The Wallbot: A Low-cost Robot for Green Wall Inspection

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Abstract

The benefits of urban green infrastructure, such as attenuating the urban heat island effect and improving air quality, are widely accepted. Regardless, the uptake of green walls (i.e. vertical gardens) is low due to the high costs relating to maintenance and OH&S. These barriers to adoption may be mitigated by using robotics to inspect and maintain green walls.

In this work we present the Wallbot, a robotic system to inspect, monitor and aid in the maintenance of green walls. In its current form the system comprises of affordable off-the-shelf components to keep the system cost low. Preliminary development of the system, results of initial tests and findings are presented. The system offers the chance to reduce OH&S issues and maintenance costs associated with green walls.

1 Introduction

There are many reasons to increase the amount of Green Infrastructure (GI) in cities and urban areas. A key motivation is to decrease the environmental impact of the built world. Urban Heat Island (UHI) is a phenomenon where ambient temperatures are found to be higher in densely populated areas compared to the surrounding areas. UHI was found to affect the temperature by up to 11^{o}C in Sydney, Australia [Santamouris *et al.*, 2017]. One of the causes of UHI is the reduction of vegetation in these areas. One method of reducing the UHI effect is through increasing Green Infrastructures (GI) such as Green Roofs (GR), Green Walls (GW) and Green Facades (GF). A Macquarie University study and 2014 UTS Institute of Sustainable Futures report showed 6^{o}C heat mitigation is possible through GI [Jacobs *et al.*, 2016], [Ossola *et al.*, 2020]. An intangible benefit of green infrastructure are biophilia effects, with humans having an innate need to experience the natural world and associated feelings of well-being [Orr and Wilkinson, 2017]. A tangible benefit is an increased property value associated with green infrastructure and property [Rosenwax, 2017].

Although there are many benefits, the adoption rate of GI, and especially GW, is low [Wilkinson and Dixon, 2016]. This is largely attributed to the high costs associated with GW maintenance. Maintenance operations require workers, often qualified horticulturists, to closely inspect the condition of the plants on the green wall, and perform interventions such as pruning and replanting. Since GW are typically part of a building's facade, these workers are required to work at heights. Methods such as using scissor lifts, Building Maintenance Units in the case of larger buildings, or abseiling are often needed to gain access, further adding to the costs associated with GW maintenance.

By reducing the cost of maintenance, the adoption of GW should be increased and in turn lead to the associated benefits. One way of reducing the maintenance cost is through the use of an automated system to aid workers in maintenance operations. A robotic system that can reduce the amount that humans are needed to physically scale the side of buildings, even a partial reduction, could significantly reduce the overall maintenance cost across the life-cycle of the green infrastructure.

In this work we present the initial developments of the Wallbot, a robotic system for aiding in the inspection and maintenance of green walls. The Wallbot has been developed with cost in mind, utilising relatively inexpensive and off-the-shelf components to form the system. Conception was based on workshops held with green wall stakeholders to understand the needs and nuances of end users. Robotics has been explored extensively for use in agriculture [Roldán *et al.*, 2018], and systems specifically for GW have been devised [Fraunhofer IPA, 2020]. However to the best knowledge of the authors, this work is the first physical robotic system developed for the purpose of aiding green wall maintenance.

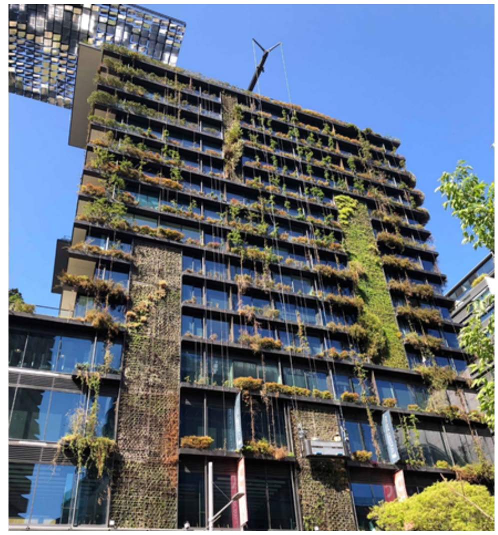
The remainder of this manuscript is organized as follows. Section 2 presents the outcomes from two workshops that assisted in defining the scope for automating GW maintenance. In Section 3, options for wall climbing systems are reviewed. Section 4 details the development of the Wallbot prototype system. In Section 5 preliminary results obtained are discussed. The future works of the the Wallbot prototype are listed in Section 6 and the conclusion of the paper is summarized in Section 7.

2 Design Workshops

To better understand the requirements and constraints associated with automating GW maintenance, two design workshops were hosted with key stakeholders. This included green wall installers and designers, landscape architects, building certifiers, urban planners, robot designers, IoT professionals and horticultural scientists.

In the two workshops, potential embodiment of the Wallbot was discussed. Various design concepts were explored in relation to the social, economic, environmental, regulatory, legal and technological impact. Based on the workshop discussions it became clear that it would be difficult for a one-size-fits-all automated system to cater to all GW. For example, a GW installed on a large building such as one shown in Figure 1a may require frequent maintenance and would benefit from a permanent installation integrated into the building. In contrast, a smaller GW like that shown in Figure 1b may benefit from temporary installation of the automated system which may be shared across several locations.

The key feature deemed important by the stakeholders involved in the workshops was the capability of monitoring the health of the plants. Additional functions such as planting and pruning, which requires physical interaction with the GW, were deemed desirable but not necessary in this early stage of development which reduces the complexity of the Wallbot system. For ease of initial testing, it was also decided that the Wallbot system should be designed to be transportable from one GW site to another, rather than a large permanent installation specific to a particular site.



(a) One Central Park, Chippendale

(b) UTS Building 10

Figure 1: A comparison of two green wall installations on the side of large buildings.

3 Wall climbing robot options

There has been many different robotic prototypes that were designed to inspect and maintain large structures. Although these robots have not yet been implemented on a GW, the core mechanics involved in developing these robots in their specific application may be transferable to a GW monitoring and maintenance system.

One method of locomotion for climbing robots is through the use of adhesion to the surface to be climbed. Through the use of magnetic footpads, a robot inspired by the inch-worm was developed to inspect steel bridges [Ward *et al.*, 2014]. The Sky Cleaners [Zhang *et al.*, 2007] used vacuum suction as a method of adhesion to glass surfaces such that the robot could be used for glass-wall cleaning in high rise buildings. Because these type of robots require contact to the surface for locomotion, in the context of the GW contact, to the surface is unfavourable. By requiring contact to the surface, there is a higher risk to cause damage to the plants. Therefore it is unlikely for the Wallbot prototype to move around the GW through adhesion.

Another common method of inspection is through the use of Unmanned Aerial Vehicles (UAV). The UAV has been used in a wide variety of applications such as bridge inspection [Seo *et al.*, 2018]. In [Dang *et al.*, 2018], a UAV was used to detect disease in radish fields, allowing for timely intervention to minimize losses. The benefit of the UAV is the capability to be used on a large number of GW with minimal additional infrastructure needed. The downside of these type of systems is the limited payload, resulting in a system that is mainly limited to inspection operations. Furthermore, with GW sometimes being located on residential buildings the use of UAV raises a concern over safety and privacy.

Cable driven robots have benefits including high payload to weight ratio, large workspace and transportability [Bosscher *et al.*, 2006]. These robots have been used in a wide variety of applications such as performing visual inspection on the top of airplanes [Monich *et al.*, 2019] to systems mounted on the side of buildings to monitor the environment [Izard *et al.*, 2013], and clean windows [Elkmann *et al.*, 2005]. Unlike UAVs these type of robotic systems require some infrastructure to be installed onto the GW itself.

Based on the key features identified from the two workshops, it was decided that the Wallbot prototype should be a cable driven robot. Although these type of robotic systems require some infrastructure to be installed onto the GW, it provides a higher payload capacity compared to UAVs. This allows the Wallbot prototype to be expanded with desirable maintenance functions to be developed in the future.

4 The Wallbot Prototype

The Wallbot prototype (Figure 2) comprises of two core elements; a set of four *smart winches* used to control movements of the Wallbot across the green wall; and the *main body* containing the sensors that are used to develop a map of the green wall and inspect the plants.

Two key factors dictated the elements of the prototype. The first is that the cost needs to be kept low such that the expense would incentivise the uptake of GW. The second design factor is safety as GW are usually installed in public spaces.

4.1 Smart Winch

The smart winchs consist of several elements as shown in Figure 3. To keep the cost of the prototype low, an off-the-shelf automotive winch was used. Added to the winch shaft is an encoder which allows the drum position to be accurately measured and the length of the rope estimated. Inside the smart winch, the rope is fed through a series of pulleys which is positioned such that the tension of the cable can be measured through the use of the load cell.

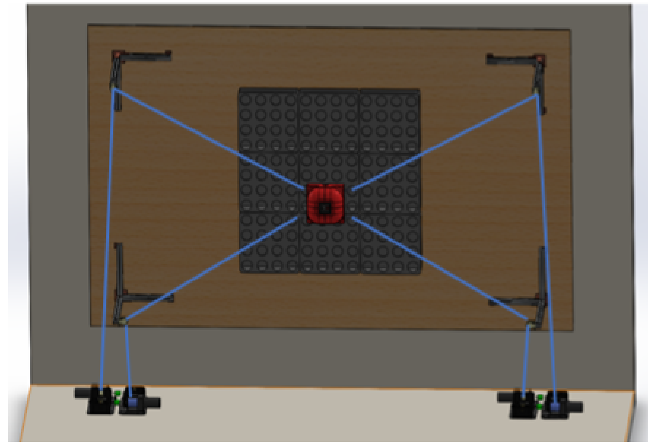


Figure 2: The Wallbot prototype, consisting of four smart winches and a main body.

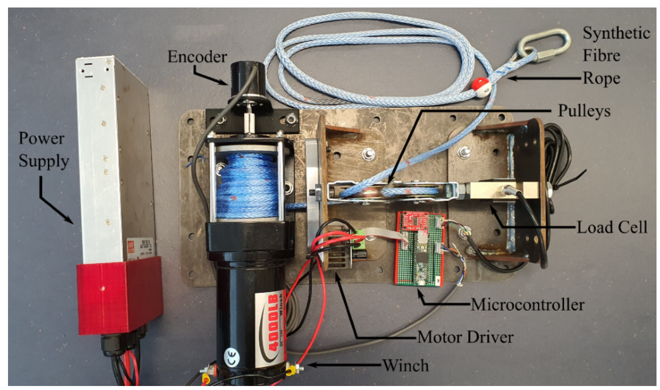


Figure 3: The components of a smart winch responsible for the positioning of the Wallbot main body.

To control the rotational speed of the winch, a microcontroller (Teensy 3.2) was used alongside a motor driver. By rotating the four smart winches, the length four ropes attached to the Wallbot main body is able to be changed to achieve locomotion. The microcontroller is also responsible for tracking the state of the smart winch, such as the tension of the cable being measured by the load cell, as well as the position and velocity of the winch. The state of each smart winch is passed on to a desktop computer which is then used for the high level control of the Wallbot prototype.

4.2 Rope and Pulley arrangement

As safety was a major concern for the system, synthetic rope was utilised. The synthetic rope was chosen over the steel counterpart as it allowed for sufficient tension to be maintained to lift and manoeuvre the Wallbot main body, whilst limiting the potential damage in case a break was to occur.

In the experimental setup, all four smart winches are located on the ground as shown in Figure 2. The ropes are fed up to pulleys that are mounted on the wall towards each corner of the green wall. We refer to the location of these pulleys as the *anchor points* on the wall as they anchor the robot to the wall and their locations define the kinematic relationship between Wallbot pose and rope length. It is envisioned that future iterations of the Wallbot, the winches may be mounted directly on the wall and form part of the GW installation.

4.3 Main Body

The structure of the Wallbot prototype main body (Figure 4 is made from a rigid aluminium frame providing four cable mounting points. These mounting points allow the ropes of the smart winches to be attached to the main body. The rigid frame is also used to house three vision-based sensors, which are:

- Intel RealSense T265
- Intel RealSense D435
- MAPIR Survey 3

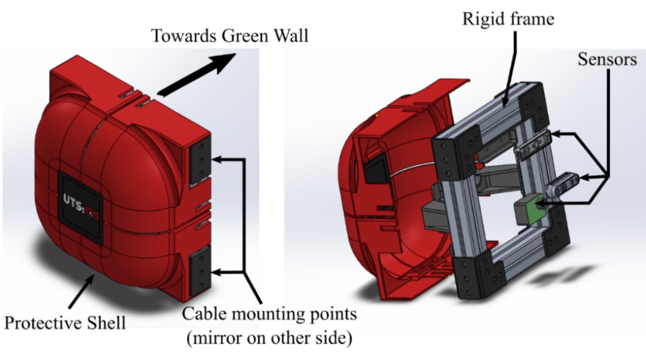


Figure 4: The main body of the Wallbot.

The Intel RealSense T265 camera was used to provide tracking information using stereo vision and its inbuilt IMU. This information is able to be used to improve the accuracy of the motion performed by the Wallbot, even when the length of the ropes is uncertain, for example due to rope stretching. When combined with the depth information provided by the Intel RealSense D435, a high fidelity 3D map of the GW can be reconstructed.

The MAPIR Survey 3 camera is used to provide a multispectral image to compute the Normalized Difference Vegetation Index (NDVI) of the green wall. Cameras used to compute NDVI are commonly used to make remote measurements and assessment of vegetation. Using NDVI, UAVs can autonomously collect data and recognize crop health. The Wallbot system takes NDVI measurements for a similar purpose, except the vegetation is vertical and the measurements are take at close distance.

The three sensors are positioned inside the Wallbot main body in such a way that the field of view overlap as much as possible and the area in which all three sensors are active can be maximized. The main body is designed to be modular and expandable, allowing for additional sensors to be integrated. For example, integrating a temperature and humidity sensor could provide additional information to be obtained, useful for plant health monitoring.

4.4 Robot Control

The control system architecture of the Wallbot prototype is divided into two levels as shown in Figure 5. The high-level control dictates the movement to be performed by the Wallbot prototype. The low-level control provides a direct interface to the hardware of the smart winch.

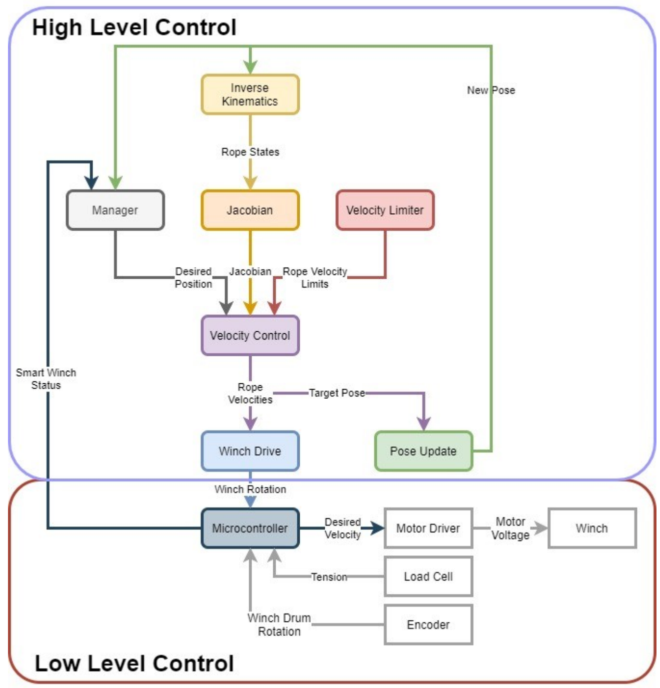


Figure 5: Flowchart of the control system of the Wallbot prototype.

High Level control

The high-level control is used to calculate the desired velocity of the four smart winches based on the current position and desired velocity of the Wallbot main body. To simplify the calculation the Wallbot is assumed to be constrained to a plane at a set distance parallel to the wall. With the location of the anchor points on the wall know, the relationship between the Wallbot body pose $\mathbf{x} = [x, y, \theta]^T$ and the rope lengths from the body to anchor points $\mathbf{l} = [l_1, l_2, l_3, l_4]^T$ can be calculated with a simple kinematic relationship:

$$\mathbf{l} = F(\mathbf{x})^{-1} \tag{1}$$

Note that we consider this as the inverse kinematic relationship, considering the length of the rope (from Wallbot body to anchor point) being the generalised coordinates of the system. The time derivative of this relationship leads to the following:

$$\dot{\mathbf{l}} = \mathbf{J}^{-1}\dot{\mathbf{x}} \tag{2}$$

$$\boldsymbol{J}^{-1} = \begin{bmatrix} \hat{\mathbf{l}}_{1,x}, & \hat{\mathbf{l}}_{1,y}, & -\mathbf{r}_{1,y}\hat{\mathbf{l}}_{1,x} + \mathbf{r}_{1,x}\hat{\mathbf{l}}_{1,y} \\ \hat{\mathbf{l}}_{2,x}, & \hat{\mathbf{l}}_{2,y}, & -\mathbf{r}_{2,y}\hat{\mathbf{l}}_{2,x} + \mathbf{r}_{2,x}\hat{\mathbf{l}}_{2,y} \\ \hat{\mathbf{l}}_{3,x}, & \hat{\mathbf{l}}_{3,y}, & -\mathbf{r}_{3,y}\hat{\mathbf{l}}_{3,x} + \mathbf{r}_{3,x}\hat{\mathbf{l}}_{3,y} \\ \hat{\mathbf{l}}_{4,x}, & \hat{\mathbf{l}}_{4,y}, & -\mathbf{r}_{4,y}\hat{\mathbf{l}}_{4,x} + \mathbf{r}_{4,x}\hat{\mathbf{l}}_{4,y} \end{bmatrix} \tag{3}$$

Where $\mathbf{J}$ is the Jacobian matrix relating the speed of the Wallbot body to the speed of the rope. $\hat{\mathbf{l}}$ represents the unit vector with a direction which is aligned to the corresponding rope, noted by the numerical subscript. The subscript x and y represents the horizontal and vertical component of the unit vector. $\hat{\mathbf{r}}$ represents the vector that extends from the Wallbot main body center of rotation to the corresponding cable mounting points. Given a desired Wallbot body pose and velocity, corresponding rope lengths and rope speeds can be computed. These are then sent as command set-points to the four smart winches.

A challenge with controlling the rope length and speed is that the effective diameter of each winch drum is not constant. As the winch winds rope onto the drum, the effective diameter increases as the rope accumulates. Therefore the rope length and winch drum rotation do not have a linear relationship. To accommodate this, a second order polynomial is used to relate the length of the rope to the winch drum rotation. The polynomial was obtained experimentally for each of the smart winches to increase the accuracy of the rope length estimation.

Low Level Control

The low level control of the Wallbot is performed by a microcontroller, responsible for interfacing with the hardware of the smart winch. Each microcontroller forms a closed loop controller, commanding winch motor voltage through a H-Bridge and using both the encoder and load cell for feedback. The control is implemented as a PI controller, tracking the desired winch velocity. Because it is desired to maintain a minimum rope tension at all times, a bias term based on the measured rope tension is applies such that the drum is wound more if the rope becomes slack, or is unwound should the tension exceed a preset threshold.

5 Results & Discussion

To test the capability of the Wallbot prototype, a simple GW setup was used (Figure 6). The wall consists of five Junglefy (https://junglefy.com.au/) plant boxes, four of which contained different plants. The setup allowed for the core elements of the Wallbot prototype to be tested in a laboratory setting.

Figure 6: Wallbot being maneuvered across a mock green wall.

The design choices of the Wallbot prototype were directed by two factors, safety and cost. Several of these choices were found to result in challenges with robot performance. An example is the use of polymer rope, which as previously explained was chosen for safety reasons. The lower stiffness of polymer rope made the control of the robot difficult. Other factors such as unguided winding, large rope diameters and multiple winding layers on the drum led to inaccurate estimation of the rope lengths, which in turn affected pose estimation. Additionally, the automotive winches used are designed for much higher load capacity. The slow speed of the winches significantly limited Wallbot speed and made precise control of rope tension difficult to achieve.

These challenges could be addressed by utilising a higher performance winch system, a mechanism to guide the rope winding, and stiffer steel rope. Such methods would add system complexity and incur cost, which may hinder the adoption of the technology. It is instead envisioned that a suitable compromise between cost and complexity may be achieved by using exteroceptive sensing to overcome the aforementioned limitations. In the current prototype the pose of the Wallbot body was estimated calculated using the T265 camera, alleviating the need to accurately measure and control the lengths of the four ropes. It is envisioned that future iterations of the Wallbot will find an appropriate compromise that will achieve acceptable performance whilst lowering system complexity and cost.

Even though the control of the Wallbot prototype needs to improve, initial testing has shown the potential of using such technology. The 3D data (Figure 7) and NDVI data (Figure 8) obtained by the Wallbot prototype could be used to perform regular inspection of the

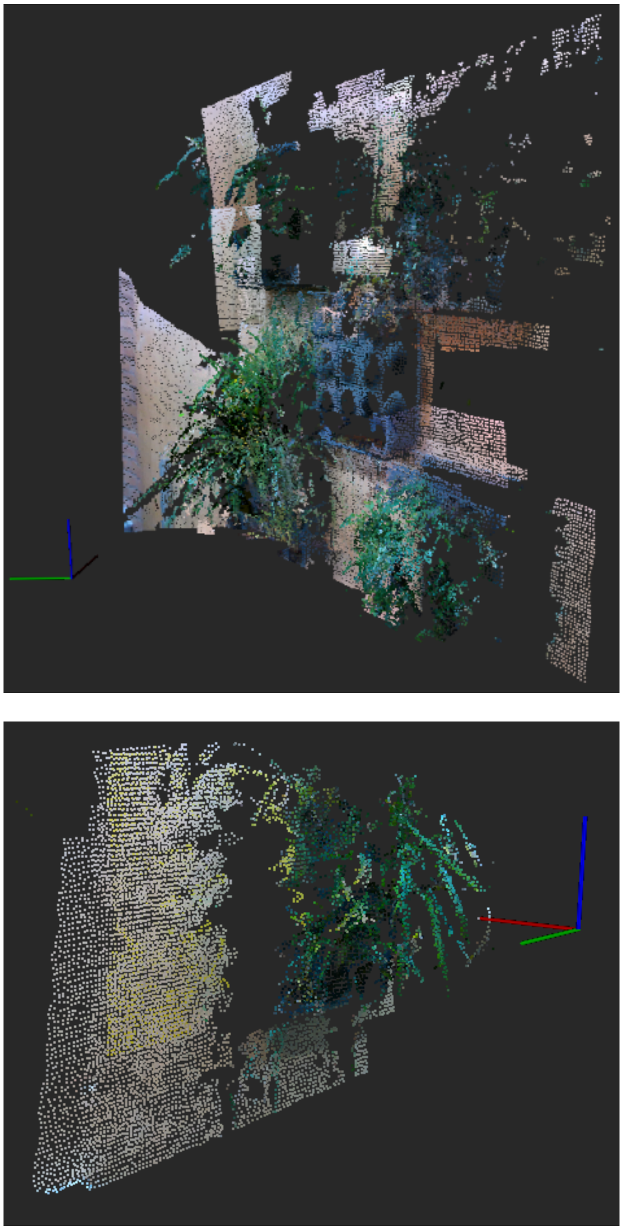


Figure 7: Reconstructed RGB-D point clouds using the data obtained from the two RealSense sensors.

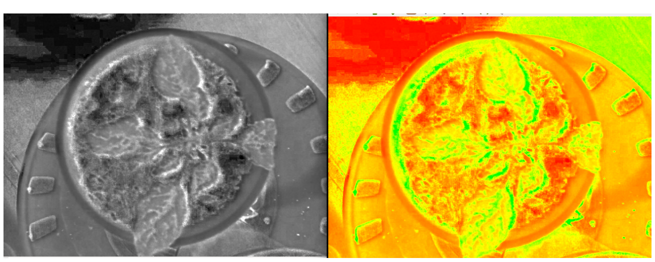


Figure 8: NDVI images captured using the MAPIR Survey 3 camera.

green wall autonomously. This would allow the plant health to be inspected at regular intervals, allowing for easier or more strategic maintenance of GW at a lower cost. With regular systematic collection of data on the GW, the decline of plant health may be observed and potentially remedied before replanting is required.

6 Future Work

In the future, the Wallbot prototype is envisioned to be deployed in real world field tests to collect data such that the environmental impacts of GW can be measured. The system would be made more capable through the addition of various sensors to measure environmental factors such as level of pollutants in the area and local ambient temperatures. The data collected from the additional sensors can be used to measure the attenuation of UHI, changes in local biodiversity, impact on air quality and the absorption of pollutants. As many large buildings already utilise Building Information Modeling (BIM) systems, data collected by the Wallbot should be compatible with such systems so that the data can be seamlessly integrated into building operations.

To improve the performance of the Wallbot prototype, custom hardware would need to be developed. This is especially true for the winch/rope system which suffers from a low rotational speed and inaccurate control. Additional capabilities to physically interact with the GW would also be beneficial. This would allow the Wallbot prototype to seed and plant various flora and fauna onto the GW, as well as remove diseased or unwanted plants. These additional capabilities would further reduce the need for costly human maintenance, however it significantly increases the complexity of the Wallbot system.

For the Wallbot prototype to be deployed in a real world application several other improvements are necessary. Notable improvements would be to weatherproof the winches and the main body such that the system could operate in the presence of moisture and other environmental factors. The Wallbot prototype is also currently controlled through a desktop PC which attaches to the main body and the smart winches through tethers which provides data to the PC. For a transportable system, the Wallbot main body is envisioned to house a small computer. This introduces other challenges such as power and communication between the smart winches and Wallbot body.

7 Conclusion

This work presented the Wallbot prototype, a robotic system designed to inspect, monitor and aid the maintenance of green walls. This prototype represents the initial step towards a robotic solution to reduce the cost relating to maintenance of green walls whilst reducing issues relating to OH&S. The benefits of the Wallbot may result in more green walls to be adopted, improving the environmental conditions in urban environments. In the current form, the Wallbot prototype comprises of affordable off-the-shelf components to keep the system cost low. Preliminary development of the system, results of initial tests and findings are presented.

A video summarising this work can be found here: https://youtu.be/irZkg9UB5cE

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