LARGE-SCALE, ROPE-DRIVEN ROBOT FOR THE AUTOMATED MAINTENANCE OF URBAN GREEN FAÇADES

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Facade vegetation is a current trend as so-called green walls or vertical gardens. Particularly in an age of global climate change, the value of urban green spaces is undisputed. There are many creative designs for the inclusion of plants and greenery in both new and existing buildings. However, their long-term maintenance is still a challenge. The automation of this task can lead to staff savings in a risky working environment. To address this issue, a large-scale, rope-driven robot has been developed. This system is capable of efficiently and automatically handling the maintenance of large green facades, even in great heights. By the use of a flexible actuator technology, individual plants can be installed, pruned or removed. Precise, spatially resolved irrigation and fertilization can be executed. In addition, integrated sensors can determine the local condition of the vegetation. Particular attention is paid to data acquisition and decision making regarding the condition of the green.

Keywords: Green wall, Vertical garden, Vertical farming, Cable robot, Rope kinematic, Parallel kinematic, High-strength, High-performance, Fiber rope, Non-redundant, Light-weight, Restrained positioning mechanism.

1 URBAN GREEN FAÇADES

Vertical gardens and traditional green facades not only provide aesthetic designs and favorable conditions for recreation, but also bring wider benefits to urban society (Cameron et al. 2016). They contribute to fresh air and save energy by insulating against cold draughts and heat loss in winter. In summer they reduce the „reliance on air conditioning by shading buildings and providing cooling through evapotranspiration and an increased albedo effect” Webster et al. (2017) and thus, counteract in particular the urban heat island effects.

Façade vegetation protects against UV radiation, unfavorable meteorological factors such as storms, hail, coldness, heavy rain and damage to property such as graffiti. In addition, green facades insulate and absorb sound and store harmful substances such as particulate matter, atmospheric carbon and nitrogen oxides.

Furthermore, they provide places to inhabit for wildlife such as a variety of birds and insects and consequently can contribute to species protection and urban biodiversity, which is usually a big concern in civil engineering, where natural habitats primarily are destroyed by the construction of new buildings.
2 MAINTENANCE OF FAÇADE VEGETATION

Besides the numerous benefits, green infrastructure raises issues concerning the responsibility and expense of maintaining and caring these spaces. In particular, the operating costs are considerably high. Studies of European best practices, conducted by the Vienna City Administration, proves the costs for maintenance and care to reach up to 60 €/m² per annum (Magistrat der Stadt Wien and Grünstattgrau 2019).

In a recent survey regarding green facades, potential builders and operators stated the expenses for maintenance and care to be the main obstacle next to the initial invest (Mann et al. 2021). The major cost drivers are the personnel expense for manual labor and the partially temporary transportation of the personnel to the workspace by the use of stationary facade access systems as well as mobile lifting technology and descend devices. In a recent review of robotic bodies for working on facades, Bock and Iturralde (2019) summarized and classified the currently used technologies. In addition, works at great heights lead to an increased risk of accidents. Thus, companies, specialized in such maintenance measures, require a trained staff in good physical condition.

A green façade needs maintenance and care on a regular basis. This includes initial planting, removing and cutting, fertilization and, where necessary, winterization. Irrigation systems primarily are controlled centrally and do not allow local adjustment. Automated solutions are not yet available. Though, robot-based approaches are already present in various research activities. In any case, systems are required, that can operate on or in front of the façade regardless of weather conditions and day time throughout the year, shown as an example in Figure 1. Such systems can significantly reduce the operating costs, improve the operating times, and consequently enhance acceptance.

![Figure 1. Visualizations of a rope-driven robot for the automated maintenance of urban green facades.](Image)

In summary the main advantages of a dedicated automated system are reduced operating costs, freedom from environmental conditions and a higher quality of work due to shorter maintenance and care intervals, and individual local adjustments. The particular challenge is not only to operate under every possible environmental condition, but also maintenance and care of large areas with various local demands. This requires the system to provide high velocities and fast acceleration to operate efficiently, without disturbing the residents.

3 STATE OF THE ART ROPE ROBOT TECHNOLOGY

The predominant mechanical systems used for equivalent automation processes are based on conventional serial kinematics. These serial kinematics not only limit the performance, but also complicate the upscaling to very large applications, as required in civil engineering. In addition,
noise emission by conventional setups proves to be quite problematic, when operated with the required accelerations and velocities.

In contrast, handling devices based on rope-driven parallel kinematics enable high dynamics and traverse speeds as well as extremely long traverse paths, while emitting low noises. This can be achieved by drastically reducing the moved loads, in particular by the use of very light-weight high-performance fiber ropes (HPFR) as motion and guiding elements. HPFR are made from high-modulus, high-tenacity fibers and consist of three or more strands, which are predominantly twisted or braided together. The HPFR’s strength is already competitive or even outperforming wire ropes, while providing a multiple times better specific weight, a much greater durability when bent over sheaves and can operate with smaller rope peripherals such as sheaves and winch drums. (Müller et al. 2018)

In their paper about the state of the art of high-strength fiber rope usage in material handling, Weis et al. (2013) already stated, that HPFR are not only facing a strongly increased interest for rope-driven applications in general, but also „have an extraordinary important effect on the usability of ... robot systems with multi-rope kinematics“ (Weis et al. 2013).

In such rope robots, shown as an example in Figure 2, the general positioning operation of the moveable work platform is carried out simultaneously by various parallel actuating ropes. The work platform carries tools, sensors and the goods to be handled. By changing the individual rope’s effective lengths, the work platform can be moved within the working space. A controller calculates the required rope lengths and synchronizes the motion of the winches. The advantages of rope robots in general can be summarized as follows:

(i) highly efficient in terms of material and energy consumption,
(ii) highly accurate in terms of positioning
(iii) scalable workspaces due to marginal mass gathering by longer actuators,
(iv) superior relation of actuator mass vs. payload enables higher dynamics and
(v) in addition, fiber ropes provide extremely smooth running characteristics.

The latter is a substantial improvement compared to conventional axis setups. Thus, rope-driven systems are more flexible and appropriate for larger applications than serial kinematics.

Figure 2. A cable-driven hexapod in accordance with Bohigas et al. (2013): a) work space, b) work platform, c) motion assembly. The platform is maintained stable due to the action of gravity.

The need for redundant attachment of the work platform in conventional rope robots is a major constraint. Redundancy in the axes directly affects the number of required independent drives (cf. Table 1) and thus the total investment and operating costs. A serial, two-dimensional,
planar motion only needs two separate drives. Consequently, a rope-driven parallel robot should, as well, contain only two separate motor-winch drives.

Table 1. Level of Redundancy in accordance with Verhoeven (2004).

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Condition*</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>IRPM</td>
<td>( m \leq n )</td>
<td>Incompletely Restrained Positioning Mechanism</td>
</tr>
<tr>
<td>CRPM</td>
<td>( m = n + 1 )</td>
<td>Completely Restrained Positioning Mechanism</td>
</tr>
<tr>
<td>RRPM</td>
<td>( m &gt; n + 1 )</td>
<td>Redundantly Restrained Positioning Mechanism</td>
</tr>
</tbody>
</table>

* \( m \) = Number of separate drives, \( n \) = degrees of freedom (DOFs)

4 NON-REDUNDANT, LARGE-SCALE, ROPE-DRIVEN ROBOT

Recently the concept of a non-redundant, two-dimensional rope-driven robot has been developed at the Chemnitz University of Technology (cf. Figure 3). As part of this development a prototype with a working space of 5 m * 10 m has been engineered and manufactured. The present study describes this new approach to rope-driven, vertical operating handling systems.

![Figure 3](image-url)  
Figure 3. Non-redundant, rope-driven robot operating in front of a façade (a) and a vertical garden (d) to be planted. Major assemblies: b) winch assembly, c) trimming tool attached to the work platform.

Application-specific requirements led to the substitution of commonly used serial kinematic systems with a rope-driven parallel kinematic. Parts typically used in serial kinematics such as drive belts or gear rods are highly responsible for extensive noise emission due to their gear contacts. In contrast, rope-driven kinematics are almost noiseless (Müller et al. 2018).

The system basically consists of two independent motion assemblies. The positioning of the work platform moving in front of a facade is realized by two driven rope slings, whereas the ends of each rope sling are attached to the same winch. This allows the work platform to be positioned planar and simultaneously maintaining tension in all rope sections due to the synchronous operation of both axes. By the use of rope slings, the attachment of the work platform is redundant, while the driving-system remains non-redundant. This enables a high degree of safety, being on a par with redundant systems.

As a result of the missing redundancy, the work platform is not attached to the ground. The individual axes are not tensioned against each other but only stressed by weight force. This results in a comparatively low stiffness of the kinematic system. Non-redundant, rope-driven robots are only kept stable by the action of gravity. Thus, the axles can be described as „weak”, because only the force of gravity leads to restoring forces in the ropes. However, the authors prefer the concept of weak axis as a matter of cost efficiency and susceptibility.

To face this issue and to achieve better dynamic stability and positioning accuracy, a concept of compensatory strategies has been developed and applied to the robot’s control. The consideration of the fiber rope’s mechanical behavior being ideally stiff is replaced by a visco-
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elastic model. This model takes into account the time-dependency of stiffness and damping phenomena. This is mandatory especially for the modelling of oscillating rope deformation. The model is utilized to continuously calculate the Manipulator Center Point. Thus, a new access to the positioning process (acceleration, velocity, breaking) is possible. The axis stiffness is virtually increased by adaptively manipulated acceleration ramps (compensation of overshooting and inertia adapted breaking).

A useful side effect due to the loss of redundant motion assemblies is the lower risk of ropes colliding with each other or the work platform. Consequently, this leads to reduced geometrical limits of movement. Another important advantage of the overhead system is not wasting any floor space, allowing cooperative works.

Evidence of functionality has been provided for the whole system by attaching multiple different end-effectors to the work platform. Various end-effectors including tools for maintenance and care of vertical greens have been developed, manufactured and tested. While the working space of that prototype is on a laboratory scale, all individual components such as motion assemblies, work platform and end-effectors are real size.

The system is low-noise and suitable for use in rough environments. Thus, it can operate in and outdoor. The efficiently operated working space extends from five to several hundred meters without requiring any substantial change to the motion assemblies or the end-effectors. Only the drum capacity has to be adapted. Plane as well as spatial movements are feasible. Table 2 summarizes major technical specifications of the developed rope-driven robot prototype. Currently the transfer of this technology to private sector is in progress.

Table 2. Technical Specifications of the developed rope-driven robot.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Parameter</th>
</tr>
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<tbody>
<tr>
<td>Positioning accuracy</td>
<td>± 5 mm</td>
</tr>
<tr>
<td>Working space</td>
<td>5 m x 10 m</td>
</tr>
<tr>
<td>Net payload of the work platform</td>
<td>20 kg</td>
</tr>
<tr>
<td>Axis velocity</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Axis acceleration</td>
<td>10 m/s²</td>
</tr>
<tr>
<td>Connections</td>
<td>0.5 l/min Water</td>
</tr>
<tr>
<td></td>
<td>100 l/min compressed air (6 bar)</td>
</tr>
<tr>
<td></td>
<td>48 V / 3.5 A electrical energy supply</td>
</tr>
<tr>
<td></td>
<td>Ethernet (transmission of control signals)</td>
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5 ACTUATORS AND SENSORS FOR THE MAINTENANCE OF GREEN FAÇADES

Various commercially available mechanical actuators such as grabs and scissors can be attached to and operated by the work platform of the robot (cf. Figure 4). Fluid systems such as nozzles and injectors can be adapted, to apply water and fertilizer with high precision.

Figure 4. Visualization of a selection of tools and sensors attached to the robot’s work platform.
Furthermore, miscellaneous sensors such as near-infrared spectroscopy, temperature and humidity (air and substrate) probes as well as all common camera systems for condition monitoring can be attached and operated. Based on the collected data, the measured values can be analyzed and consequently specific actions can be derived for each plant individually.

These specific actions can be individual nutrition release, harvest, pruning and removal. Currently various supplier of agricultural systems and automation technology specialize in digitalized automated condition monitoring of plants. Thus, increasingly specialized sensor- and actuator systems are brought to market and subsequently can be equipped to the rope robot.

6 CONCLUSIONS

At the Chemnitz University of Technology a non-redundant, large-scale, rope-driven robot has been designed, manufactured, tested and proven to be a suitable solution for automated maintenance and care of green facades, especially in urban applications. The development not only includes the motion assemblies, mounting and working platform, but also the adaption, implementation and operation of various end-effectors. In contrast to common rope-driven robots the new design approach uses a completely restrained, non-redundant positioning mechanism to increase cost efficiency and susceptibility. Innovative compensatory strategies successfully have been applied to counteract the system specific weaker axes.

Further development needs to address the optimized compilation of applied sensors and the use of the acquired data. By means of artificial intelligence (AI), optimized decision making regarding the condition of the green should be derived and performed automatically. Successful implementation of AI enables the robot to operate vertical farming in general largely autonomous.

References