and decorative purposes. It can be done manually, using a variety of tools for cleaning and access. More recently, in high tech societies, the use of fully automated robotic window cleaners is starting to become common. However, cleaning high glass and windows can be a very risky job and presents very real dangers to the operative. High-rise window and glass cleaning used to be one of the most dangerous jobs in the world with many fatal accidents occurring each year. Luckily in recent years with the advent of new technologies, the risk has decreased significantly but safety among operatives who carry out these high-risk cleans is still paramount. Given this condition, it became the research interest of the authors to design and fabricate a semi-automated window washer for high-rise buildings wherein the prototype is controlled using an Arduino system. The design and fabrication consist of three parts: the design of the hydraulic system, the automation system, and the mechanical system. Each material used in the prototype was properly tested and calculated to carry the load of the whole prototype with the window-cleaning features. Therefore, it can be concluded that the semi-automated window washer prototype can be effectively used in the cleaning of windows for a high-rise building.

Keywords
Window washer, design and fabrication, high-rise building, prototype

1. Introduction
A robot is a machine that can do a complex task accurately and precisely. It can be programmed through a computer and are classified to be automated, semi-automated, or remotely controlled (Oxford Dictionaries, 2016). Industrial robots were invented and now, there is a very high demand for industrial robots. According to Statista (2015), worldwide shipments of multipurpose industrial robots are forecasted to exceed 207,000 units in 2015, up from around 159,000 in 2012. Rosenbaum (2012) stated that robots are used to replace people whose jobs are either risky or repetitive. Along with this, today's civilization continues to develop; many buildings are constructed each year. In a construction statistic in the Philippines, the number of total constructions increased by 4.0 percent compared with the constructions recorded in 2014. Therefore, the need for window cleaning became higher as building construction increases.

Window cleaning or window washing is the task that involves exterior cleaning of glass used for structural, lighting, and decorative purposes. It can be done manually, using a variety of tools for cleaning and access. More recently, in high tech societies, the use of fully automated robotic window cleaners is starting to become common (www.gizmag.com).

However, cleaning high glass and windows can be a very risky job and presents very real dangers to the operative. High-rise window and glass cleaning used to be one of the most dangerous jobs in the world with many fatal accidents occurring each year. Luckily in recent years with the advent of new technologies, the risk has decreased significantly but safety among operatives who carry out these high-risk cleans is still paramount (www.ccscleaning.com).

To address the hazards in manual window cleaning of high-rise buildings, the researchers intend to design and fabricate a semi-automated window washer prototype. The research design will be divided into two parts: the design of the window washer main body and its carrier system. The researchers aim to make the two systems to function properly by setting the actuation time of each component for a whole cleaning process and calibrate it to make the systems work efficiently. Also, it aims to design a functioning hydraulic system for the window washer prototype and to conduct testing on the hydraulic system design that will measure the volume used by the prototype in one process, the volume flow rate of the liquids and the speed of the liquid from the pump to the solenoid valves.

This research design is limited to cleaning windows with flat surfaces only. The prototype is designed to do segmented cleaning like a column by column cleaning of the building windows. The volume of the liquid soap will not exceed 11.3 liters. The base of the prototype will be placed at the top of the building to disregard the water pressure. A 3x4-foot glass is used for the testing of the prototype. Air resistance, drag, and friction force are not considered in the study.

1.1. Hydraulic System and Components

The hydraulic system is composed of the following components which were researched and calibrated in connection with the automation and mechanical system. The pure water and liquid soap used the same hydraulic system. The connection diagram for both the pure water and liquid soap hydraulic system is shown in Figure 1. The components used in the hydraulic system include pump, hose, solenoid valves, nozzles, coupling, T-tube fitting, liquid soap, and water containers.

The researchers used a hose that is capable of transferring water and the liquid soap even if it is rolled. After examining every type of water hose, the researchers decided to use a plastic rubber-type garden hose for the inlet water in the pump which has a diameter of 0.5 inches and a length of 3 meters from the container. For the outlet, the researchers used a 10mm rubber-type clear tubing hose with a length of 5 meters measuring from the solenoid valve.

Since the pump needs a steady flow for it to work efficiently, the flow of water must continue even if the solenoid valves are closed. To do that, a T-tube fitting was introduced. A T-tube fitting works in a way that when the solenoid valve is closed, the liquid will be transferred back to the container until the solenoid valve opens again.

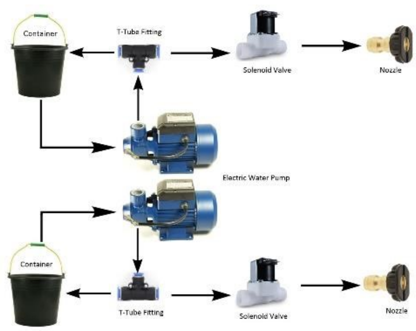

Figure 1. Connection Diagram of the Hydraulic System

1.2. Automation System and Components

Two automated systems were used for the prototype: the window washer and the carrier system. The two systems are synced with correct timing or delay in the codes uploaded to each Arduino module for each system. Figures 2-3 show the schematic diagrams for window washer and carrier system respectively. The components used for the two systems include the following: Arduino, breadboard, DC motor, servo motor, solenoid valves, diodes, resistors, BJT, MOSFET, AC adapter, and batteries.

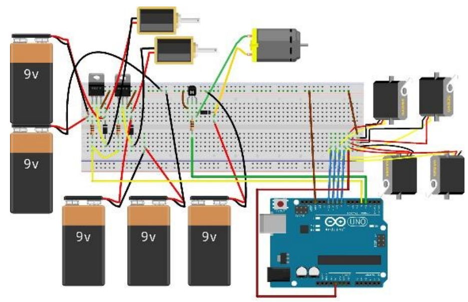

Figure 2. Window Washer Prototype Schematic Diagram

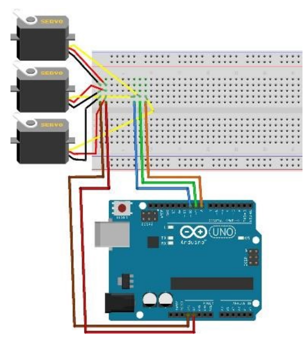

Figure 3. Carrier System Schematic Diagram

1.3. Mechanical System

The mechanical system is responsible for the housing of hydraulic system components, automation system components, mobility, and stability of the prototype. The researchers considered two concepts relating to stability which are pulley system and rail and cab system that was adapted from previous studies (Alexander et al., 2007).

The pulley system mechanism has a rod attached to the top of the window supported by a motor system. The ropes with the pulley system allow the window-cleaning robot to move vertically. To allow a horizontal movement, the rack of the pulley which carries out a rotary motion will be manually adjusted. Also, the railing is needed to execute linear motion in which it is supported by the system. For safety purposes, guidelines are fixed on the output and the other on the railing connected in tension at the top of the building (Alexander et al., 2007). The graphical representation of a pulley concept is shown in Figure 4.

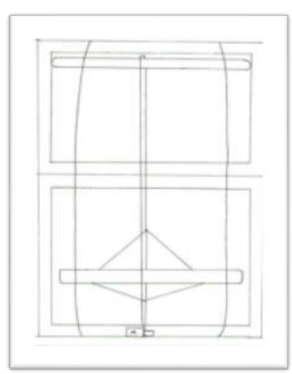

Figure 4. A graphical representation of a pulley concept
(Source: Winrobo Window-Washing Robot 2007)

Rail and cab are similar to the pulley concept. In this concept, a rover has a railing as a guide for the movement of the cab which contains the motor and the system of the output. The wheels of the cab will allow the rover to move vertically. The railing is close to the glass surface in which it can also be adjustable for different areas of the window by using the pulley system (Alexander et al., 2007). A graphical representation of a rail and cab is shown in Figure 5.

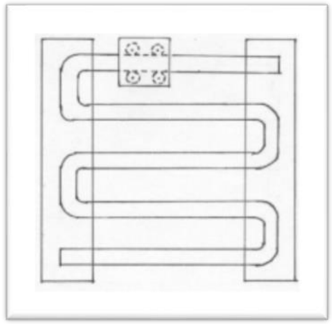

Figure 5. A graphical representation of a rail and cab concept
(Source: Winrobo Window-Washing Robot 2007)

The components used in the mechanical system include the following: roller wheels, aluminum, nylon rope, acrylic, and zinc-plated full-extension ball-bearing slide runners.

2. Methodology

The process flowchart for the design of the hydraulic system, automation system, and mechanical system is shown in Figure 6. The torque needed to lift the weight of the window washer and its track would determine the two servo motors that were needed on each corner of the track and one servo motor for the window washer. The velocity of the window washer gave the researchers the correct time delay for the servo motor for the window washer to stop and go on the reverse, back to its initial position. The Ohm's law was used to obtain the voltage enough to run the motors and solenoid valves. This was also used to obtain the current needed by the Arduino to supply its servomotors.

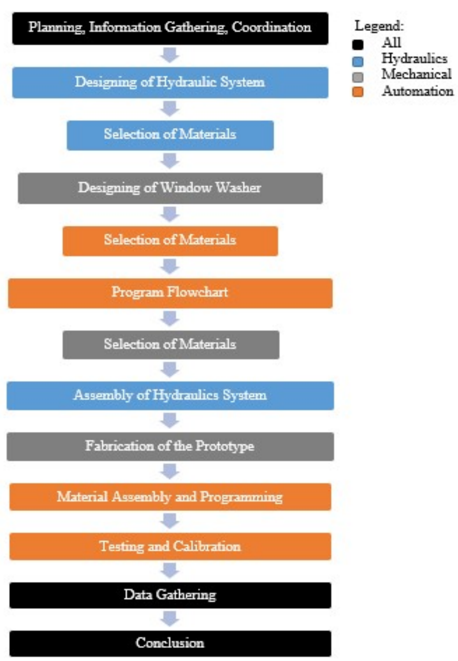

Figure 6. Process Flowchart

The process of the window washing prototype starts from the water container that provides adequate water and liquid soap needed for the window washing. Then, water is transferred to a water pump which is connected to a hose. The water from the water pump then travels through the T-tube in which two hoses are connected, one is connected to the solenoid valve, then the other is connected to the water source in the cylindrical plastic container. This is accomplished so that when the solenoid valve is closed, the water will just return to the storage container, thus, creating a steady flow. The solenoid valve that is controlled by the automation system is responsible for the discharge of water in the prototype. The liquid soap used the same system. The positioning of the carrier system on the high-rise building is also considered in the research design to maintain the stability of the track and the window washer. The prototype can be controlled vertically to position the track containing the window washer along the glass surface while the body of the carrier should be horizontally positioned for the mobilization of the window washer and track. There will be a carrier system for the track and the window washer. For the track, both ends have pulley ropes to secure it from moving sideways. For the window washer, it has ball bearings in the standard slide runners to support the mainframe so that it will not slip from the track. The window washer has multiple components such as the squeegee, brush, and nozzle for the water and liquid soap. An acrylic plastic sheet is used for the housing of these features considering that this material is chemical resistant and light-weight for the pulley system since the 3kg main load is suitable for a 5-mm nylon rope. A sequence of processes for the design of the automation system is shown in Figure 7.

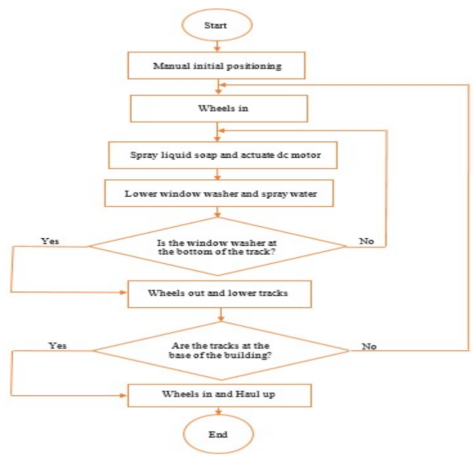

Figure 7. Program Flowchart – Automation System

The vertical movement and the cleaning operation of the window washer were semi-automated and controlled using an Arduino. An Arduino module was programmed for the window washer and another Arduino for its carrier system. The two systems were synced with proper timing or delay. A trial connection was done in a breadboard to guarantee that the components are working properly as programmed. Then, the electronic components were installed in collaboration with the mechanical and hydraulic group. After the window washer prototype has been fabricated, it was tested in a sample segmented window to check its automation and controls. First, the prototype was positioned to ensure its safety. Then the Arduino was powered to start its operation. The electronic components' actuation time, response time, discharge water pressure, velocity, and effective cleaning width were observed and analyzed by the researchers. Then, based on the testing operation of the prototype, the delay codes were calibrated to match the two systems.

3. Results and Discussion

3.1. Time Test

In this test, a stopwatch is used to measure the amount of time the window washer prototype takes to finish a single process. Table 1 shows the recorded values after finishing all ten trials. The results for this test were precise with minor fluctuations. The average was taken and was further assessed by comparing it with the delays which were set in the Arduino.

Table 1. Recorded Time

Trial	t (s)
1	42.83
2	42.76
3	42.36
4	43.61
5	43.82
6	44.36
7	43.21
8	43.01
9	43.70
10	42.61
Average	43.227

3.2. Delay in Arduino

Table 2 shows the encoding delay time in the Arduino as well as the description of each delay command in the Arduino program. Based on the data, the theoretical or expected time that the entire window washing of a 3x4-foot glass panel will take to complete is 42 secs.

Table 2. Arduino Delays

Time Description	Window Washer (s)	Time Description	Carrier System (s)
Wheels retract	1	Middle sheave rotates	5
DC Motor and Solenoid Valve Actuate	5	Middle sheave stops rotation	1
Wheels actuate	8	Side sheaves rotate	8
Wheels retract	1	Side sheaves stop rotation, Middle sheave rotates	5
DC motor and Solenoid Valve actuate	5	Middle sheave stops rotation	1
Wheels actuate	22	All sheave reverse rotation	14
		Side sheaves stop rotation	8
TOTAL	42	TOTAL	42

3.3. Comparison of Arduino Set Time and Recorded Time to Complete One Process

To compare the theoretical value and the experimental value, the researchers used the percentage error formula shown in equation 1. percentage error is below 5% which signifies that the difference between the theoretical and experimental time is relatively small. Therefore, the computed expected time to complete one glass panel of window washing is acceptable.

$$\%\ Error = \frac{|E.V. - T.V.|}{T.V.} \times 100 \tag{1}$$

3.4. Downward and Upward Velocity

Table 3 shows the time for the window washer prototype to reach the bottom track and time to return to its initial position, as well as the measured velocity during the process. The velocity was used to compute the acceleration and the tension force applied to the rope to determine if the used nylon rope is safe to carry the load.

Table 3. Measurement of Downward and Upward Velocity

TRIAL	DOWNWARD VELOCITY		UPWARD VELOCITY	
Trial	t (s) d = 1.5ft	$v_{downward}$ (ft/s)	t (s) d = 4.5ft	v_{upward} (ft/s)
1	5.12	0.293	21.42	0.210
2	4.66	0.322	21.01	0.214
3	4.16	0.361	21.53	0.209
4	4.82	0.311	21.85	0.206
5	5.00	0.300	21.78	0.207
6	4.47	0.336	22.97	0.196
7	4.74	0.316	22.34	0.201
8	5.21	0.288	21.68	0.207
9	4.89	0.307	22.45	0.200
10	4.32	0.347	21.69	0.207
Average	4.739	0.3181	21.872	0.2057

3.5. Effective Width

Table 4 shows that the prototype was efficient to be able to clean or occupy more than the robotic window washer's width. The results showed that the average width of the cleaning window panel is 24.8 cm.

Table 4. Effective Width of Cleaning of the Robotic Window Washer

Trial	The effective width of Cleaning (cm)
1	25
2	24
3	26
4	23
5	27
6	25
7	23
8	26
9	25
10	24
Ave	24.8 cm

3.6. Water Container Volume

Table 5 shows the volumetric changes that happened on the water container. By getting the volume after the process, the researchers were able to know how much water and liquid were used in the process. The summary of the volume for 10 trials is shown in table 5.

Table 5. Volume Measurement per process

Trial	Pure Water		Liquid Soap	
	$V_{original}$ (L)	V_{after} (L)	$V_{original}$ (L)	V_{after} (L)
1	11.3	10.56	11.3	10.50
2	11.3	10.56	11.3	10.50
3	11.3	10.54	11.3	10.52
4	11.3	10.52	11.3	10.50
5	11.3	10.54	11.3	10.50
6	11.3	10.52	11.3	10.47
7	11.3	10.52	11.3	10.47
8	11.3	10.50	11.3	10.45
9	11.3	10.52	11.3	10.47
10	11.3	10.52	11.3	10.47
Pure Water	Vafter ave. = 10.530 L		Vloss ave. = 0.77 L = 770 mL	
Liquid Soap	Vafter ave. = 10.485 L		Vloss ave. =0.815 L = 815 mL	

3.7. Water Pump

By using the volume loss shown in Table 6, the researchers computed the flow rate of the liquid that has been discharged in the nozzle. Since the solenoid valve opens for 5 seconds and it opens twice in the whole process so the researchers used 10 seconds as duration time. Doing this, the researchers were able to compute the flow rate for both pure water and the liquid soap mixture. Ten trials were made to measure the volume flow rate of pure water and mixture as shown in Table 6.

Table 6. Volume Flow Rate per process

Trial	t (s)	Qpure water (mL/s)	$Q_{mixture}$ (mL/s)
1	10	74	80
2	10	74	90
3	10	76	78
4	10	78	80
5	10	76	80
6	10	78	83
7	10	78	83
8	10	80	85
9	10	78	83
10	10	78	83
Average	10	77	82.5

The solenoid valve was programmed to open with the delay of 5 seconds for both pure water and liquid soap. The researchers made 10 trials to measure the average time the solenoid valve opens for the nozzles to release fluid as shown in Table 7.

Table 7. Start-up time for Solenoid Valve

Trial	$t_{start\text{-}up}$ (s)
1	5.35
2	5.20
3	6.12
4	5.12
5	5.43
6	5.12
7	5.35
8	6.07
9	5.20
10	5.23
Average	5.42

4. Conclusion

In this study, the researchers were able to design and fabricate a window washer prototype for high-rise buildings. Each material used in the prototype was properly tested and calculated to carry the load of the whole prototype with the window-cleaning features such as the squeegee, brush, nozzles, and the electrical wirings. The 5-mm nylon rope carried the load of the window washer which is approximately 3 kg. Its tensile strength was enough and below the safe load which makes it suitable for the system. The acrylic plastic sheets were also used to house the carrier system since it is chemical resistant and light-weight. The track system of the prototype was able to perform its task evenly and efficiently with the support of the nylon ropes in the pulley system and a horizontal bar to connect the two slide runners. At one vertical operation, the prototype would be able to clean an area of 762 mm x 250 mm under an average of 43 seconds, after which, it will move to another direction horizontally. For each cycle, the semi-automated prototype needs approximately 0.77 liters of pure water and 0.815 liters of liquid soap and water mixture for it to clean one cycle of cleaning. After a series of testing and calibration, it was proved that the three continuous servo motors could carry the 3-kg window washer prototype without slip. The prototype could move downwards and upwards but there were some slips seen caused by the track itself. The wheels in the 180° servo motors worked properly which allows the prototype to move away from the glass and to slide with less friction since the wheels rotate as the carrier system lowers the window washer prototype. A 7V 4 ampere AC power adapter was used in the Arduino and the carrier system of the window washer prototype to supply enough current required for their actuations. Also, the solenoid valves which are controlled by the Arduino worked properly, they could shut off the water and the liquid water solution at the designated time. Therefore, it can be concluded that the semi-automated window washer prototype can be effectively used in the cleaning of windows for high-rise buildings.

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