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Climbing robots for maintenance and inspections of vertical structures—A survey of design aspects and technologies

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HIGHLIGHTS

- Comprehensive state-of-the-art in climbing robots for maintenance and inspections.
- Overview on locomotion and attraction principles for climbing robots.
- Discussion and classification of requirements for commercial systems.
- Schematics and design aspects of climbing robots.

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ABSTRACT

The maintenance and inspection of large vertical structures with autonomous systems is still an unsolved problem. A large number of different robots exist which are able to navigate on buildings, ship hulls or other human-made structures. But, most of these systems are limited to special situations or applications. This paper deals with different locomotion and adhesion methods for climbing robots and presents characteristics, challenges and applications for these systems. Based on a given set of requirements these principles are examined and in terms of a comprehensive state-of-the-art more than hundred climbing robots are presented. Finally, this schematics is applied to design aspects of a wall-climbing robot which should be able to inspect large concrete buildings.

1. Introduction

Climbing robots in the field of vertical structures are of increasing importance for technical applications, inspections, maintenance and construction tasks. Researchers all over the world are working on systems which are able to navigate on manifold and vertical human-made structures. Most of these research groups started in the 90s and developed first prototypes which are able to climb on vertical walls. The fields of application reach from welding of ship hulls to the inspection of steal bridges or nuclear power plants. Often-cited systems Rest [1], Robug II [2] or Ninja 1 [3] are applied for such tasks. It can be notified that such climbing systems are mainly adopted in places which cannot be reached by humans, where the direct access of a human technician is too expensive or too dangerous.

In general, climbing robots need to be developed depending on the desired tasks and field of application. These aspects define, which locomotion principles or adhesion systems are suitable and which dimension the robot must have. This paper will present design aspects related to climbing robots suitable for inspection and maintenance applications. It will sum up the state of the art from the 90s up to 2013 and classify the different systems related to their application, locomotion and adhesion technology. The survey is focused on robots which are able to climb up vertical structures and does not include so-called *step-* or *stair-climbing robots* as well as systems which are e.g. able to climb along horizontal electrical power lines for inspections.

Section 2 will give an overview on applications of climbing robots and will present requirements to fulfill the desired task in an optimal way. Section 3 sums up suitable principles for locomotion and discusses advantages and disadvantages of the different methods. Section 4 presents the different adhesion mechanisms including some physical fundamentals and an overview on existing climbing robots. It contains magnetic (Section 4.1) and negative pressure adhesion (Section 4.2), mechanical adhesion (Section 4.3) as well as electrostatic (Section 4.4) and chemical attraction

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(Section 4.5). Afterwards, Section 5 discusses and compares the locomotion and adhesion principles and shows, in which way certain design aspects lead to a highly sophisticated wall-climbing robot which should be able to inspect large concrete buildings. Finally, the conclusion is given in Section 6.

2. Applications and requirements

Over the last two decades climbing robots became more and more important in the scientific society. Starting with simple systems equipped with adhesion mechanisms like electromagnets [1], suction cups [4] or slide-rails [5], the applications of these robots grow with their ability to handle different surfaces and to perform faster or more accurate navigation. At the very beginning of climbing robot research these systems have been designed to fit exactly one application or object like a steel bridge or a nuclear power plant. This limitation has decreased due to new locomotion types and adhesion mechanisms during the last years. At this point of time climbing robots are considered to support inspection, maintenance and construction tasks everywhere. In fact, they are helpful if they are able to perform the desired tasks more effectively, cost efficient and more accurate than existing approaches or those tasks, which are dangerous for human beings. Especially this safety aspect is of importance. Common applications for such systems which are dangerous for humans are inspections of nuclear power stations (e.g. leakage detection, measurement of wall thickness or analysis of welding seams) and inspections of tanks and pipelines in chemical industry. Furthermore, climbing robots are used to paint, coat or clean facades of buildings, to perform welding tasks in ship industry or clean and inspect airplane wings and wind turbines. An investigation of aspects related to cleaning robots for glass facades is given by [6], additional information about application fields and climbing robots can be found in [7,8]. Fig. 1 depicts some of the mentioned areas.

Nearly all of the climbing robots have a practical application. This especially counts for robots using well-known and reliable adhesion techniques like magnets or grips designed for ship industry or for inspections of planes, petrochemical tanks or other steel surfaces. The exceptions are those systems whose adhesion principle (e.g. thermal glue) is still in the focus of research. But, although there exists a wide range of different systems, only few climbing robots have been brought to commercial application, like [11–16].

To execute the desired tasks, climbing robots as well as all other technical systems have to fulfill certain requirements. Of course, the requirements and their importance and focus depend on the individual application. Nevertheless, a general set of requirements can be postulated suitable for nearly all climbing robots in the range of inspection and maintenance:

1. *Velocity and mobility*: The vehicle speed and its ability to move are two main aspects in this field. Depending on the dimension of the vertical structures it might be required to achieve relatively high velocity even in vertical direction or overhead for a sufficient fast navigation between inspection areas or similar points of action. Another requirement is related to the desired manipulation and positioning capabilities of the system. This includes the precision of locomotion as well as its trajectory, since some inspection sensors (e.g. a cover meter) need to be moved in a smooth and continuous way over the surface. It might also be desired that the robot is able to move sidewards or to turn 360° to position sensors or tools. Last, but not least, the system should be able to handle steps or protrude structures to be able to reach all positions at the building.
2. *Payload*: Depending on the application the system must be able to carry a payload of different weights. E.g. for the inspection of concrete surfaces a payload of 10 kg and more is mandatory to carry inspection sensors like impact echo, cover meter or a Wenner probe. This requires a much bigger robot in contrast to a system which should only be equipped with a simple camera with a weight of only several hundred grams. Therefore, the dimension of the robot as well as its adhesion and motion components need to be adapted according to the application.
3. *Reliability and safety*: A further important non-functional aspect is the robustness of the system. If the climbing robot fails often during one inspection task it would not be usable in practice. The requirements reliability and safety include robust hardware, optimal controllers and methods to detect and handle hazardous situations and to recover from them. Finally, it might be prescribed by law to secure the system via a cable or rope to eliminate the danger of a drop-off which could harm persons and destroy the robot. But, nevertheless, the system itself should be safe enough to ensure its adhesion, since even a controlled drop-off might become dangerous.
4. *Usability*: Velocity, maneuverability, and the capability of carrying a certain payload are important, but, they are only the basis of the general operability of the system. To bring a robotic system into application it has to be more powerful, more efficient and less dangerous than common approaches e.g. in terms of inspection devices. This includes also aspects maintainability and a broad range of handable tasks. Therefore, it must be able to carry different payloads (e.g. inspection sensors or tools) depending on the desired task, high mortality parts need to be easily replaceable, and the operation must be faster and less complicated compared to existing approaches. Additionally, also aspects like energy consumption, weight or dimension of the system can be important.

Based on the individual task, a robot developer has to decide which requirements have to be fulfilled and select a suitable locomotion and attraction principle. Next sections will introduce these approaches and discuss pros and cons of each method.

3. Locomotion types

As mentioned before, mobile climbing robots have been in the focus of research the last two decades. In literature various combinations exist combining different types of locomotion with different adhesion principles [7]. During robot development a question has to be considered: What kind of locomotion principle is the optimum for the given task and the environment? In general, one can distinguish four classes of locomotion with their individual assets and drawbacks:

Arms and legs A very common locomotion principle in the range of climbing robots is the use of arms or legs. In many cases nature is the inspiration for the chosen robot setup [17], e.g. in terms of insects or geckos which can climb walls and ceilings. Depending on the individual task, climbing robots have been created with different numbers of limbs of different degrees of freedom. In literature one mainly finds robots with two [18–23], four [24–28,3,2,29,30] and six [1,31–34] legs. Systems equipped with eight or more legs [35] can also be found, but, are less common. The main advantage of legged climbing robots is, that they are highly adaptable to the surface structure, that they can overcome obstacles and steps, or translate from ground to wall. This is possible due to the fact that each foot is equipped with adhesive components which also allows a testing of the foothold for the desired attraction forces. However, the high number of degrees of freedom leads to a complicated mechanical structure and control system in terms of a smooth and harmonic gait control. This also results in a higher weight and larger torques. In general, the velocity of these system is comparably