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Glass facade cleaning robot with passive suction cups and self-locking trapezoidal lead screw drive

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ABSTRACT

We report on the mechanism, design iteration, and performance of a new glass facade cleaning robot, *vSlider*. The passive suction cups, driven by self-locking lead screws, are used to engage the *vSlider* robot to the glass facade. This mechanism has higher efficiency, compared to active suction cups, and offers better power consumption and safety in the case of power disruption or power loss. Due to the self-locking leadscrews, the counter-moment in a static position is not transferred to the motor, and thus, the servos which drive the lead screws only consume the power needed for a typical free load. A DC motor with encoder generates the primary locomotion in *vSlider* which was tested both in position- and velocity-control modes. This paper also details the design iteration efforts and discusses the key findings from the experiments involving the first prototype, *vSlider 1.x*, and the application of these findings in the development of the second prototype, *vSlider 2.x*. Experiments were performed to validate the proposed design approach and to benchmark the performance of the two robot prototypes that were developed.

1. Introduction

Glass facade cleaning robots are fast becoming one of the key research topics within the robotic field. The need is mainly attributed to many high-rise glass facade buildings along with the advancement in the architecture. Environmental concerns, including a move to sustainable buildings, is the motivating factor behind developing glass-facade high-rise buildings due to the attractive properties of glass such as transparency, workability, 100% recyclability, resistance to corrosion, and energy efficiency, among others. The enormous technical advancements in the building and construction industry are increasingly transforming the form of modern high-rise buildings. Many contemporary high-rise buildings are characterized by large-area glass facades [1]. Hence, the need for maintaining such buildings and servicing new ones that are yet to be built has significantly increased. Currently, almost all maintenance works are performed by manual labor, where safety, cost and cleaning efficiency are of great concern. Driven by additional factors such as labor shortage, immigration policies, and productivity drives, there has been a recent trend in developing and deploying robotic systems for cleaning glass facades in such buildings. *RobuGlass* presented in [2] was designed for cleaning the Paris museum known as the *Louvre Pyramid* which is 21 m high and inclined by 50 degrees. The device has four caterpillar tracks for locomotion and eight vacuum pumped-suction cups to engage to the glass panels. This 55 kg robotic system also has a rotating brush and wiper for cleaning purpose, and the overall dimensions are 1200 × 900 mm.

Another robotic system with similar features is *SkyBoy*, designed for cleaning the glass facade of the control tower at the Guangzhou Airport, Guangzhou, China [3]. This robotic system consists of a cleaning robot and a conveyor system which is composed of a top dolly and a bottom dolly. The cleaning robot is driven up and down by the conveyor system where the top and bottom dollies orbit around the cone-shaped structure tower with similar angular velocities. Moreover, to simplify the robot design process for cleaning the four floors of the tower, the individual *SkyBoy* system is deployed on each floor rather than one system which can climb over the stainless-steel ring on each floor. Another robot platform that requires support from operating infrastructure was developed by the Fraunhofer Institute of Manufacturing Engineering and Automation (*IPA*) [4]. The system is known as the Standard Facade Cleaning Robot (*SFR I*) and the iterated design (*SRF II*) has three degrees of freedom to move up and down, left and right, and to overcome the standard facade frame. The additional units, such as the supply unit and control unit, are located on the ground floor. Moreover, the Fraunhofer Institute for Factory Operation and

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Automation (*IFF*) has introduced other robotic systems such as *Leipzig*, *Filius*, and *Sirius*. A built-in guided robotic system which comprises of VMR (vertical-moving robot) and HMR (horizontal-moving robot) was introduced [5], and this robotic system also needs the support of the operating infrastructure. Another similar system, known as BMR (Built-in guide Maintenance Robot), was also introduced by Moon et al. [6]. However, the robot, developed to clean the first skyscraper, made of anodized aluminum in Munich, was a gondola-based system which does not require the additional modification or guided system to the existing infrastructure [7].

With the advent of component technologies, a series of pneumatic glass cleaning robots: *Sky Cleaners 1*, *2* and *3* were developed without any modification to the operating infrastructure [8]. *Sky Cleaner 3*, the latest model, was deployed for cleaning the Shanghai Science and Technology Museum. It has four degrees of freedom where the additional degree of freedom, compared to *SRF II*, is the waist joint, connecting the X and Y axis. Additionally, the used water is sucked out by the vacuum pump to the supply unit, filtered and recycled. Another similar robotic system like *Sky Cleaner 3* was also reported by Sun et al. in their work of motion planning and visual sensing [9]. On the other hand, Giuk Lee et al. presented an alternative field of multilinked track-type climbing robots which use dry adhesive, magnet and suction mechanism [10]. Recent years have also witnessed vacuum based commercial products such as *GEKKO facade*, launched by *SERBOT AG* and later, *GEKKO solar* and *GEKKO solar farm* [11]. *GEKKO facade* is a type of individually-controlled vacuum legged robot in which a series of vacuums are executed in two kidney-shaped conveyor systems. Another vacuum based biped cleaning robot, *CleanAnt*, which can overcome complicated shapes and obstacles, including concave and convex surfaces, is currently being developed by *SERBOT AG* [12]. Additionally, *SERBOT AG recently* launched *GEKKO Gondola Robot* in which the supply system can be integrated into a varieties of the existing building maintenance units (BMU),and it has 400 m^2/h cleaning capacity and 10,000 m^2/day maximum cleaning surface [13].

Other interesting robotic systems in glass facade cleaning are the bio-inspired and biomimetic robots. The robotic platform designed by Jiang Jin-gang et al. is inspired by spider locomotion, and the pulling of their silk draglines [14]. Additionally, in contrast to the conventional method of engaging the glass facade using a vacuum pump, active suction cups with the pneumatic control, or a passive suction cup, their robotic platform is equipped with an absorbing propeller. Another bio-inspired robot called the *Planar Walker*, yields inchworm-like movements through a planar eight-bar closed-loop mechanism [15]. A pneumatic cylinder produces inchworm-like movement, and four of them are connected to a closed-loop quadrilateral mechanism using a revolute joint at each junction where a vacuum suction cup is integrated to stick to the glass panel. A revolute joint connects two slider shafts, and the closed-loop quadrilateral linkage joints slide on these shafts, producing the planar locomotion upon the correct actuation sequences of the cylinders and vacuum suction cups. The trunk-driven locomotion of vertebrates is used as a source of inspiration that integrates the concept of modularity, enabling the user to configure a number of motion modules based on the complexity of the structure or terrains [16].

A biomimetic robotic system has also been proposed, using a five-linkage and one piston mechanism, with four fluid-driven vacuum cups [17]. Two T-linkages each with a rotating joint are connected to two individual linkages which are driven by a piston linkage bar. This linkage mechanism mimics the vertical climbing and turning gait cycles commonly found in geckos. In addition to the mechanism discussed above, recent years have also witnessed the use of the impeller-based mechanism due to its compatibility with many types of facades, including glass, concrete, steels, and aluminum, among others. One of the early demonstrations of an impeller based mechanism was the *TITO 500* from *RatioForem* [18]. Another impeller based adhesion wheel-driven mechanism, *LARVA*, is also reported by Koo and Trong [19]. One of the popular window cleaning commercial products, *Hobot-268*, is also based on the impeller mechanism to engage to the glass panel [20].

In this paper we present a new glass facade cleaning robot, *vSlider*, that uses passive suction cups, driven by the self-locking lead screws to engage the glass surface. The key hypothesis demonstrated in this paper is to validate the proposed self-locking trapezoidal lead screw mechanism and use of passive suction cups towards realizing mobility over vertical glass facades, reducing the continuous high-power consumption and considering a part of safety factor during power disruption. This type of mechanism has higher efficiency, compared to active suction cups, and offers better power consumption and safety in the case of power disruption or power loss [21,22]. Due to the self-locking lead screws, the counter-moment in a static position is not transferred to the motor, and thus, the servos which drive the lead screws, only consume the power needed for a typical free load. A DC motor with encoder generates the primary locomotion in *vSlider* which was tested both in position- and velocity-control modes. The main challenges tackled in this paper includes designing, prototyping and validating the proposed *vSlider* robot and the engaging mechanism, hardware-software integration issues and the non-trivial process of implementing theoretical designs generated analytically into physical mechanisms. All these aspects are detailed in this paper, concluding with experimental results using two versions of the *vSlider* robot that validate the proposed approach. The *vSlider* robot herein presented is an initial design towards building a highly adaptive energy-efficient robot that is capable of autonomously cleaning glass facades while avoiding any positive and negative obstacles in its environment.

The remainder of this article is structured as follows. Section 2 “System Architecture: *vSlider 1.x*” describes the proposed main engaging/disengaging mechanism using the self-locking lead screw and the associated design calculations. Additionally, it also covers the static force analysis and locomotion details. Section 3 “System Architecture: *vSlider 2.x*” discusses the key findings from the experiments involving the first prototype, *vSlider 1.x*, and application of these towards the development of the second prototype *vSlider 2.x*. Section 4 “Experimental Results” presents further details on the locomotion performance of the robot prototypes *vSlider 1.x* and *vSlider 2.x*. Finally, the Section 5 “Conclusion” concludes this study and discusses future work.

2. System architecture: *vSlider 1.x*

2.1. Mechanical system

The *vSlider 1.x* system, as shown in Fig. 1, consists of a central unit and two side units where the leadscrew-driven passive suction cups are implemented to engage and disengage the glass. The central unit has four leadscrew driven mechanisms, whereas the two side units have two mechanisms on each unit. Two linear shafts, guided by the central unit, connect the two side units, which are driven by a DC motor with encoders residing on the central unit through a sprocket and chain mechanism. The alternating and synchronized motor control operates the engaging and disengaging of the suction cups and the robot locomotion.

2.1.1. Leadscrew-driven mechanism

In the design phase, we carefully designed the leadscrew-driven mechanism to realize the engagement and disengagement of the suction cups to the glass panel. The proposed modular design of the leadscrew-driven mechanism is both time- and cost-efficient, with respect to the fabrication process. In addition, any parts which develop faults over time can be easily replaced with modular spares. As shown in Fig. 2, the leadscrew with bearings at both ends is fixed in position between the mounting plate and the robot base plate through three linear shafts with tapping at both ends.

These linear shafts also serve as the linear guide for the leadscrew nut. The remaining three holes in the leadscrew nut are attached to the suction cup legs. Upon driving the *Herkulex* servo in the continuous