Foot Location Algorithm considering Geometric Constraints of Façade Cleaning

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Abstract. The purpose of this study is to propose a foot location algorithm for a glass façade cleaning robot. As an initial stage of this study, we set three assumptions regarding aimed module robot and window shape. These assumptions set the system some geometric constraint conditions: Right edge of the right cleaning unit moves along with the line of the right window frame. The cleaning area of right and left cleaning unit overlaps a little. The module robot walks with a step at a time. From the conditions, a foot location determination algorithm is constructed corresponding to four situations. The effectiveness of the algorithm is verified through a numerical simulation.

Keywords: Façade cleaning robot, Foot Location Algorithm, Gait Generation

1. Introduction

In recent decades, a lot of skyscrapers have been built by their cutting-edge construction technologies and processes. Even in such modern skyscrapers, outdated methods were used for glass façade cleaning and maintenance. The cleaning practice possess high chances of accidents and concomitant casualties, which may result in the loss of life. Numerous accidents have been reported even with the use of a gondola for façade cleaning jobs. For instance, the sudden blow of storm at Shanghai World Financial Center [1] resulted in the loss of control of gondola. In another example, the gondola got suspended at a height of 240 m during the maintenance of the World Trade Center in New York city [2]. The involvement of robots in scenarios like glass façade cleaning can potentially minimize the risk of accidents and maximize the productivity.

We have identified plenty of research works on the robot involved solution for the façad cleaning, which have sprouted up in a decade. A series of sky-cleaners that are driven by pneumatic actuators for the concurrent locomotion and cleaning of a glass wall by using the vacuum suction cups are discussed in [3, 4]. The works mentioned above explore sky-cleaners with suction cups on the both ends of actuators in the $X$–$Y$ stage and suction cups attached to a vacuum pump [5]. Seo et al. has developed ROPE RIDE [6], which can climb
vertical surfaces by utilizing a rope dropped down from the top of the building. The ROPE RIDE is installed with two additional propeller thrusters to ensure a strong attachment to the wall. A new wall cleaning unit using an impedance control system is proposed in the work mentioned in [7]. As an extended work, authors also experimentally demonstrated the effectiveness of the force control system to press the brushes into the wall by exerting a constant force [8]. Furthermore, Fraunhofer IFF, a research institute, developed a wall cleaning robot named SIRIUS [9]. The SIRIUS robot is capable of performing an up-and-down motion on a vertical surface, using a crane installed on buildings for façade maintenance. The robot adheres to the wall by the suction system and moves with the help of linear actuators [10]. Even though the existing robot-aided solutions for façade cleaning each excel in their effectiveness and experimental results, the performance of the current robots are constrained to their target buildings. Precisely, the robots require additional equipment such as a crane, —i.e. the system is still required significant development to adapt to various building architecture. Hence, adaptability is a factor that lacks in the present façade cleaning scenario.

Our ultimate goal is to develop a glass façade cleaning robot capable of adapting to any skyscrapers. To work a robot system at different shaped buildings, to possess some different morphologies is required. A self-reconfigurable robot is one of potent solution to realize high adaptability. Reconfigurable modular robot system allows to realize different morphology through assembling/disassembling/organizing system of each module. This research aims to implement the glass façade cleaning robot through development of a module robot possessing cleaning ability and design of both its locomotion control system and a assembling/disassembling/organizing system. The modular robot strategy accomplishing the façade cleaning on any skyscrapers has been proposed [11]. And, the modular robot based on the strategy has been developed in our previous study [12]. However, the module robot is still operated the target foot location manually, it is necessary to design an autonomous control system to determine its foot location appropriately. Research efforts with respect to locomotion control system for wall climbing robot have also been published, for example, Yano et al. have developed a self-contained biped wall climbing robot, and have demonstrated its effectiveness via their experiment [13]. For another instance, Hirose and Nagakubo et al. have developed a quadruped robot capable of walking and climbing on floors, walls and ceilings [14], and have proposed walking gaits of the quadruped robot for both dynamic and static walk [15]. Their researches have contributed a lot for breakthrough of the area of wall climbing robot. However, since the researches have focused on only wall climbing, they are unable to satisfy some requirements in order to accomplish the wall cleaning. Regarding to Skycleaner [3], ROPE RIDE [7], and SIRIUS [9], they have mainly focused on adsorption method to wall surface, thus, a comprehensive locomotion control system accomplishing wall cleaning with adapting to different façade has not been addressed.

This paper aims to construct the foot location determination algorithm for the façade cleaning robot. As initial stage of this study, following three assumptions are supposed: the rightest module of the modular robotic system is addressed. A window frame is arbitrary quadrangle. Coordinates of the window frame’s vertex are known. These three assumptions impose geometrical constraints on the system. And, the constraints fall into two sources which are cleaning process and mechanical design. By formulating the constraints, the
foot location algorithm is constructed. The algorithm consists of four situations including initial location, middle area, final location and left foot location. And, effectiveness of the algorithm is verified through the numerical simulation and discussion.

This paper is organized as follows: Section 2. discusses the geometric constraints of façade cleaning robot. The constraints are caused by the three assumptions. The foot location determination algorithm is constructed in Section 3.. The algorithm consists of equations with respect to each situations. In Section 4., effectiveness of the constructed algorithm is verified via the numerical simulation. Section 5. concludes this paper.

2. Geometric Constraint for Façade Cleaning

Figure 1 shows our developed module robot. The developed module possesses a morphology like a biped robot. Each foot part as foot unit has equivalent elements/abilities: It includes the cleaning unit, a suction cup, a vacuum pump, a seal mechanism, a mechanical valve to break vacuum as well as servo motors for joint actuate. In order to accomplish the window cleaning, the robot’s locomotion is constrained caused by cleaning processes and its motion range.

2.1. Cleaning Process

To clean the window well, cleaning tools have to be handled appropriately. Corresponding to the way of glass façade cleaning done by experts, we find following three constraints:

- Right edge of the right cleaning unit moves along with the line of the right window frame.
  Since cleaning liquid drop down from top to bottom of the window, the window is generally cleaned from top to bottom. And, by simplifying the experts works, the window area is able to be separated to some columns and is cleaned column by column.
Figure 2: The cleaning strategy adopted by the experts. Firstly, the experts wash the dirt off by using the scrubber and cleaning liquid (a). Secondly, the dust residue is wiped by squeegee which is manipulated from top to bottom of the window (b). The wiping is done towards a single direction with respect to each column as shown as (b)→(c)→(d). (see Fig. 2). Thus, in order to the most right module cleans the window well, the right edge of the right cleaning unit needs to move along with the line of the right window frame.

- The cleaning area of right and left cleaning unit overlaps a little. To prevent to leave the cleaning liquid on the window, the window is cleaned towards a single direction (see Fig. 2 (b)→(c)→(d)). By overlapping the cleaning area between each column, to flow out the cleaning liquid to the right side of the cleaning unit can be prevent. In this paper, the overlap distance of the right and left cleaning unit is set as 10% of its length.

- The right cleaning unit goes in advance of the left cleaning unit during cleaning. The general walking locomotion moving forward left and right leg alternatively is not effective in order to clean the window towards to a single direction. Thus, the right cleaning unit goes in advance of the left cleaning unit during cleaning.

Above constraint conditions are formulated next Section. And, the foot location determination algorithm is constructed based on the formulated constraint conditions.

2.2. Motion Range

The robot can always moves under a limit of its motion range. To maximize transfer efficiency, to move with a step as long as possible is preferred, however, the robot must avoid straight line posture, since such posture is a singular configuration. In this paper, the maximum step length is set as 90% of maximum motion range.

3. Foot Location Algorithm

The foot location determination algorithm is constructed based on the constraint conditions. The algorithm corresponds to four situations. Figure 3 shows a schematic figure of the system. Physical parameters and function variables are defined as Table 1 and Table 2. A core of proposing algorithm is to determine appropriate $s$ and $\Delta s$ situationally.
From Fig. 3, the foot locations are formulated as follows:

\[ P_r = p_{op} + p_{pr} = s \begin{bmatrix} \cos \theta_0 \\ \sin \theta_0 \end{bmatrix} - h_r \begin{bmatrix} \cos(\theta(s) + \theta_{hr}) \\ \sin(\theta(s) + \theta_{hr}) \end{bmatrix}, \]  

\[ P_l = p_{oq} + p_{ql} = (s - \Delta s) \begin{bmatrix} \cos \theta_0 \\ \sin \theta_0 \end{bmatrix} - h_l \begin{bmatrix} \cos(\theta(s - \Delta s) + \theta_{hr}) \\ \sin \theta(\theta(s - \Delta s) + \theta_{hr}) \end{bmatrix}, \]  

where \( \theta_0 \) is the angle of the top window frame, \( \Delta s \) is the step length, \( h_r \) and \( h_l \) are the maximum and minimum safety margin to avoid collisions, respectively, and \( \theta_{hr} \), \( \theta_{hr} \), and \( \theta_{hr} \) are the angles of the right, bottom, and left window frames, respectively.
### Table 2: Function variables

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to edge of right cleaning unit</td>
<td>$s$ [m]</td>
</tr>
<tr>
<td>Angle of right cleaning unit</td>
<td>$\theta(s)$ [rad]</td>
</tr>
<tr>
<td>Gap between edge of left and right cleaning unit</td>
<td>$\Delta s$ [m]</td>
</tr>
<tr>
<td>Foot location of both leg</td>
<td>${P_r, P_l}$ [m]</td>
</tr>
<tr>
<td>Coordinate of edge of right cleaning unit</td>
<td>$P_p$ [m]</td>
</tr>
<tr>
<td>Coordinate of edge of left cleaning unit</td>
<td>$P_q$ [m]</td>
</tr>
</tbody>
</table>

![Diagram](image)

Figure 4: The cleaning process of the algorithm. The process is illustrated from (1) to (5). Determination algorithms of $s$ and $\Delta s$ fall into four patterns (initial location, middle area, left foot location, and final location) with corresponding to differences of each property.

where $p_{mn}$ represents vector from $P_m$ to $P_n$. Hence, by determining appropriate $s$ and $\Delta s$ situationally, the foot location of both left and right leg is calculatable. And, based on discussions in Section 2, the cleaning process is visualized as Fig. 4, i.e., determination algorithms of $s$ and $\Delta s$ fall into four patterns (initial location, middle area, left foot location, and final location) with corresponding to differences of each property.

In Fig. 3 and Table 1, in order to interpolate between $\theta_{l_0}$ and $\theta_{h_0}$ smoothly, $\theta(s)$ is
formulated by utilizing fifth polynomial interpolation as follow:

$$\theta(s) = \sum_{i=0}^{5} a_i s^i,$$

where $a_i$ ($i = 1, \ldots, 5$) are denoted as coefficients of the fifth polynomial interpolation, and are defined as follows:

$$a_0 = \theta_{to}, \quad a_1 = 0.0, \quad a_2 = 0.0,$$

$$\begin{bmatrix} a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} 20s_f^2 \\ 12s_f^3 \\ 5s_f^4 \end{bmatrix}^{-1} \begin{bmatrix} \theta_{to} - \theta_{io} \\ 0.0 \\ 0.0 \end{bmatrix}.$$ 

And, $s_f$ represents the length of right window frame, and $s_f = \sqrt{x_{rb}^2 + y_{rb}^2}$.

### 3.1. Initial Location

At the initial location, edge of the right cleaning unit is on the right-top vertex, i.e., $s = 0, \Delta s = 0$. Thus, by substituting $s = 0, \Delta s = 0$ to (1) and (2), we obtain

$$\mathbf{P}_r = -h_r \begin{bmatrix} \cos(\theta_{to} + \theta_{hr}) \\ \sin(\theta_{to} + \theta_{hr}) \end{bmatrix}, \quad \mathbf{P}_l = -h_l \begin{bmatrix} \cos(\theta_{to} + \theta_{hl}) \\ \sin(\theta_{to} + \theta_{hl}) \end{bmatrix}. \quad (3)$$

### 3.2. Middle Area

At the middle area, the right foot location is on maximum step from the left foot location. From (1) and (2),

$$\mathbf{p}_{lr} = -\mathbf{p}_{ol} + \mathbf{p}_{or} = \begin{bmatrix} s \cos \theta_0 - h_r \cos(\theta(s) + \theta_{hr}) - l \cos \theta_l \\ s \sin \theta_0 - h_r \sin(\theta(s) + \theta_{hr}) - l \sin \theta_l \end{bmatrix}, \quad (4)$$

where $l = \|\mathbf{p}_{ol}\|$ and $\theta_l = \angle \mathbf{p}_{ol}$. When $\|\mathbf{p}_{lr}\| = b_{max}$, it is the maximum step length. Thus, $s$ satisfying the maximum step length is calculated by solving following equation:

$$f_1(s) = 0,$$

$$f_1(s) = \|\mathbf{p}_{lr}\|^2 - b_{max}^2,$$

$$= s^2 + h_r^2 + l^2 - b_{max}^2 - 2sh_r \cos(\theta(s) + \theta_{hr} - \theta_0) - 2ls \cos(\theta(s) + \theta_{hr} - \theta_0)$$

$$+ 2h_r l \cos(\theta(s) + \theta_{hr} - \theta_0). \quad (5)$$

### 3.3. Left foot location

For the left foot location after calculating $s$ for determining the right foot location, it has to satisfy two requirements: The cleaning area of the left leg overlaps the one of the right a little. Both legs have to avoid collision. To satisfy these requirements, the left leg is located
Figure 5: The location of left foot with collision avoidance.

at 10% right of the cleaning unit’s length than standard distance from the left leg. — *i.e.*
$h_{1l} = 2.8h_1$. And, in order to avoid collision, edge of the one cleaning unit possesses a
distance from another cleaning unit as shown in Fig. 5. In Fig. 5, distance from edge of the
right and left cleaning unit denoted as $d_r$ and $d_l$ have to possess minimum margin defined as
$b_d$. That is, $\Delta s$ is determined so that shorter way of either $d_r$ or $d_l$ equals to $b_d$. Both right
and left cleaning units are able to formulated by linear equations as follows:

$$y = a_r x + b_r,$$
$$a_r = \tan \theta(s), \quad b_r = s(\sin \theta_0 - \tan \theta(s) \cos \theta_0),$$
$$y = a_l x + b_l,$$
$$a_l = \tan \theta(s - \Delta s), \quad b_l = (s - \Delta s)(\sin \theta_0 - \tan \theta(s - \Delta s) \cos \theta_0).$$

Note that $s$ is addressed as a constant value, since $s$ has already been determined by (3), (5)
and (7). Thus, $\Delta s$ for the left foot location is calculated by solving following equation:

$$g(\Delta s) = 0,$$

$$g(\Delta s) = \frac{-ax_c + y_c - b}{\sqrt{a^2 + 1}} - b_d, \quad (\theta(s) \geq 0)$$
$$g(\Delta s) = \Delta s \sin(\theta_0 - \theta(s)) + 1.8h_1 \sin(\theta(s) - \theta_0) - \theta(s - \Delta s) - b_d,$$
$$g(\Delta s) = \frac{-ax_c + y_c - b}{\sqrt{a^2 + 1}} + b_d, \quad (\theta(s) < 0)$$
$$g(\Delta s) = 2h_1 \sin(\theta(s - \Delta s) - \theta_0) - \Delta s \sin(\theta(s - \Delta s - \theta_0) + b_d,$$

where $b_d$ represents minimum distance as margin for collision avoidance, and $(x_{cr}, y_{cr})$ and
$(x_{cl}, y_{cl})$ represent the coordinate of right and left edge of the cleaning unit.

### 3.4. Final Location

At the final location, to avoid collision against bottom window frame, the leg has to take a
distance from the bottom window frame as well as the right window frame. Thus, the foot
location is determined so that distance between $P_r$ to the bottom window frame equals to
The bottom window frame is able to be formulated by a linear equation as follow:

\[ y = ax + b, \]
\[ a = \tan \theta_{bo}, \quad b = s_f (\sin \theta_0 + \tan \theta_{bo} \cos \theta_0). \]

Thus, \( s \) for the final location is calculated by solving following equation:

\[ f_2(s) = 0, \quad (7) \]
\[ f_2(s) = \frac{-ax_r + y_r - b}{\sqrt{a^2 + 1}} - b_{min}, \]
\[ = s \sin(\theta_l - \theta_{bo}) + h_r \sin(\theta_{bo} - \theta(s) - \theta_{hr}) + s_f \sin(\theta_{bo} - \theta_l) - b_{min}. \]

The foot locations for both left and right leg are determined by solving (3), (5), (7), and (6) corresponding to the situations. And in this paper, Newton-Raphson method is utilized to solve (5), (7), and (6).

### 4. Numerical Simulation

The effectiveness of the algorithm is verified in this section via a numerical simulation. The physical parameters are set as Table 1. The simulation is performed by MaTX VC version 5.3.45 [16]. The simulation result is shown in Fig. 6. In Fig. 6, “×” marks represent the determined foot locations by solving (3), (5), (7), and (6). And, “T”-like shape represents the foot unit of the module robot including the cleaning unit.

Figure 6 shows that the algorithm calculates the foot locations along the right window frame. And, the area of both left and right cleaning unit are overlapped a little. Thus, the most right column is fully covered by the cleaning unit of the module robot. Hence, the algorithm determines appropriate foot locations satisfying the constraint conditions.

### 5. Conclusion

This paper has constructed the foot determination algorithm for façade cleaning robot in order to develop the autonomous façade cleaning robot. In this paper, we set three assumptions due to early stage of this study: the most right module of the modular robotic system is addressed. The window frame is arbitrary quadrangle. Coordinates of the window frame’s vertex are know. From these assumptions, three geometric constraint conditions have found. And, by formulating the constraint conditions, the foot location determination algorithm has been constructed. The constructed algorithm has consisted of four situations (initial location, middle area, final location, and left foot location). Corresponding to the situations, the equations to calculate the foot location have been formulated. Finally, the numerical simulation has been performed to verify the constructed algorithm. As the result of the simulation, the effectiveness of the algorithm has been shown and discussed.
Figure 6: The simulation result of the algorithm. “x” marks represent the determined foot locations by solving (3), (5), (7), and (6). And, “T”-like shape represents the foot unit of the module robot including the cleaning unit.
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