COS Environmental Grant Project Report

The Green Wallbot

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Contents

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Nomenclature
LGA – Local Government Area
GI – Green Infrastructure
GR – Green Roof
GW – Green wall
OHS – Occupational Health and Safety
UHI - Urban Heat Island

Executive Summary

The need and demand for robotic technology to increase the uptake of green walls and facades whilst reducing OHS and maintenance costs is clear. The benefits of urban green infrastructure are widely accepted and include urban heat island attenuation, increased bio diversity, reduced carbon emission, biophilia effects, provision of spaces for social interaction, attenuation of rainwater flooding and improved air quality. With climate change and increasing temperatures a stark reality, resilience and liveability as well as sustainability are greatly enhanced through the adoption of Green Infrastructure (GI).

Wallbot, a robotic installation to inspect, monitor and maintain green walls offers the chance to reduce OHS issues and maintenance costs associated with green walls.

An extensive literature review focussed on existing robots and wall climbing mechanisms, power sources, pruning technologies, and green waste collection as well as sensor technology and costs. A summary is provided in the report focussed on climbing mechanisms and sensor technology. Appendix A provides an extensive review of all aspects.

The research design comprised the review of secondary data such as research reports, peer reviewed journal papers, technical guidelines and appraisal of all options, which were proposed and discussed at two workshops with key stakeholders and experts in delivering GI in cities. Based on the review of the experts, a prototype design based on a 4-cable climbing mechanism was designed and prototyped at UTS.

Development and trials were conducted over a 2 month period on the movement and control systems. Planted green wall pods, provided by Junglefy, enabled the team to collect data on plant health and Wallbot sensors ability to assess plant health.

Plates **Page no.**

Tables **Page no.**

1.0 **Introduction**

1.1 Background and rationale

Despite over a decade of contemporary green roof and wall (GR & GW) research outlining the numerous social, economic and environmental benefits, take up of GR & GW has been slow (Wilkinson & Dixon, 2016. Davis et al, 2017). By 2012, in the City of Sydney LGA, development had resulted in only 4% of indigenous flora and fauna remaining since European settlement. The 2018 IPCC report predicts a 2 degree temperature increase, making the urban heat island (UHI) effect in the CBD and surrounding areas hotter than ever (IPCC, 2018). GR & GW attenuate the UHI and we need more. Wilkinson and Reed (2009) showed it is possible retrofit around 40% of existing commercial office rooftops as green roofs. Similarly, retrofits of walls are possible and offer greater areas overall. Using façade areas, it is possible to be net positive in green infrastructure in dense urban areas and our aim is to develop the means to achieve this safely and cost effectively. With knowledge and expertise in GR & GW and robot design, this report presents a solution to the main barriers to GW adoption in respect of occupational health and safety (OHS) and maintenance costs.

The ability to design, install and maintain GW in Sydney at scale are amply demonstrated by the iconic Central Park development in Broadway installed in 2012. However there has not been widespread uptake despite increased property values associated with GI and property (Swinbourne and Rosenwax, 2017). The key barriers are the ongoing high maintenance costs (Wilkinson & Dixon 2016, Wilkinson et al, 2017); Central Park has employed a team of 6 maintenance people year round working from cradles suspended from rooftop mounted cables. OHS issues arise when maintaining GW over public footpaths and roads and in high winds.

Increasingly there is adoption of technology and the use of smart sensors in the built environment. Such knowledge enables the design of a green ‘wallbot’ that overcomes these OHS and economic barriers. No wallbot exists currently and this is a world first; positioning Sydney as an incubator of smart living technology. The ‘wallbot’ is envisioned to seed, weed, trim and maintain GWs. Furthermore, new employment opportunity is created in robot design, fabrication and installation and maintenance as a result.

As a result of using robot technology, areas currently not considered suited to GW locations will become viable, for example; bridges over roads. Adoption of GW in these areas will add to total GI infrastructure in COS with the aims of being GI positive; a living city. The social, environment and economic benefits of GI are well documented and this technology will allow the delivery of GW safely and more economically than ever before.

Furthermore, the introduction of smart sensors in the Wallbot will ensure optimum watering and collection of data on air quality and bio-diversity. Air quality and habitat for bio-diversity are important issues the city needs to address urgently as the impacts of climate change and temperature increases have greater effect. Air quality issues in Sydney were highlighted in December 2019 due to bushfire smoke from surrounding areas.

This project adopted traditional knowledge and technology to care for country, working with Jumbunna and Eora and Gadigal elders.

This feasibility study summarises the design and fabrication of a robot to monitor, inspect and maintain green walls. This technology will reduce ongoing maintenance costs and overcome OHS issues that are barriers to green wall adoption. In addition a new smart technology / industry is created.

1.2 Project alignment with City of Sydney strategic directions

This project aligns to COS strategic directions, with programme outcomes as follows;

1. *SD1, SD2, SD9 - Strengthened climate resilience measures as GI produces oxygen and attenuates the UHI effect*
2. *SD1, SD9 - Contribution to improved air quality as plants absorb CO2 and emit oxygen. Smart sensors measure air quality on Green walls.*
3. *SD1, SD2, SD9 - Increased urban greening and enhanced urban ecology and biodiversity – habitat provided by the Green walls.*
4. *SD1, SD2, SD9 - Reduced maintenance liability and costs means greater uptake by owners*
5. *SD1 Enhanced knowledge arises as results of the project are published nationally and internationally, skills sharing and enhanced capacity in best practice environmental performance is delivered, as a new business area created; 'wallbot' design and installation and 'wallbot' maintenance, placing Sydney in the lead of smart technologies for greener cities.*

1.3 Aims and Objectives

The project outcomes are;

1. The design,
2. Fabrication and
3. Testing of prototype wallbot technology to reduce OHS and cost barriers to GW installation in Sydney.

The project objectives are the;

1. Erection of a 3 metre tall green wall on campus, planted with a range of green wall plants.
2. Hosting two design workshops with key stakeholders including; green wall installers and designers, Indigenous elders, landscape architects, building certifiers, urban planners, policy makers, construction companies, property developers, bot designers, IoT professionals and horticultural scientists to consider the attributes of the wallbot technology.
3. Design and fabrication of a prototype wallbot.
4. Testing and data collection using the prototype wallbot.
5. Production of a project report:
    a. Outlining design, testing and outcomes.
    b. Production of video footage showing the wallbot in action.

1.4 Performance measures

The project measures and evaluates the wallbot system for the following;

1. Ability to move vertically and laterally across a green wall.
2. Create 3D visualisation of plants.

1.5 Scope and Limitations

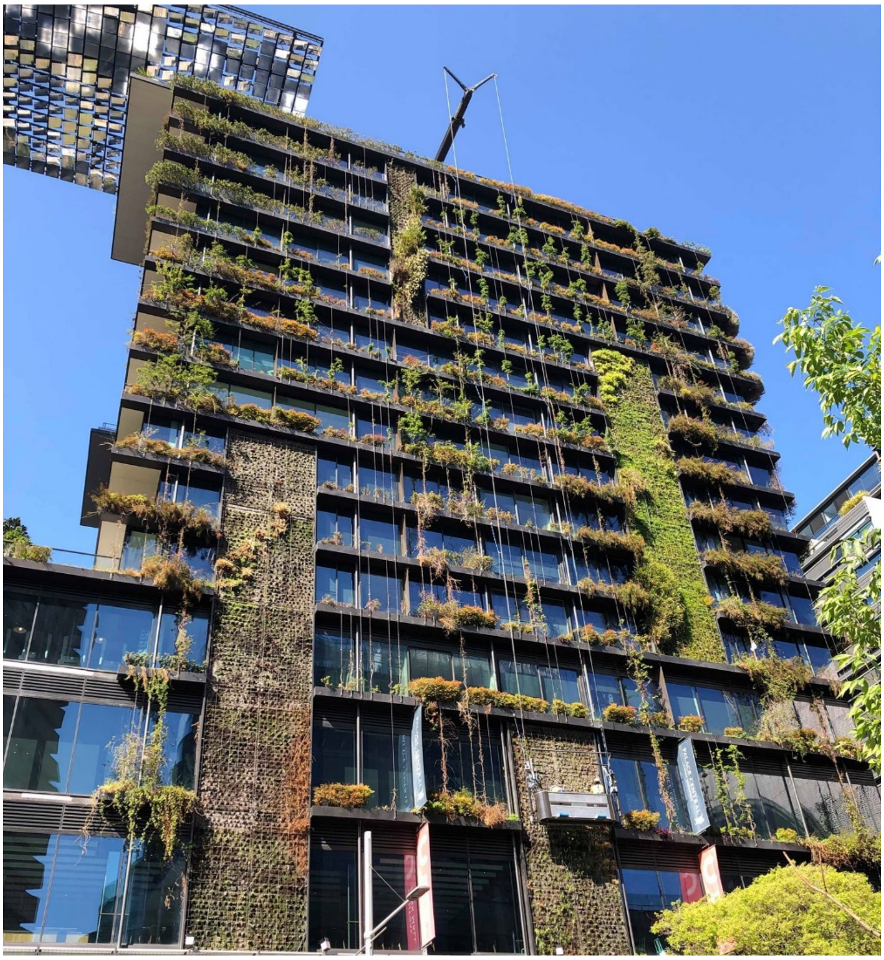
All research has limitations, and in this project the timeline of the duration of the project and reporting requirements meant that following the design workshops, the testing period reported here for the wallbot is short; 2 months. Extended testing will enable the verification and confirmation of more reliable results.

The initial scope of the project was reduced following the workshops and the implications of functionality and quality were evaluated. It was decided to focus on movement and monitoring and inspection initially with an internal laboratory tested prototype and to extend wallbot functionality in a follow up project.

2.0 **Literature**

Existing methods of monitoring and inspecting green walls are shown in Plate 1 below. They comprise green wall maintenance staff working from cable mounted cradles. This method is slow and expensive and has significant OH&S risks. It is also vulnerable to adverse weather such as high winds and intense heat. Furthermore, as shown on Plate 1, when regular maintenance is suspended plant health deteriorates to a point where replanting of entire sections of wall is needed. Typically, workers scale the walls every three months to complete inspection checks and maintenance activities. This infrequent work results in large volumes of green waste that must be disposed of, requiring multiple trips up and down the wall.

Plate 1 – existing methods of monitoring and maintaining green walls Central Park Sydney 2019



(Source: Top2Bottom Engineers).

With advancement in bot technology and smart systems, a proposal to design a *Wallbot* to replace human maintenance of green walls is made. The proposed system would act to cut and maintain various plant species on green walls and collect data on the conditions of the wall, such as pH levels, soil moisture levels, air quality as well as monitoring heat and humidity levels. This smart and innovative technology will overcome issues of high maintenance costs and OH&S risk, creating a platform for robotic design and increasing opportunities for green walls to be included in future building developments.

2.1 Existing façade and wall climbing technology

Wall climbing mechanisms

The following selection of wall climbing robots possess features that may be appropriate for Wallbot. For an in depth overview of current wall climbing technologies and their respective advantages and disadvantages see Schmidt and Berns (2013) or Nansai and Mohan (2016).

SkyBoy

The SkyBoy (Plate 2) is a window cleaning robot for high rise glass facades specific to the control tower at the Guangzhou Airport, in Guangzhou, China.

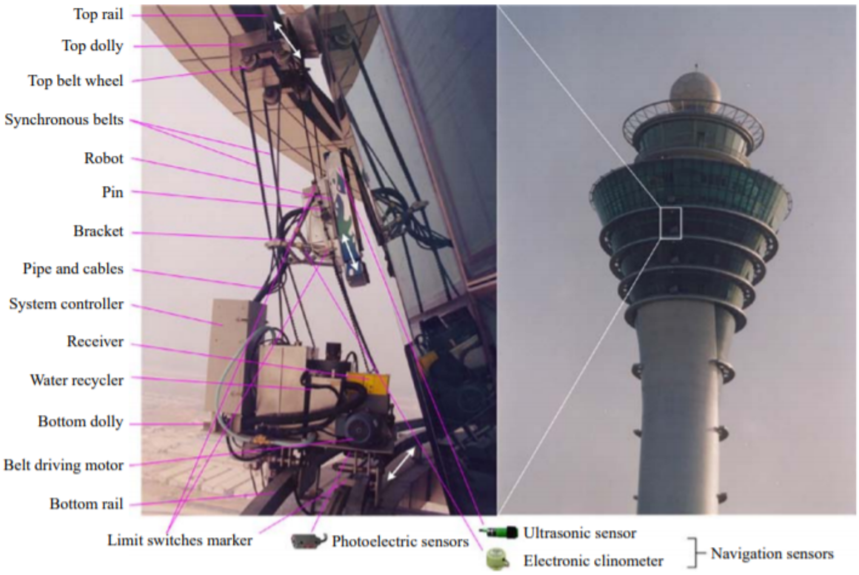


Plate 2 Skyboy (Wang et al. 2010)

- **Multiple Robots:** The system comprises 4 Robots located between the steel rings dividing the glass paneling as part of the buildings infrastructure.
- **Gravity Resist and lateral movement:** The robot uses rails and a dolly system that moves along the circumference of the steel ring. A belt system moves the robot vertically. A high level of control was not required to synchronise the two dollies due to the flexibility of the soft belts.
- **Façade connection:** SkyBoy maintains connection with the façade using suction cups. (Wang et al. 2010)

An advantage of SkyBoy is that it is not subject to falling due to power loss yielding high security (Wang et al. 2010).

SIRIUSc

SIRIUSc (plate 3) is a high rise window cleaning robot developed by the IFF in Germany.

- **Gravity resist and lateral movement:** SIRIUSc is supported by a rooftop crane and gantry that supports and moves the robot laterally via rails. This system is fully automated.

Plate 3 Rooftop Gantry of SIRIUSc (Elkman et al. 2005)

- **Data Transfer & Power supply:** Power and data are supplied/transferred over the gantry connection cables.
- **Façade connection:** SIRIUSc uses a sliding frame fitted with suction cups to maintain connection to the wall as the robot moves vertically. The suction cups are fitted with actuators that can move the suction cups perpendicularly to the building surface allowing the robot to move over obstacles (Elkman et al. 2005).

Roboclimber vs Landslides

Roboclimber (plate 4) is used to navigate and consolidate rocky walls and slopes for the prevention of landslides.

- **Gravity resist**: for slopes greater than 30°, Roboclimber uses cables secured by Tirfor winches.
- **Lateral and vertical movement**: Roboclimber uses a combination of tension in the ropes and manoeuvring of the legs to move vertically and laterally. The lateral span of the robot is limited by several factors including, distance of anchorage of two tensioning ropes, average slope of wall and vertical height as illustrated by in figure x below.

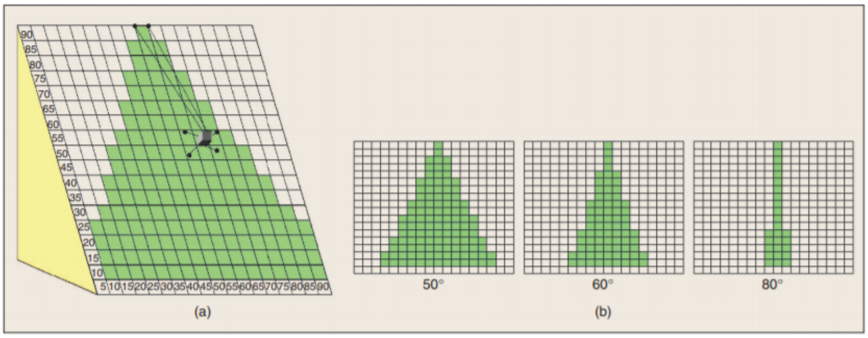


Figure 8. *(a) Example map of reachable wall region for 20° wall average slope (the robot is shown at the starting location). (b) Other example maps of reachable wall region for 50°, 60°, and 80° wall average slopes.*

Plate 10 Reachable regions for the Roboclimber (Cepolina et al. 2006)

- **Rock interface/Legs**: Cylindrical RPP (revolute prismatic joints) (plate 5) are used to manoeuvre and hold the Roboclimber in place whilst undertaking deep drilling tasks.

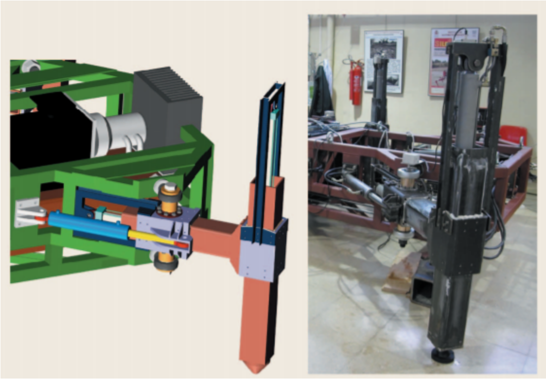


Plate 11 Roboclimber legs/limbs (Cepolina et al. 2006)

- **Power:** Onboard hydraulic power to actuate legs and perform high torque drilling operations.

Propeller Type Wall Climbing Robot

A prototype for a wheel based thrust force climbing robot that is capable of independent flying has been developed for firefighting applications (plate 6)(Nishi & Miyagi 1994).

- **Gravity resist**: Propellers use thrust force inclined at an angle towards the wall to produce a frictional force with the wheels and stabilise the robot. The robot can fly independently in order to access walls or land.

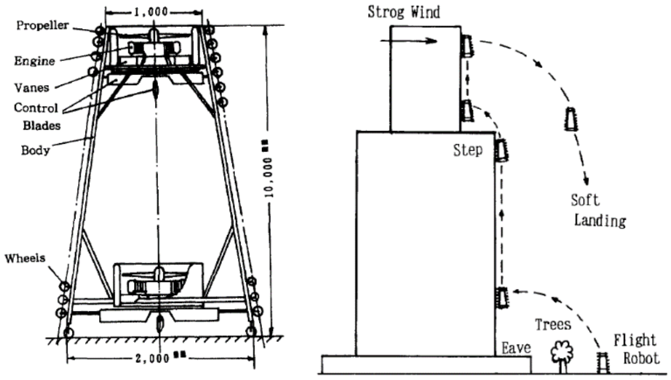


Plate 12 Propeller type wall climbing robot and operational schematic (Nishi & Miyagi 1994)

- **Lateral motion**: Vanes direct the propellers slip stream in order to move laterally along walls. Further, a set of control blades produce side thrust when the robot is in flight mode.
- **Wall interface**: Sets of passive wheels attached to the robot frame for landing on walls. (Nishi & Miyagi 1994)

LEMUR IIb

The LEMUR IIb (plate 7) is developed as a multiuse flexible robot that uses limbs to move through vertical surfaces.

- **Gravity resist & lateral movement**: The LEMUR uses 4 limbs, each with 3 revolute joints, to move the 7kg body by manoeuvring limbs to attach to 'holds' which are typical features of a rock climbing wall including extrusions and holes.
- **Wall connection**: the end part of each limb comprises a single peg with a high friction rubber coating. The robot uses control to carefully place its centre of mass between the holds.

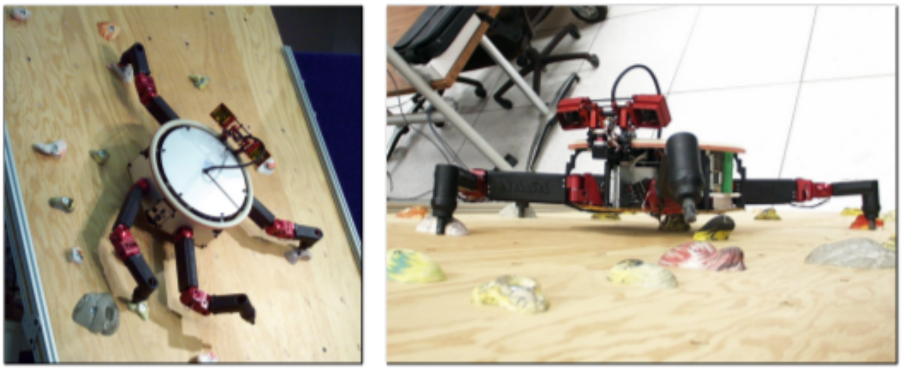


Plate 13 LEMUR IIb (Bretl et al. 2006)

ROPE RIDE

Rope Ride (plate 8) is a robot that cleans high rise façades without the use of water.

- **Gravity Resist**: The ROPE RIDE uses a single free rope and a motorised rope ascender to move vertically.
- **Wall connection**: The ROPE RIDE maintains connection to the wall via propellers that produce a thrust force.
- **Triangular tracks**: Rope ride has 4 triangular tracks that assist in lateral movement and can rotate for moving around obstacles.

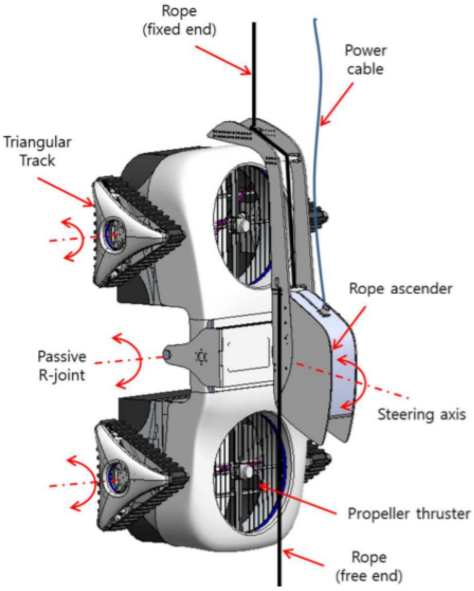


Plate 14 ROPE RIDE Robot (Kin et al. 2014)

BWMR (Building Wall Maintenance Robot)

The BWMR (plate 9) uses inbuilt guided rails within façade frame structure to perform façade maintenance.

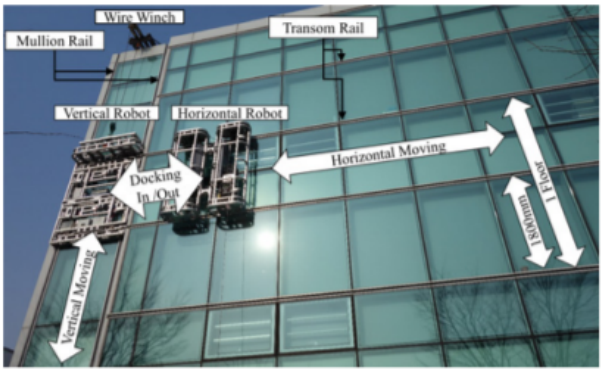


Plate 15 The BWMR Robot (Moon et al 2015)

- **Multiple Robots**: The BWMR comprises two robots; a horizontally traversing robot that cleans the façade, and a second vertically moving robot that transports the horizontally moving robot between levels of glass panelling.
- **Gravity resist**: The vertical robot uses a cable and winch system to support its vertical motion. Whereas the horizonal robot utilizes the inbuilt rails and an interlocking wheel driving system.

SkyScraper-I

The SkyScraper-I is a window cleaning robot (Plate 10) that utilizes the buildings window frame structure to clamp in position (Imaoka et al. 2010).

- **Gravity Resist and lateral motion**: The SkyScraper-I uses two cables with corresponding reel mechanisms to support the robot and control position using the respective lengths of each cable.
- **Wall connection**: The Robot utilises the inclination of clamping arms that rotate from the vertical hanging position to gain connection to the wall.

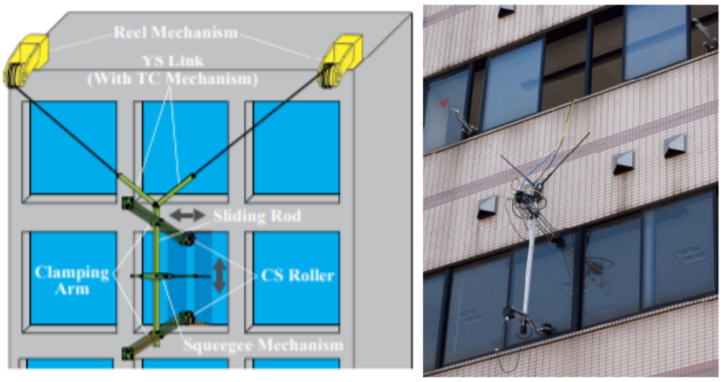


Plate 16 The SkyScraper-I (Imaoka et al. 2010)

KITE Robot

The Kite robot (plate 11) is a window cleaning robot that is automated and designed to manoeuvre high rise building (KITE Robotics, 2019).

- **Gravity resist and Lateral Motion:** A cable system the functions off a pulley is installed on to the face of the building. The cables are thin, but strong, and the KITE robot is programmed to have multidirectional capabilities to all parts of the building.
- **Transportability:** The cable system can be set by two people and is already preset to know its location and origin once it is set up
- **Removability:** Due to this, the system required little work to set up and does not need any rails or large permanent fixtures. It is able to be used and disassembled without affecting the appearance of the building.

Plate 17 Kite Robot (KITE Robotics, 2019)

Claw Hook Robot

The claw hook robot (plate 12) utilises patterns common with animals in nature, using claw like hooks to fasten itself to the surface of a wall and climb (Xu, 2012).

- **Gravity resist**: Uses several minute hooks to attach itself to a wall.
- **Lateral Motion**: Moves vertically and laterally using two hooked feet on either side, moving back and forth between each side to climb up a wall.

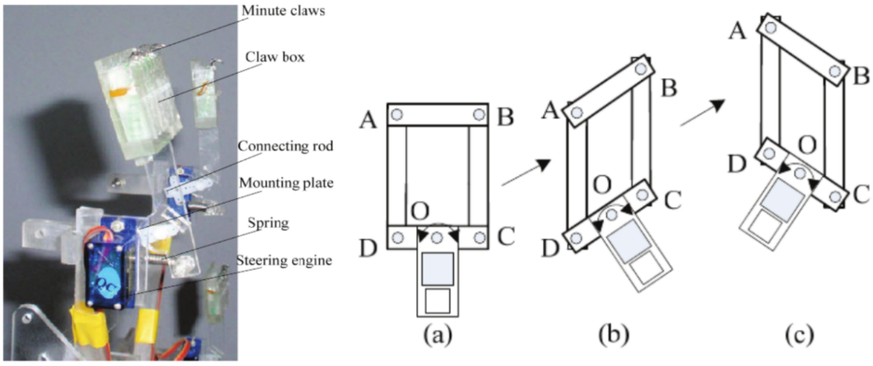


Plate 18 Claw Hook Robot (XU, 2012)

2.2 Sensor options

Onboard sensor probes

Key Information

- Fitting Wallbot with onboard sensors that analyse parts of the wall when Wallbot travels across it
- Measures key parameters such as temperature, humidity, heat level, wind speed, wind direction and soil moisture

Table 1 Sensor characteristics

Advantages	Disadvantages
• Consolidates sensors to one device • Can measure a variety of different gardening measures • No probes needed on the wall	• Robot has to be active in order for sensors to operate • Cannot get multiple readings simultaneously

External sensor probes

Key Information

- Device that places probes at desired points in the wall
- Able to adapt type of sensor to correspond with measurement needed, moving arm will be necessary
- Covers all detection of key garden elements
- Able to perform EC (electrical conductivity) testing to gain data on soil health

Table 2 External Sensor characteristics

Advantages	Disadvantages
• Can have cross coverage of a wall by probing sensors in multiple points that work concurrently • Is not limited to type of sensor that can be placed in wall • Adopts similar process to current model of green wall maintenance	• Sensors have limited lifespan and must be replaced • Extra parts attached to wall can increase safety risk • Once placed in one area cannot be transferred easily

An analysis and comparison of external and onboard sensors was undertaken and is summarised below;

Onboard Sensors

Table 3 Onboard Sensor characteristics

<table>
<tr><th colspan="10">Onboard Sensors</th></tr>
<tr><td colspan="10">Key Information
• Fitting Wallbot with onboard sensors that analyse parts of the wall when Wallbot travels across it
• Measures key parameters such as temperature, humidity, heat level, wind speed, wind direction and soil moisture</td></tr>
<tr><th colspan="5">Advantages</th><th colspan="5">Disadvantages</th></tr>
<tr><td colspan="5">• Consolidates sensors to one device
• Can measure a variety of different gardening measures
• No probes needed on the wall</td><td colspan="5">• Robot has to be active in order for sensors to operate
• Cannot get multiple readings simultaneously</td></tr>
<tr><th colspan="10">Project Rating</th></tr>
<tr><td colspan="2">Flexibility</td><td colspan="2">Cost</td><td colspan="2">Safety</td><td colspan="2">Maintenance</td><td colspan="2">Waste Collection</td></tr>
<tr><td colspan="2">Not as flexible as a device that could place multiple sensors which operate concurrently, however is able to adapt and move sensors instantly to a new position without set up</td><td colspan="2">Less probes/ sensors needed so less cost</td><td colspan="2">The safety increases as the robot will not be leaving sensors externally up on the wall</td><td colspan="2">Allows the robot to recognise areas where key gardening parameters may not be ideal, and can perform maintenance on these areas</td><td colspan="2">N/A</td></tr>
<tr><td colspan="2">Good 😊</td><td colspan="2">Good 😊</td><td colspan="2">Good 😊</td><td colspan="2">Extremely Beneficial 😊 😊</td><td colspan="2">N/A</td></tr>
</table>

Table 4 External Sensor Probe characteristics

<table>
<tr><th colspan="2">External Sensor Probe</th></tr>
<tr><td colspan="2">Key Information
• Device that places probes at desired points in the wall
• Able to adapt type of sensor to correspond with measurement needed, moving arm will be necessary
• Covers all detection of key garden elements
• Able to perform EC (electrical conductivity) testing to gain data on soil health</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• Can have cross coverage of a wall by probing sensors in multiple points that work concurrently
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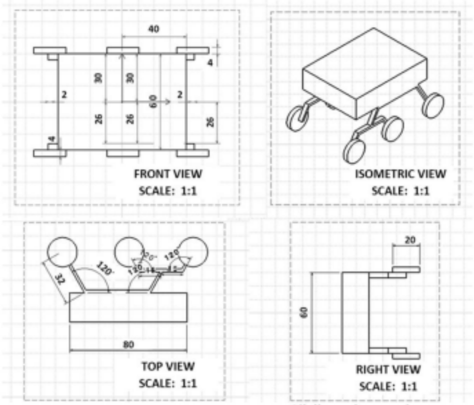
• Extra parts attached to wall can increase safety risk
• Once placed in one area cannot be transferred easily</td></tr>
</table>

Project Rating				
Flexibility	Cost	Safety	Maintenance	Waste Collection
Able to place multiple sensors at desired points in the wall which can operate concurrently	Increased cost with increased number of sensors necessary	Increases hazards, i.e. sensor not being attached properly and potentially falling off	Allows user to compare different sections of a wall which need a higher priority for maintenance	N/A
Extremely Beneficial 😊😊	☹ Poor	☹ Poor	😊 Good	N/A

Smart Autonomous Gardening Rover with Smart Recognition using Neural Networks (Kumar et al. 2016).

- Measures the key parameters for gardening such as temperature, humidity, heat level, wind speed, wind direction and soil moisture. The data acquired from the on-board sensors of the gardening rover are sent to the cloud storage platform on a regular basis



All dimensions are in cm

Fig.1. Mechanical design of the rover

Plate 13 Smart Autonomous gardening Rover (Kumar et al. 2016).

- Insertion of sensor done by ATmega2560 microcontroller
- The robot uses M265 temperature, soil moisture probe and relative humidity sensor module DHT11 for measuring the garden’s humidity, heat level and moisture content (Kumar et al. 2016).

2.3 Design parameters

Taking the options above into account, we considered also various design related parameters. In order to ensure we have considered all aspects, a PESTLE framework is adopted. PESTLE is an acronym for political, economic, social, technological, legal and environmental. Consideration of PESTLE allows for a comprehensive analysis of all influencing factors. With respect to the Wallbot, these are outlined below;

Political factors

In February 2020, increases in the height of tall buildings in the Sydney CBD were announced. The changes will remove the 235-metre cap on building height limits and could allow for towers in

Barangaroo, Central Station, Circular Quay and Town Hall to be as high as 330 metres. Building heights in the city were capped for decades to stay below the Sydney Tower, which stands at 309 metres. Such development will increase the Urban Heat Island effect, which can be counteracted through adoption of green walls and facades.

The City of Sydney 2030 plan moves towards a green cityscape which is potentially good for the uptake and further development of wallbot technology and application.

Economic factors

Manufacturing costs for green walls and facades will increase if demand requires more labour, however Wallbot can overcome this by reducing maintenance costs.

As the City implements its' 2030 Plan with greater green walls and facades, there will be increased demand and a greater market for Wallbot technology.

Social factors

There is a danger that Wallbot will replace current green wall maintenance employment for local people, however there is also the creation of new jobs in manufacture of wallbot, wallbot installation and manual operation and performance of green wallbot maintenance.

Technological factors

This is a fast developing area and ever-changing technology may decrease demand for the Wallbot due to the development of better bots.
The technology used for operation and control of the Wallbot should be updated regularly in order to ensure optimum efficiency.

Legal factors

All OHS risks must be acknowledged and accounted for to ensure that operation is safe. This will involve factors such as insurance,

Environmental factors

Environmental methods, such as wind or solar, for powering the wallbot system should be put in place to allow the company/building to run the machine at minimal environmental costs.

Where possible low energy, low impact materials should be used in the Wallbot. The non-reusable components must be disposed of responsibly at the end of the lifecycle.

Following a thorough review of each option and based on the parameters discussed above the 4 cable positioning system was deemed the best prototype design to adopt for Wallbot 1. The summary table overleaf highlights the key information, perceived advantages and disadvantages and project rating and relevance.

Table 5 - Four cable positioning system characteristics

4 Cable Positioning System

Key Information

- Ability to carry high loads
- Requires 4 motors and control systems
- Consideration, tradeoff between permanent Wallbot vs setup and down times
- Potential for mains power supply through the cables.

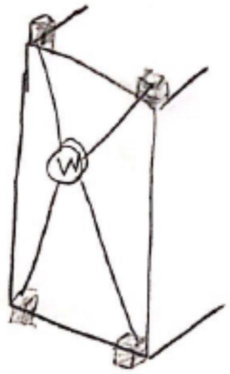


Figure 19 Four Cable Positioning Concept Sketch

Advantages	Disadvantages
• Total façade coverage (can reach all coordinates of façade) • Security: the connections of 4 cables minimizes the risk of the wall bot falling from the building façade.	• Aesthetics need to be considered • Side walk/ground provisions required (potentially expensive cable equipment) • Considerations for wind conditions and cable tensioning required • Cannot easily be transported to different facades of the building • Regular service of 4 winches

Project Rating

Flexibility	Cost	Safety	Maintenance	Waste Collection
This technology can be applied to a range of facades, however, may have limitations regarding set up and down times.	Easy to control, however requires 4 anchorage points and rigging equipment.	This component does not necessarily contribute to the reduce high risk work performed by the green wall maintenance personnel.	This component does not necessarily contribute to the maintenance of green walls.	The ability for this component to carry high loads means that it has the potential to carry a large amount of waste on board.
Good 😊	Good 😊	N/A	N/A	Good 😊

3.0 **Research design**

3.1 Workshops aims

Two workshops were convened with key stakeholders to determine the design features and requirements of a Wallbot. Workshops enable knowledge and experiences to be shared in real time, speeding up the identification of features and verification of the validity of ideas and proposals (Patton, 2014).

Workshop 1, held on August 14th 2019 at UTS, was attended by 16 stakeholders representing green wall installers, designers and maintenance professionals, architectural, construction, mechatronics and engineering professionals and government organisations.

In this workshop various movement mechanisms were discussed and the advantages and disadvantages of each were debated in respect of social, economic, environmental, regulatory, legal and technological factors.

Other variables discussed included monitoring and inspection (plant health, air, soil and moisture measurements), and maintenance activities such as pruning and replacement of plants. In each case potential and available technologies were debated and the advantages and disadvantages of each were agreed.

Workshop 2, held on October 3 2019 at UTS, was attended by 14 stakeholders representing green wall installers, designers and maintenance professionals, architectural, construction, mechatronics and engineering professionals and government organisations. In this workshop the team presented a potential design to the participants in respect of discussions from workshop 1.

3.2 Workshop outcomes

Workshop 1

The scope of the design was agreed in principle and the researchers agreed to explore various options in respect of Wallbot movement mechanisms, functionality (monitoring and inspection and maintenance).

Workshop 2

The project scope for wallbot 1 was agreed to focus on movement and monitoring and inspection functions only. Following workshop 2 the UTS FEIT mechatronic engineering team lead by Dr Marc Carmichael, finalised a design of the prototype Wallbot discussed in section 4 below.

4.0 The Wallbot Prototype Design

4.1 Design

Overview

The Wallbot V1 prototype comprises of two core elements; a set of smart winches used to control movements of the Wallbot across the green wall; and the main body of the Wallbot containing the sensors that are used to develop a map of the green wall and inspect the health of the plants.

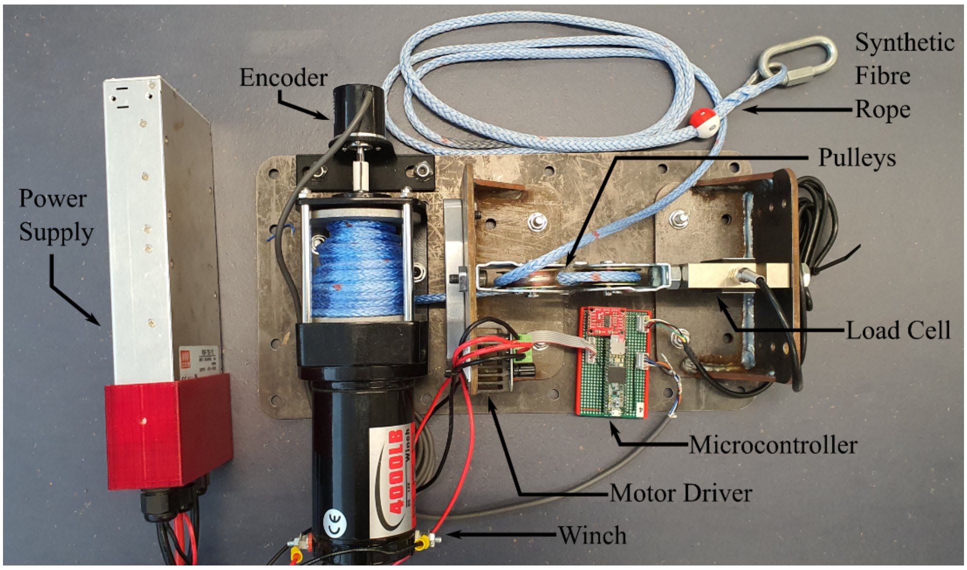
Key design factors

Two key factors were kept in mind during the development of the Wallbot prototype. The first is that the cost needs to be kept low. The main incentive of the Wallbot development is to increase the uptake of Green walls so the plant monitoring system should not be an expense that will detract from this. The second factor is safety. The Wallbot needed to be safe for use on the green wall which are often situated in public spaces.

The smart winch consists of several elements, which are:

- Winch
- Encoder
- Load cell
- Pulleys
- Microcontroller
- Motor driver

Plate 14 Smart winch



(Source: Authors)

Winch and encoder

The core of the smart winch system is a common automotive winch. Using the automotive winch allows the cost to be kept low. To use the winch in an application like the Wallbot, several additions were needed to upgrade the capabilities of the winch. Attached to the shaft of the winch is an encoder which allows the position of the drum rotation to be accurately measured. This allows for the length of the rope to be estimated based on the amount of rotation that has occurred.

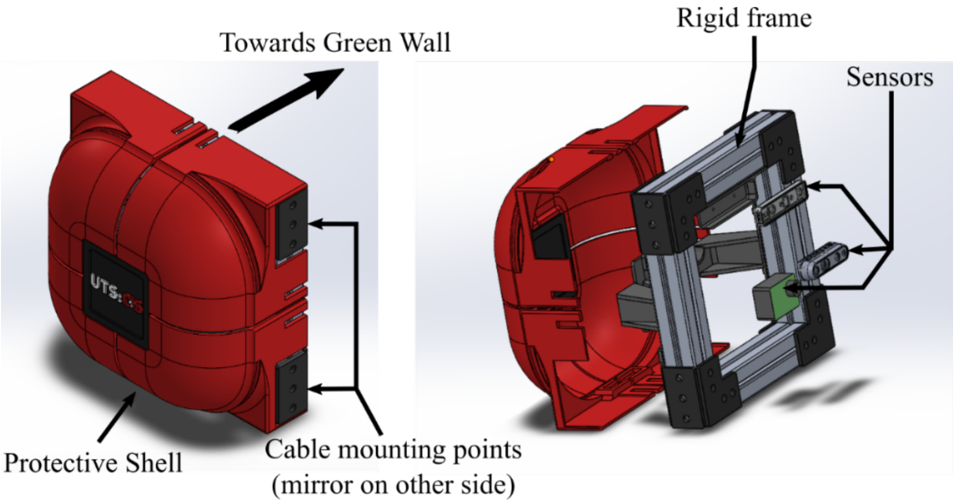
Pulleys and load cell

The rope of the winch is fed through a series of pulleys to allow for the tension of the rope to be measured. By monitoring the tension measured by the load cell, the rope of the winch can be kept taut during the operation of the Wallbot. This ensures that the Wallbot is not likely to sway which may risk damage to the green wall.

Microcontroller and motor driver

Unlike the normal operation of a winch, the speed of the rotation of the winch needs to be accurately controlled, this then in turn control for the length of the rope. By changing the length of the ropes, locomotion of the Wallbot main body can be achieved. This is achieved through a combination of the microcontroller and the motor driver. The microcontroller is responsible for the low-level control of the winch whilst also keeping track of the encoder position and the tension measured by the load cell. The microcontroller is also used to communicate with the main computer which handles the high-level control such as the desired position of the Wallbot main body.

Plate 15 Wallbot body



(Source: Authors)

Main body

The main body of the Wallbot V1 prototype is made up of a rigid aluminium frame, which houses the sensors used. The frame is also used to provide cable mounting points which allows the rope from each smart winch to connect to the main body. Three vision-based sensors are mounted onto the main body of the Wallbot, each providing a unique set of information. The three vision-based sensors used in Wallbot V1 prototype are:

- Intel RealSense T265 (https://www.intelrealsense.com/tracking-camera-t265/)
- Intel RealSense D425 (https://www.intelrealsense.com/depth-camera-d435/)
- MAPIR Survey 3 (https://www.mapir.camera/collections/survey3)

T265 Camera

The Intel RealSense T265 sensor is an optical tracking camera, providing RGB video feed of the green wall through two fisheye lenses. This tracking camera also provides motion information through an inbuilt Inertial Measurement Unit (IMU). The motion information provided by this camera can be used to improve the accuracy of the motion performed by the Wallbot as well as providing the path taken by the Wallbot, useful for developing an accurate map of the environment.

D425

The second vision-based sensor attached to the Wallbot is the Intel RealSense D425. On top of providing RGB video feed, this sensor also provides an additional depth information. This sensor uses infrared light projection to measure the distance between the camera to objects viewed by the sensor. The depth information can then be used to build a 3D mesh of the objects. When combined with the motion information from the T265 sensor, a high-fidelity 3D map of the green walls can be constructed.

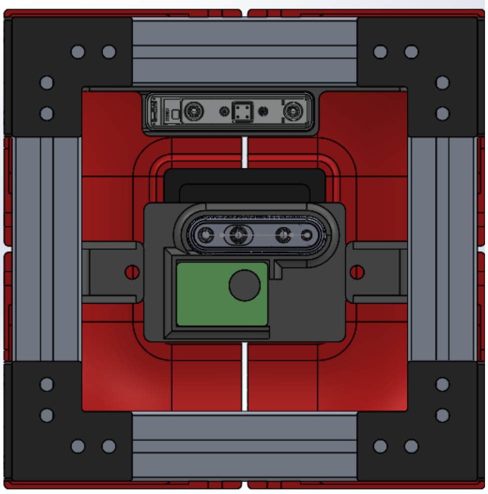
Survey 3

The third vision-based sensor used is the MAPIR Survey 3. This sensor is a multi-spectral survey camera which collects multi-spectral images or video. The collected information can be used to calculate the normalized difference vegetation index (NDVI) of the plants. The NDVI allows for the general health of the plants to be measured. As the Wallbot manoeuvres across the green wall, the NDVI of the plants can be calculated and combined with the information collected by the other two sensors. This allows for a map of the plant health to be created.

Sensor layout

The three vision-based sensors each have varying field of view. To ensure that the information collected are from the same area of the green wall, a specific layout of the sensors is required (PLATE 15). The sensors are positioned in such a way that the field of view of each camera can be overlapped thus the same region can be viewed by all three sensors.

Plate 16 Sensor layout



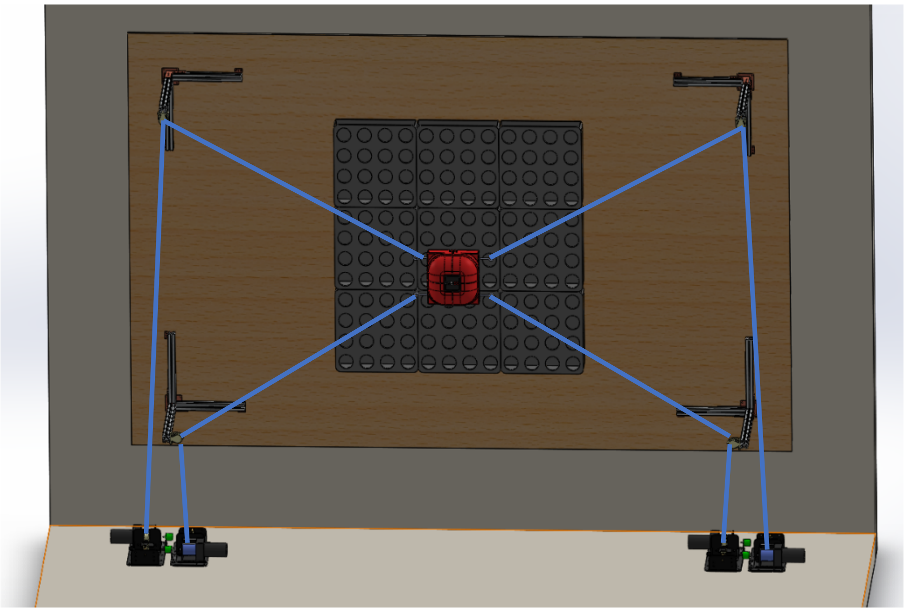
(Source: Authors)

Expandable

The main body of the Wallbot is designed to be modular and expandable, allowing for various other sensors to be integrated. For example, the addition of a temperature sensor would allow for the local temperature to be collected. This information could be then integrated into the map. Other sensors that are planned to be integrated include but not limited to humidity, wind, pressure and volatile organic compounds (VOC) which will provide the Green Wall maintenance team with rich information that can be collected by the Wallbot. This allows for the health of the green wall to be closely monitored without the need to send a human to climb the green wall.

Layout

Plate 17 Wallbot winch layout



(Source: Authors).

The Wallbot V1 prototype currently utilises four smart winches. The rope from each smart winch connects to the Wallbot main body by going through one of the four pulleys attached to each corner. The corner supports are made from aluminium supports and are designed to be attached to the green Wall.

Software

The software of the Wallbot V1 prototype can be simply summarised as shown in the plate below (PLATE X). The architecture of the software can be divided into two based on the level of control. The high-level control provides code that dictates the general behaviour of the Wallbot V1 prototype. The low-level control provides a direct interface to the hardware of the smart winch.

High level

The behaviour of the Wallbot V1 prototype such as the path to take and the order in which different operations is to take place is handled by the manager. By combining information from the other parts of the code, the velocity control decides the velocity of each of the four ropes such that the desired position set by the manager can be achieved. The desired rope velocities are then passed onto the microcontroller which handles interfacing with the hardware of the smart winch. (See plate 18).

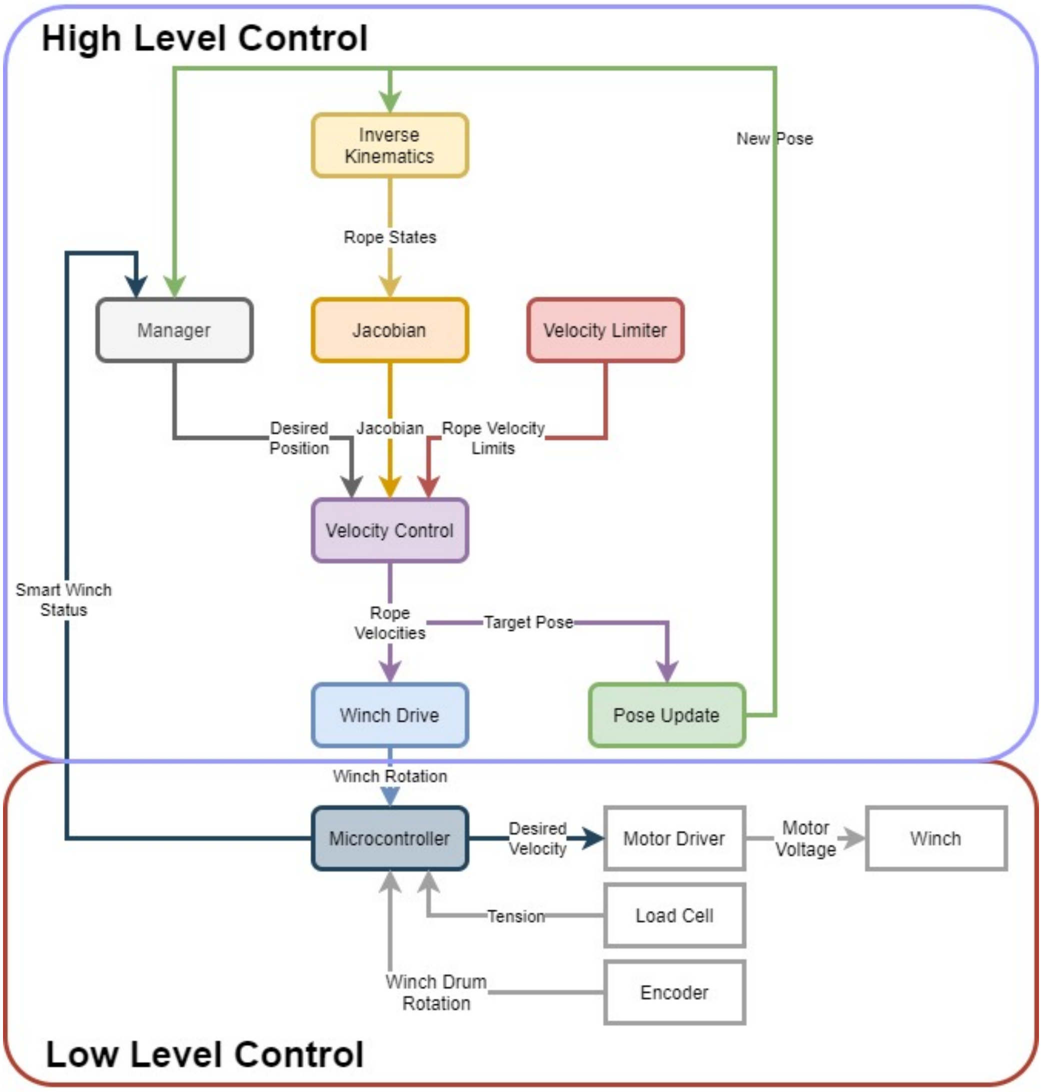
Low level

The low level control of the Wallbot is handled by the microcontroller which performs multitude of operations. Some of the operations handled by the microcontroller include:

- Measuring the tension on the load cell,
- Measuring the rotation velocity and the current winch drum position,
- Sending the desired winch velocity to the motor driver, and;
- Providing the manager with live feedback of the current status of the smart winch.

(See Plate 18).

Plate 18 Wallbot - High and Low level Control.

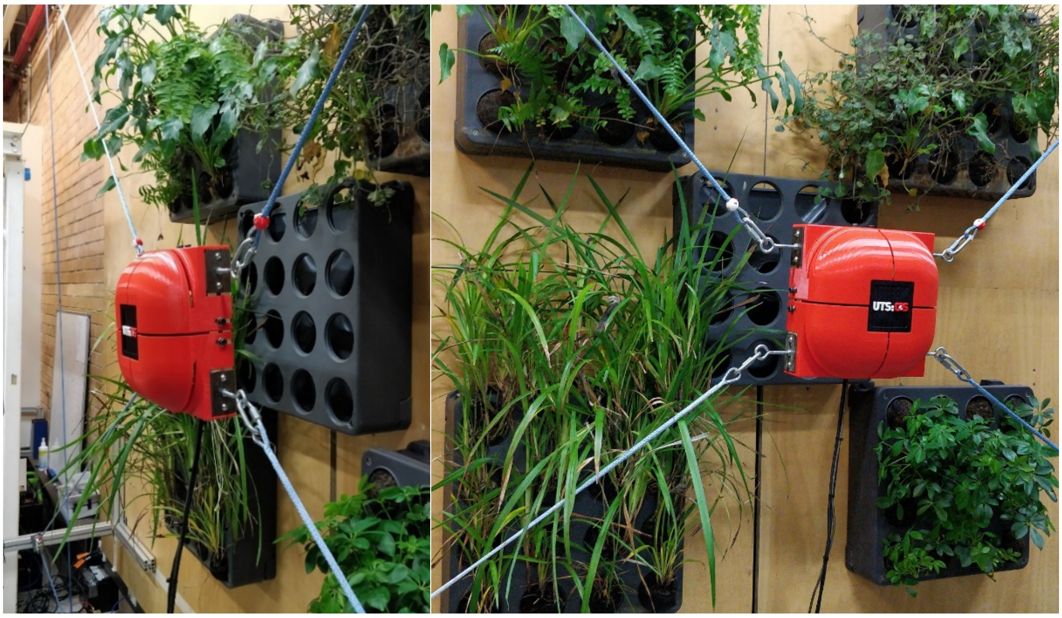


(Source: Authors).

4.2 Site

The Wallbot V1 prototype currently resides in a UTS lab where a simple green wall has been set up. The green wall consists of five Junglefy planter boxes laid out in a simple pattern shown below (Plate 19). Four of the planter boxes are filled with different plants. The simple green wall setup at UTS allows for the core elements of the Wallbot to be tested.

Plate 19 Wallbot 1 Prototype

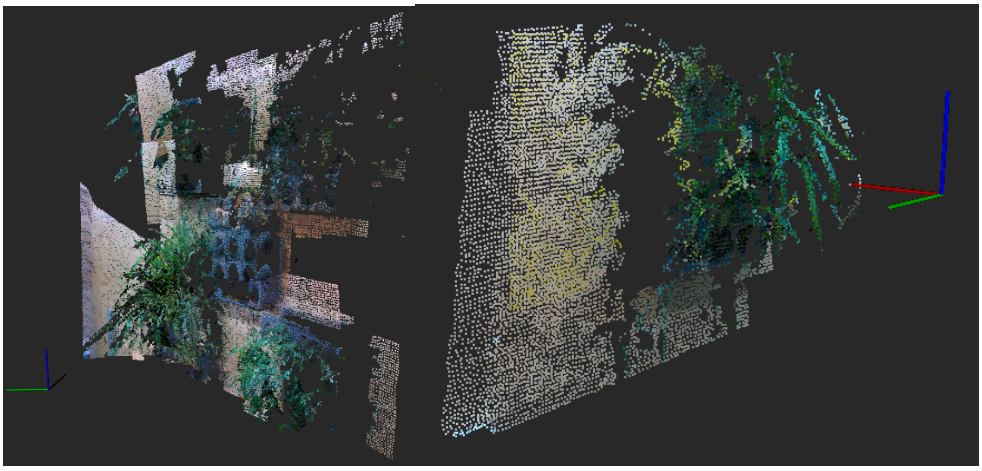


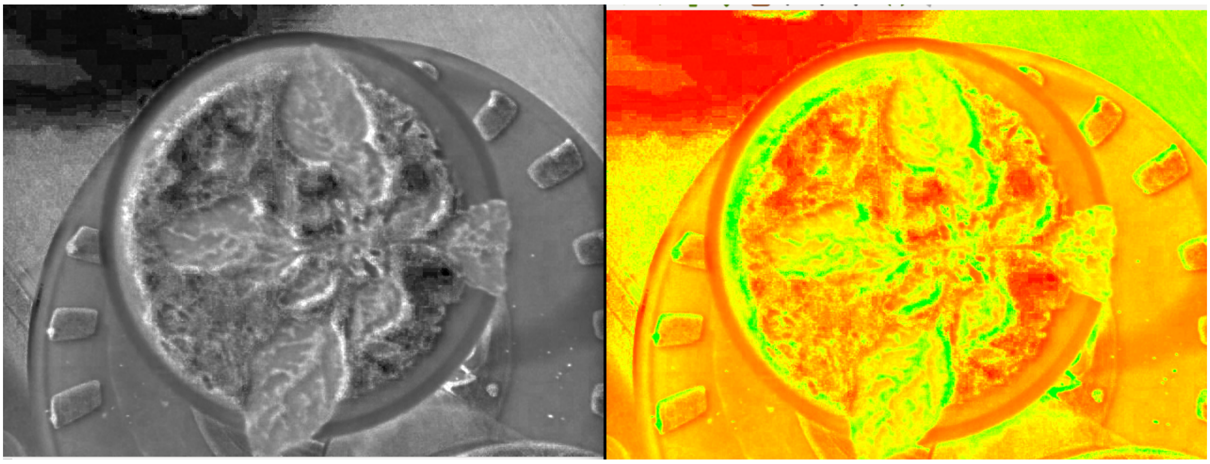
(source: Authors).

4.3 Testing

Initial tests of the capability of the Wallbot have been performed. The aim of the initial tests is to develop a map of the green wall as well as monitor the health of the four Junglefy planter boxes. During the test, the Wallbot V1 prototype was moved around the green wall such that as much of the wall can be mapped. Plate 20 shows the map that was developed by combining the information collected using the RealSense D435 camera and T265 camera.

Plate 20 Plant Health Map





(Source: Chi Tse, Phillipa Cooper)

4.4 Findings and where to now?

During development of the Wallbot V1 prototype, two important factors were that the prototype is safe to use, and that cost had to be kept low. Although the use of polymer rope is inherently safer to use, this choice results in difficulty when trying to accurately position the main body. Unlike the steel rope, synthetic rope is more likely to stretch, causing unpredictable rope behaviours. The diameter of the rope affects the change in rope length each time the winch rotates. This leads to complications when attempting to accurately move the main body of the Wallbot around the green wall. For this reason, the pose of the Wallbot body on the wall was calculated using the T265 camera rather than monitoring how the lengths of the four ropes changed, as this was found to be more accurate. The choice to use commercial automotive winches for actuation was made to lower overall system cost, which ended up being a significant compromise as automotive winches are slower with more load capacity than is needed in this application. Furthermore, the quality of the electric motors in these winches was poor and made the control system difficult to implement.

Despite the challenge and compromises which came with developing an economical solution, the Wallbot v1 prototype has been shown to be capable of developing a map of the green wall to assist with the regular inspection of the green wall. The health of the plants can be monitored automatically and regularly without the need for on-site human inspections. Maintenance, such as pruning, would still require human intervention. A proposed solution is a combination of Wallbot and human workers, with Wallbot providing regular and systematic monitoring of green walls, minimising the time required for humans to perform targeted intervention tasks. This paradigm reduces requirements for human maintenance, therefore reducing risk and recurring maintenance costs. Furthermore, with regular systematic collection of data on the wall the demise of plants could be observed, and potentially remedied if corrective action can be performed in time.

Future versions of Wallbot will perform more challenging tasks. Additional sensors for collecting data on temperature, humidity, heat level, wind speed, wind direction and soil moisture content, as well as attachments to allow tasks such as pruning plants or spraying nutrients may be added, extending the capabilities of the system. Furthermore, the Wallbot concept could be extended to perform other related operations on the side of buildings, such as facade and other types of infrastructure inspection.

5.0 Conclusions and next steps

The workshops highlighted the growing need, and demand, for robotic technology to increase the uptake of green walls in dense urban environments. Furthermore the literature review and workshops identified the key features to prioritise in the initial Wallbot prototype.

Issues related to options regarding power sources, green waste collection, pruning mechanisms and costs were investigated and are discussed in the Top2Bottom Report attached in Appendix 1. They have not be discussed in this report as the focus, following workshop 2 was on climbing mechanisms and control and sensors.

5.1 Expected program outcomes

The programme outcomes are aligned to Sustainable Development Goals SD1, SD6 and SD9 and adoption of wallbot technology will deliver a safer, more cost effective green wall solution to attenuate the UHI, increase biodiversity and habitat, improve air quality, absorb pollutants such as CO2 and particulates in Sydney. Heat stress in the Sydney CBD will grow over time and will impact health and ability to work outside.

5.2 Further work

Field tests of Wallbot and collection of data will record and measure the amounts of attenuation the UHI, increases in biodiversity and habitat possible, improved air quality, and absorption of pollutants such as CO2 and particulates in the COS. Scientific papers will be published detailing the results of the field tests.

As the prototype was tested in a laboratory, we were unable to measure and evaluate the wallbot system for the following;

1. Ability to seed and plant indigenous flora and fauna
2. Ability to remove weeds from GW pods
3. Measurement of air temperature at GW pod and air temp generally in area
4. Measure of air quality for CO2 levels and particulates
5. Measurement of bio-diversity.

Outcomes from development and experiments with the Wallbot prototype highlighted both the potential and the technical challenges associated with the concept. The control of the Wallbot to perform manoeuvres across the wall was more challenging than expected. This was exacerbated by the use of non-ideal hardware that was chosen primarily with low-cost in mind. It is recommended that future work include development of custom hardware, in particular the winch system, so that the performance can be improved.

It is with great regret that the planned visit to see the Wallbot in action during April and May 2020 was not possible due to COVID19 social distancing restrictions in place.

The follow on project Wallbot2 will extend functionality to include these parameters and test the bot in an external environment.

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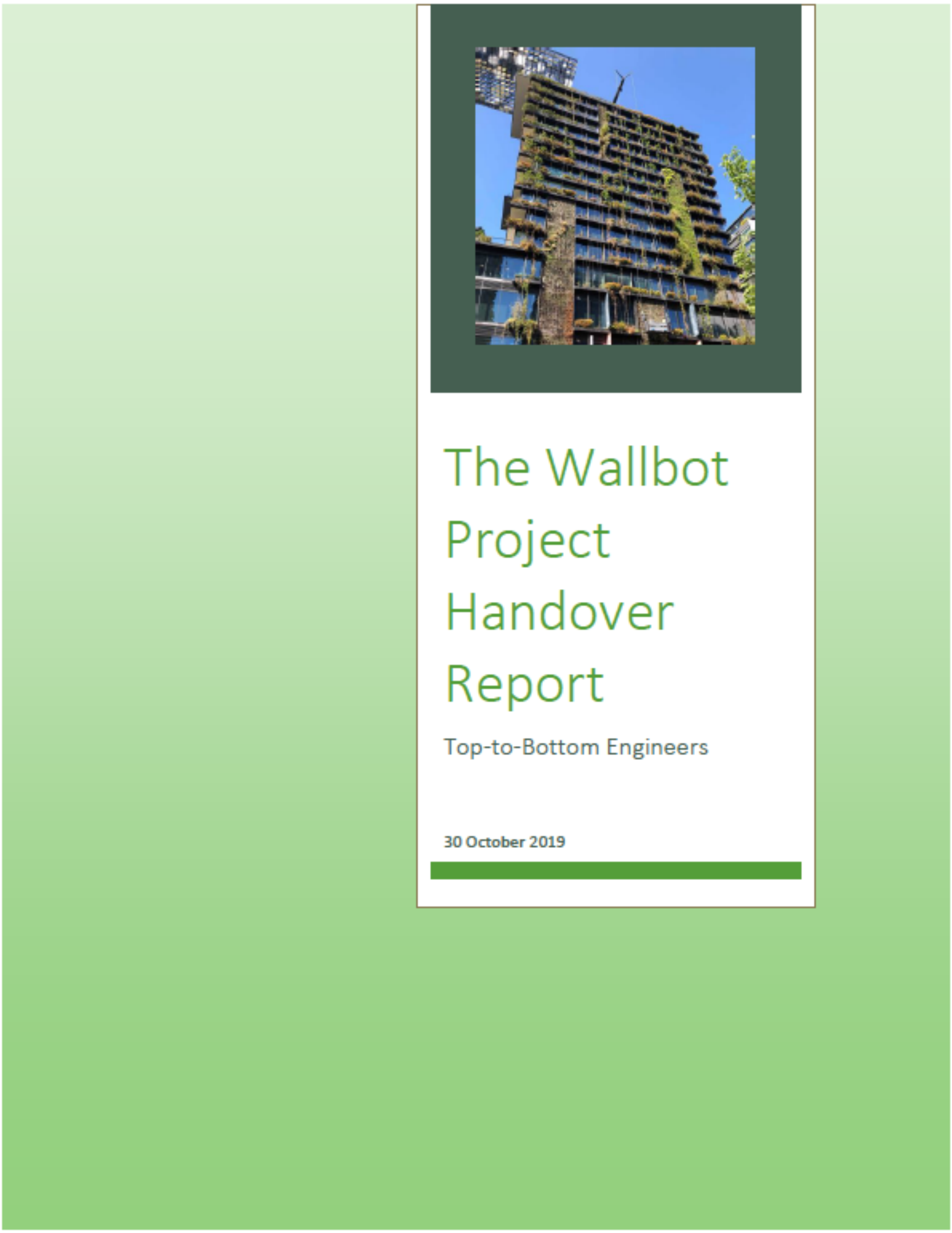
Appendix 1 Top2Bottom Engineers Report



The Wallbot Project Handover Report

Top-to-Bottom Engineers

30 October 2019

TOP-TO-BOTTOM ENGINEERS

The Wallbot Project Handover Report

Top-to-Bottom Engineers

Table of Contents

Table of Figures

1 Overview

Contained in this report is the project progress to date (30th October 2019) on the Wallbot project conducted by Top-to-Bottom Engineers on behalf of University of Technology, Sydney.

The key recommendations for design of the Wallbot have been included, as well as future design recommendations for commencement of prototyping.

2 Project Progress

2.1 Recommended Designs

Three designs have been recommended by Top-to-Bottom Engineers; high, medium and low-cost options, based on complexity level of each design option. Further analysis can be viewed in the detailed Design Guide that describes the functionality and reasoning behind each section of the Wallbot design options.

2.1.2 Low Cost

The lowest cost option is an extension of the buildings BMU (building management unit) that is currently being used to support window cleaning cradles and human workers. This option allows for the attachment of Wallbot to the existing infrastructure and can be dismantled for further maintenance by human workers. This option is the lowest cost to existing buildings with existing infrastructure, however, may be costly to new buildings (including costs to develop and install a BMU).

Mechanism	Component
Gravity Resist and Lateral Movement	Window cleaning gantry extension: utilising the exiting crane, cables and rail for traditional window cleaning/green wall maintenance operations, with an robotic extension
Distance Control	Telescopic legs
Pruning	N/A (sensor and data reporting only)
Power	Mains Power Supply
Waste	N/A (sensor and data reporting only)
Sensors	Probe on controllable arm
Face Transition	Rail (as part of window cradle assembly)

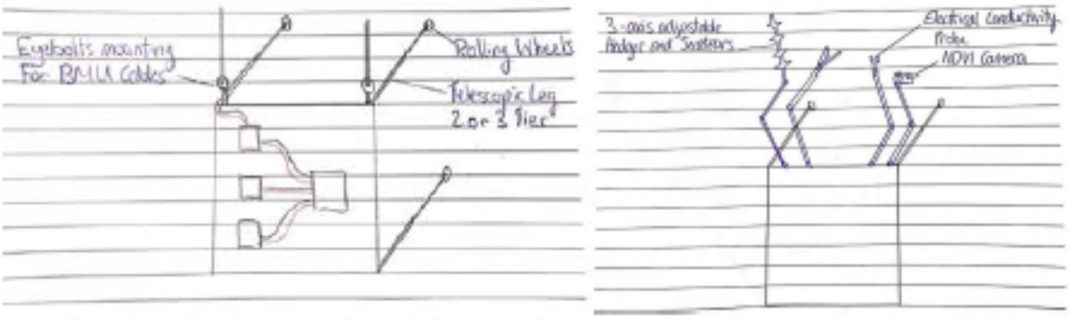


Figure 1 Low Cost Attachment Sketch (Left) and Low Cost does not include Pruning or Blade System (Right)

2.1.3 Medium Cost

This design is best suited to a semi-autonomous system. By utilising two rails on the exterior of the building that move the robot laterally and two vertical cables that act to move the robot vertically. Wallbot has complete coverage on all four of the buildings facades however may be less accurate then a four cables system. There also may be more unwanted movement caused by wind due to the elastic and non-rigid nature of the cables. A telescopic mechanism will allow Wallbot to move further or closer to the wall depending on either the contour of the wall or the size of the plants on the green wall. Motorized secateurs will be used to trim and maintain the green wall, which in turn will require a moderate complexity system to detect and appropriately trim the plants.

This task will not require high levels of electricity and therefore multiple batteries will be able to supply power for these tasks. In order to ensure this concept is not too complex a simple catchment bag for all removed vegetation will be added to Wallbot. In addition, a probe on a controllable arm is a common device that doesn't require a high level of complexity as well as also being able to be battery operated. In order to best utilize this cable system, rails would have to be retrofitted at the top and bottom of the building. If the green wall facade covers more than one face of the building then a having a track around the perimeter at the top and bottom of the building will increase efficiency of Wallbot allowing it to be used on sides areas of the building.

Mechanism	**Component**
Gravity Resist	Two cables
Lateral Motion	Rail
Distance Control	Telescopic mechanism
Pruning	Pruning system only
Power	Multiple battery and replacement charging system
Waste	Catchment Bag and netting
Sensors	Probe on controllable arm
Face Transition	Rail

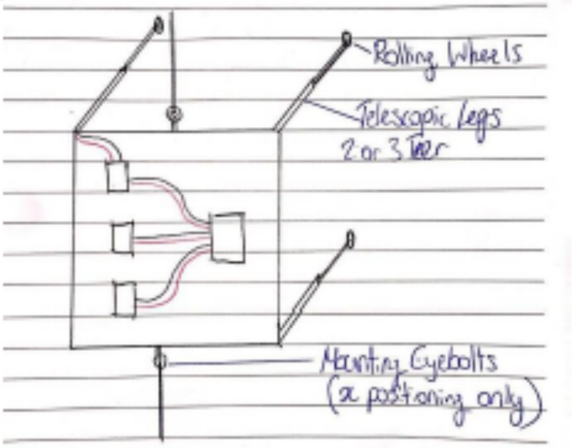


Figure 2 Medium Cost Attachment Sketch

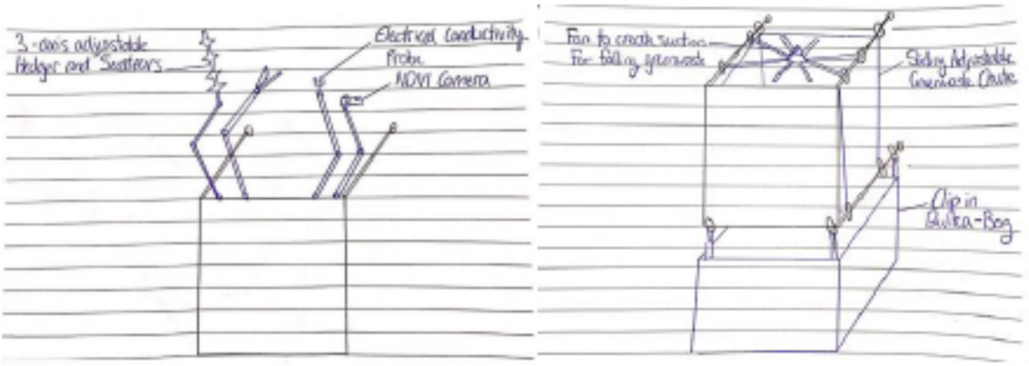


Figure 3 Medium Cost does not include Blade System (Left) and Typical Catchment Sketch (Right)

2.1.4 High Cost

Four individually tensioned cables allow the robot to gain a robust positioning system alongside control components. This design caters for complete automation and has the potential for development of AI and visual inspection technologies. A clear drawback of this system is the high costs especially due to the use of 4 independent Wallbots to cover each façade. It is noted that this selection is best suited to permanent installations.

Mechanism	**Component**
Gravity Resist and Lateral Movement	**Four independently actuated Cables**
Distance Control	**Multiple insect legs**
Pruning	**Pruning system and Motorized blade**
Power	**Mains Power Supply**
Waste	**Vacuum, Shredder & Bag**
Sensors	**NDVI sensors**
Face Transition	**One robot for each facade**

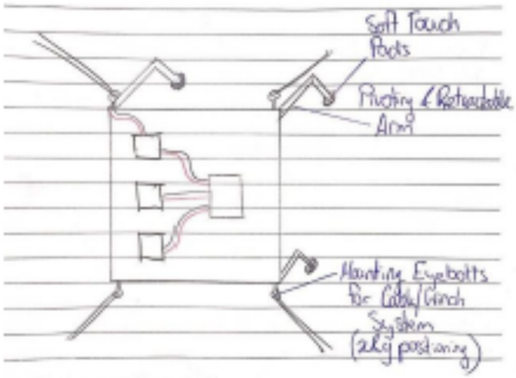


Figure 4 High Cost Attachment Sketch

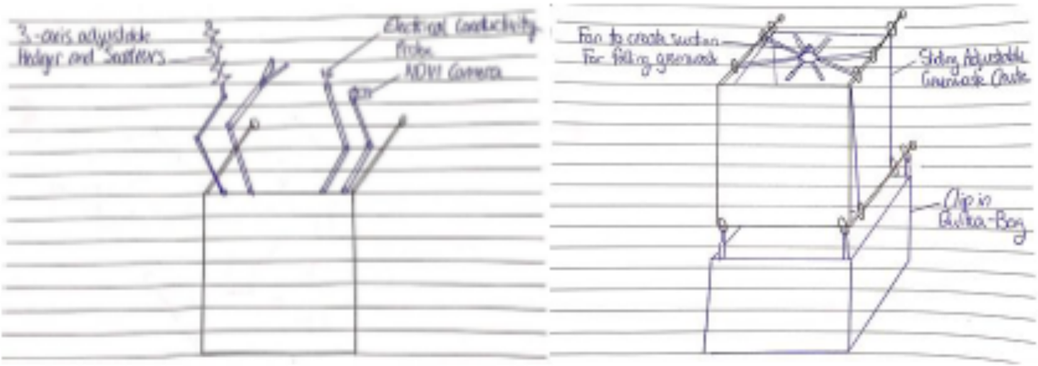


Figure 5 High Cost Tools and Sensors (Left) and Typical Catchment Sketch (Right)

2.2 Recognised Limitations

These three design options were presented to approval by Top-to-Bottom Engineers to key stakeholders of the project, i.e. UTS, Junglefy and NSW Transport. From this point, several limitations were considered:

1. **Cost of production, particularly cost of NDVI Sensors**
2. **Face-to-face transition with cables**
3. **Aesthetics of rail systems and cables**
4. **Intricate gardening movements with AI or operator**
5. **Application across multiple green walls across Sydney**

Overall, these recognised limitations are the basis of beginning prototyping the Wallbot, and recommendations for these process are discussed in section 4 of this report.

In the interim, the design guide was improved/ finalised and a key was created for the morphological chart for assistance in developing future design options and understanding how each system can or can not interrelate.

3 Stakeholder Meeting Summaries

3.1 Initial Concept Ideation Meeting with Junglefy and Transport NSW (21/08/2019)

- Problem Focus Brainstorming Session
    - Gathered and compiled data on the key issues surrounding Green Wall maintenance
    - Many different stakeholder perspectives were discussed about the potential application of the Wallbot
- Information given of specific Junglefy systems in constructing and maintaining green walls
    - Created requirements for the Wallbot (pending client approval)
    - Specifics of plant types/ species and maintenance given
    - Options for Wallbot manoeuvring systems discussed

3.2 Follow Up Stakeholder Ideation Meeting (03/10/2019)

- Discussed Design Guide and its components
- Delved into development of each Wallbot operation and its viability
- Came to conclusion that initial version of the Wallbot should focus on inspection of Wallbot to manage pest control and plant and air health
- Discussed future of the Wallbot project and areas for developmental prototyping
    - Work on movement and sensor protype in the UTS Industrial Lab with scaled down wall to for the purpose of transferring to the Manly vale carpark for further testing

4 Future work recommendations

4.1 Areas for further Research

Through the extensive research in the literature review as well as generation and consolidation of ideas created in the design guide, we have been able to utilise existing designs and technology as well as ideate new designs. This was done to create our 3 concepts or recommended designs. Through our second stakeholder meeting we were able to prioritise elements that would be essential to the progression of the Wallbot project. With the level of funding that this project currently has, not all components analysed in the morphological chart and subsequently the design guide can be implemented. This is due to the insufficient funds. In order to work around this, focus into firstly using the Wallbot as an inspection device has been decided.

4.2 Decisions for Focus on an Inspection Robot

Using the Wallbot as a vehicle that monitors green walls via inspection, would require prototypes and testing of lateral and horizontal movement and sensors. These two components would give the largest cost to benefit ratio as companies that create and monitor green walls such as Junglfy have identified. When maintaining a green wall companies take samples from several areas of the green wall for testing. They test for electrical conductivity, pH, moisture content and overall plant health. This is then averaged to give a general idea of the condition of the green wall. When blockages of the water system of the green wall is failing or plants are dying an inspector is required to manually inspect the green wall to discover where this is occurring. Green walls typically have drainage systems every 2-3 stories, making it hard to pinpoint where the problem is occurring until manual inspection has occurred. This is a costly procedure as it is performed at least once a month, also the data isn't very accurate as it is averaged from only a few modules from the green wall (modules are 50cmby 50cm planter boxes). With the focus on an inspection Wallbot, this would decrease risk for inspection as it would be performed by the Wallbot through sensors and automated probe and sampling of the modules. Secondly using a robot allows this procedure to occur more and can be conducted on every module, or significantly more samples than done manually as samples will be immediately process on-board the Wallbot. This would make determining the health of the green wall considerably more accurate.

Areas that will require to be further researched and investigated will be pricing, prototyping and testing a movement system for the Wallbot. This is vital as it is essentially the main obstacle for the Wallbot project, as vertical movement around a green wall has not been created. With referral to the Design Guide, engineers that are working on wall climbing systems, autonomous systems engineers and new designs either created or discovered, choosing a prototyping a design will begin. Prioritising this not only will reduce cost but will also reduce time. Also, being the most important component of the Wallbot, if this system was able to become a functioning prototype, it could be used as a means to gain further funding.

In addition, this process will also be conducted for appropriate sensors that the Wallbot would use, such that with movement and sensors an inspection Wallbot can be made. Pricing for sensors is also vital in order to ensure costs stay to a minimum, at this early stage.

Prototyping will occur at two places. This will be at the industrial lab at UTS and the Green wall installation at the Manly Vale Carpark and testing will occur in this order respectively. A small-scale green wall will be installed at the Industrial lab, provided by Junglfy. This will be to reduce time spent moving and testing prototypes at Manlyvale, as well as it focus and center emphasis on the movement and censoring capabilities of the Wallbot, without external factors such as wind, safety hazards, possible loss of property, and installation procedures. The small-scale green wall will be set up exactly as it is installed on commercial green walls such that prototypes and test have applicability to green wall facades on buildings, consisting of the modules and planter boxes. This small scale set up will be between 4-5m high and wide, depending on the space in the lab. Lateral and Horizontal movement of the Wallbot as well as monitoring will be created, prototyped and tested here before then moving out to the Manly Vale Green wall for further improvements and design elements.

These areas will begin to move ahead after November 2019 and into the foreseeable future. This project is a development that will require considerable time in order to move through the design process until all components are finished and the entire Wallbot could be used for all Green wall capabilities of maintenance. Despite this the subsequent steps that this project will undergo will put the project in a positive place for growth and continued research, funding and development.

4.3 Initial Physical Prototyping Recommendations

4.3.1 Cable Based Prototype

Top-to-bottom engineers recommend a cable-based system for the initial prototype of the Wallbot. Using a cable system is the best solution with respect to gravity resist mechanisms as it is not only energy efficient but can support high loads. This is beneficial for future steps in the project where the Wallbot can be developed further to trim and collect green waste.

4.3.2 Three cable solution

Out of the three chosen design concepts top-to-bottom engineers recommend developing a cable system that is independent from existing BMU infrastructure. While utilising a buildings existing infrastructure will enable easy supplementation with human maintenance work it still poses significant limitations and weather constraints which significantly affects maintenance. Further to this, this technology may have limited flexibility as BMU systems can vary significantly between different building infrastructure. Further to this, the greatest return and smallest payback period for green walls implementing this technology are large scale buildings as they incur the highest costs and time associated with maintenance. This means that these buildings will benefit from permanent and highly targeted Wallbot maintenance systems which can be achieved with a fixed cable system.

A preliminary analysis of tension acting in cables has been performed in both a four cable and three-cable design. This three-cable design includes a top rail that allows the top winch to move along the x-axis of the building façade. A comparison diagram of these two systems can be seen below.

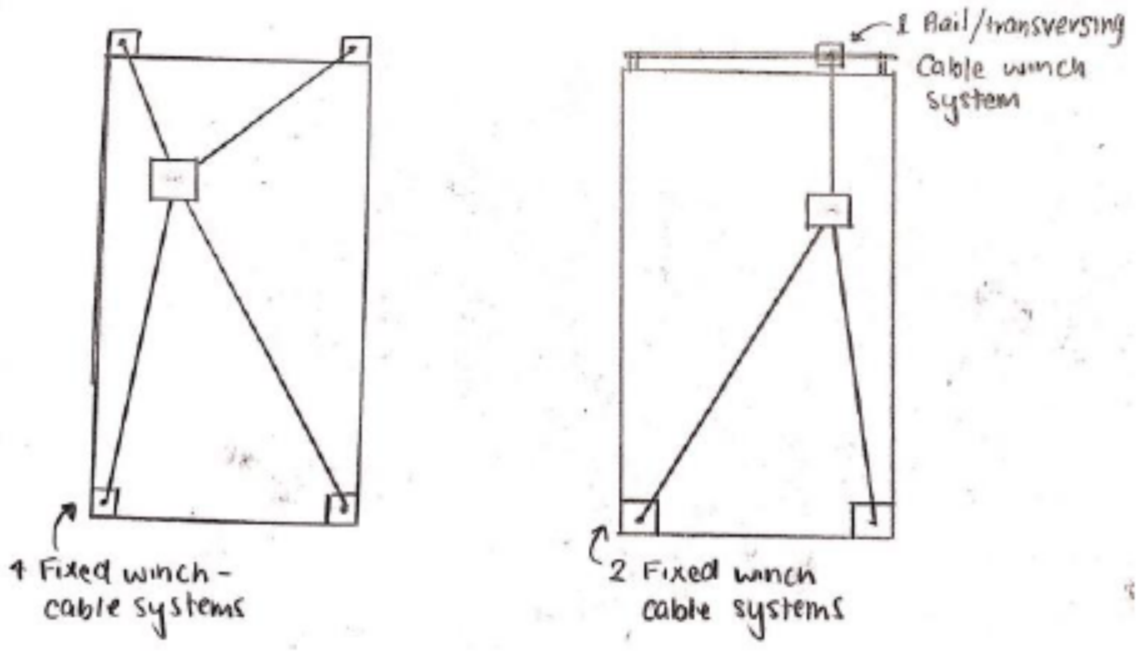
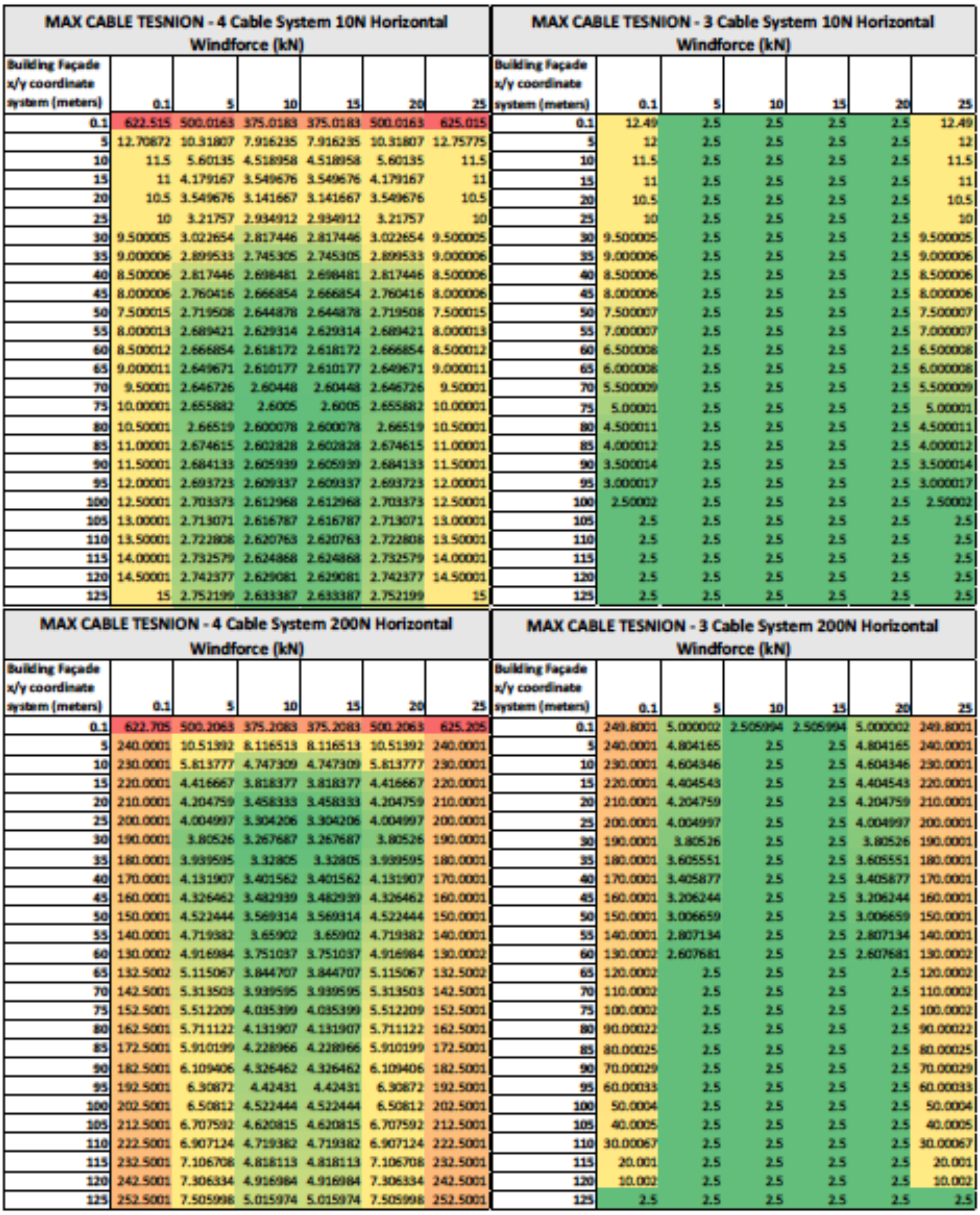


Figure 6 4 Cable/fixed winch concept sketch (left) 3 Cable/2 fixed 1 traversing winch concept sketch (right)



MAX CABLE TESNION - 4 Cable System 10N Horizontal Windforce (kN)

Building Façade x/y coordinate system (meters)	0.1	5	10	15	20	25
0.1	622.515	500.0163	375.0183	375.0183	500.0163	625.015
5	12.70872	10.31807	7.916235	7.916235	10.31807	12.75775
10	11.5	5.60135	4.518958	4.518958	5.60135	11.5
15	11	4.179167	3.549676	3.549676	4.179167	11
20	10.5	3.549676	3.141667	3.141667	3.549676	10.5
25	10	3.21757	2.934912	2.934912	3.21757	10
30	9.500005	3.022654	2.817446	2.817446	3.022654	9.500005
35	9.000006	2.899533	2.745305	2.745305	2.899533	9.000006
40	8.500006	2.817446	2.698481	2.698481	2.817446	8.500006
45	8.000006	2.760416	2.666854	2.666854	2.760416	8.000006
50	7.500015	2.719508	2.644878	2.644878	2.719508	7.500015
55	8.000013	2.689421	2.629314	2.629314	2.689421	8.000013
60	8.500012	2.666854	2.618172	2.618172	2.666854	8.500012
65	9.000011	2.649671	2.610177	2.610177	2.649671	9.000011
70	9.50001	2.646726	2.60448	2.60448	2.646726	9.50001
75	10.00001	2.655882	2.6005	2.6005	2.655882	10.00001
80	10.50001	2.66519	2.600078	2.600078	2.66519	10.50001
85	11.00001	2.674615	2.602828	2.602828	2.674615	11.00001
90	11.50001	2.684133	2.605939	2.605939	2.684133	11.50001
95	12.00001	2.693723	2.609337	2.609337	2.693723	12.00001
100	12.50001	2.703373	2.612968	2.612968	2.703373	12.50001
105	13.00001	2.713071	2.616787	2.616787	2.713071	13.00001
110	13.50001	2.722808	2.620763	2.620763	2.722808	13.50001
115	14.00001	2.732579	2.624868	2.624868	2.732579	14.00001
120	14.50001	2.742377	2.629081	2.629081	2.742377	14.50001
125	15	2.752199	2.633387	2.633387	2.752199	15

MAX CABLE TESNION - 3 Cable System 10N Horizontal Windforce (kN)

Building Façade x/y coordinate system (meters)	0.1	5	10	15	20	25
0.1	12.49	2.5	2.5	2.5	2.5	12.49
5	12	2.5	2.5	2.5	2.5	12
10	11.5	2.5	2.5	2.5	2.5	11.5
15	11	2.5	2.5	2.5	2.5	11
20	10.5	2.5	2.5	2.5	2.5	10.5
25	10	2.5	2.5	2.5	2.5	10
30	9.500005	2.5	2.5	2.5	2.5	9.500005
35	9.000006	2.5	2.5	2.5	2.5	9.000006
40	8.500006	2.5	2.5	2.5	2.5	8.500006
45	8.000006	2.5	2.5	2.5	2.5	8.000006
50	7.500007	2.5	2.5	2.5	2.5	7.500007
55	7.000007	2.5	2.5	2.5	2.5	7.000007
60	6.500008	2.5	2.5	2.5	2.5	6.500008
65	6.000008	2.5	2.5	2.5	2.5	6.000008
70	5.500009	2.5	2.5	2.5	2.5	5.500009
75	5.00001	2.5	2.5	2.5	2.5	5.00001
80	4.500011	2.5	2.5	2.5	2.5	4.500011
85	4.000012	2.5	2.5	2.5	2.5	4.000012
90	3.500014	2.5	2.5	2.5	2.5	3.500014
95	3.000017	2.5	2.5	2.5	2.5	3.000017
100	2.50002	2.5	2.5	2.5	2.5	2.50002
105	2.5	2.5	2.5	2.5	2.5	2.5
110	2.5	2.5	2.5	2.5	2.5	2.5
115	2.5	2.5	2.5	2.5	2.5	2.5
120	2.5	2.5	2.5	2.5	2.5	2.5
125	2.5	2.5	2.5	2.5	2.5	2.5

MAX CABLE TESNION - 4 Cable System 200N Horizontal Windforce (kN)

Building Façade x/y coordinate system (meters)	0.1	5	10	15	20	25
0.1	622.705	500.2063	375.2083	375.2083	500.2063	625.205
5	240.0001	10.51392	8.116513	8.116513	10.51392	240.0001
10	230.0001	5.813777	4.747309	4.747309	5.813777	230.0001
15	220.0001	4.416667	3.818377	3.818377	4.416667	220.0001
20	210.0001	4.204759	3.458333	3.458333	4.204759	210.0001
25	200.0001	4.004997	3.304206	3.304206	4.004997	200.0001
30	190.0001	3.80526	3.267687	3.267687	3.80526	190.0001
35	180.0001	3.939595	3.32805	3.32805	3.939595	180.0001
40	170.0001	4.131907	3.401562	3.401562	4.131907	170.0001
45	160.0001	4.326462	3.482939	3.482939	4.326462	160.0001
50	150.0001	4.522444	3.569314	3.569314	4.522444	150.0001
55	140.0001	4.719382	3.65902	3.65902	4.719382	140.0001
60	130.0002	4.916984	3.751037	3.751037	4.916984	130.0002
65	132.5002	5.115067	3.844707	3.844707	5.115067	132.5002
70	142.5001	5.313503	3.939595	3.939595	5.313503	142.5001
75	152.5001	5.512209	4.035399	4.035399	5.512209	152.5001
80	162.5001	5.711122	4.131907	4.131907	5.711122	162.5001
85	172.5001	5.910199	4.228966	4.228966	5.910199	172.5001
90	182.5001	6.109406	4.326462	4.326462	6.109406	182.5001
95	192.5001	6.30872	4.42431	4.42431	6.30872	192.5001
100	202.5001	6.50812	4.522444	4.522444	6.50812	202.5001
105	212.5001	6.707592	4.620815	4.620815	6.707592	212.5001
110	222.5001	6.907124	4.719382	4.719382	6.907124	222.5001
115	232.5001	7.106708	4.818113	4.818113	7.106708	232.5001
120	242.5001	7.306334	4.916984	4.916984	7.306334	242.5001
125	252.5001	7.505998	5.015974	5.015974	7.505998	252.5001

MAX CABLE TESNION - 3 Cable System 200N Horizontal Windforce (kN)

Building Façade x/y coordinate system (meters)	0.1	5	10	15	20	25
0.1	249.8001	5.000002	2.505994	2.505994	5.000002	249.8001
5	240.0001	4.804165	2.5	2.5	4.804165	240.0001
10	230.0001	4.604346	2.5	2.5	4.604346	230.0001
15	220.0001	4.404543	2.5	2.5	4.404543	220.0001
20	210.0001	4.204759	2.5	2.5	4.204759	210.0001
25	200.0001	4.004997	2.5	2.5	4.004997	200.0001
30	190.0001	3.80526	2.5	2.5	3.80526	190.0001
35	180.0001	3.605551	2.5	2.5	3.605551	180.0001
40	170.0001	3.405877	2.5	2.5	3.405877	170.0001
45	160.0001	3.206244	2.5	2.5	3.206244	160.0001
50	150.0001	3.006659	2.5	2.5	3.006659	150.0001
55	140.0001	2.807134	2.5	2.5	2.807134	140.0001
60	130.0002	2.607681	2.5	2.5	2.607681	130.0002
65	120.0002	2.5	2.5	2.5	2.5	120.0002
70	110.0002	2.5	2.5	2.5	2.5	110.0002
75	100.0002	2.5	2.5	2.5	2.5	100.0002
80	90.00022	2.5	2.5	2.5	2.5	90.00022
85	80.00025	2.5	2.5	2.5	2.5	80.00025
90	70.00029	2.5	2.5	2.5	2.5	70.00029
95	60.00033	2.5	2.5	2.5	2.5	60.00033
100	50.0004	2.5	2.5	2.5	2.5	50.0004
105	40.0005	2.5	2.5	2.5	2.5	40.0005
110	30.00067	2.5	2.5	2.5	2.5	30.00067
115	20.001	2.5	2.5	2.5	2.5	20.001
120	10.002	2.5	2.5	2.5	2.5	10.002
125	2.5	2.5	2.5	2.5	2.5	2.5

Figure 7 Max Cable Tension Heat Map for 4 and 3 Cabled systems with 10N and 200N Windforce

This study has several limitations and many assumptions during the calculation process where made. To see methodology for calculating these forces please see Appendix A – Maximum Cable Tension Matrix Calculations and Assumptions. While the study may yield inaccurate results, it does provide a good estimation of high stress zones throughout the building façade. From this it is clear a fixed four cable system is coupled with significant stress concentrations as the Wallbot aims to reach the top of the façade. It is noted that as the Wallbot approaches 0° from the horizontal the tension force in the cable's approaches infinity. For this reason an offset of 10cm was used for calculation purposes. This poses several issues as the Wallbot will be unable to doc for maintenance and inspection on the top of the roofs façade. Further to this if a baseline value for the minimum breaking force is taken as 238kN for 16mm diameter cable (LB wire ropes 2019) and factor of safety of 2 is ensured this means that the maximum stress that can be experienced by the cables is 119kN which is not feasible for the four cable Wallbot. Utilising the proposed 3-cable system eliminates the high concentration of force along the top of the façade and hence is our recommended solution to develop as the initial prototype. Further to this we recommend future works for the Wallbot include a windspeed sensor and Wallbot maintenance zoning, where the Wallbot will engage on high tension areas only in windspeeds below a certain threshold and that the Wallbot prioritises these areas in calm weather.

4.4 Sensor Systems

Top-to-bottom Engineers recommend trialing a NDVI sensor within the first prototype. These sensors use light to detect plant health and can potentially alert human maintenance workers where plant health is beginning to fall so that they can take action. It is noted that NDVI sensors are commercially available for areal analysis of farms and for other agricultural purposes. For this application NDVI sensors typically have a wide field of view and commercially available products may not be applicable to the project. For further information on NDVI sensors and a sensor supplier summary please see Appendix B – NDVI Sensor Overview and Supplier Summary.

Further to this Top-to-bottom engineers recommend investigating and developing electrical conductivity, pH and moisture content sensor probes to determine soil health and detect potential blockages or issues with the irrigation systems. Ideally this data could be wirelessly stored and analysed to give a location specific overview of plant and green wall health.

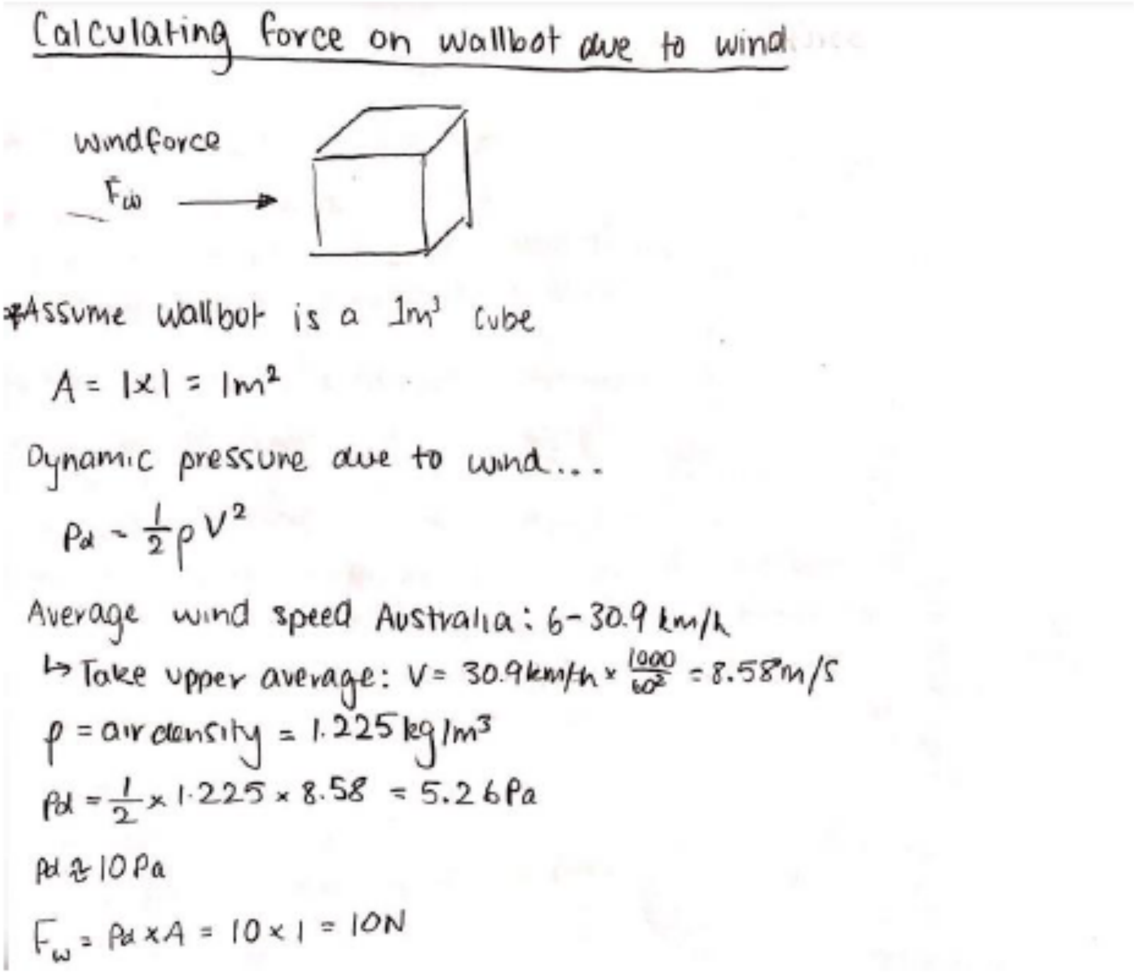
5 References

LB Wire Ropes 2019, *Spiral Strand*, viewed 26 October 2019, https://www.lbwireropes.com.au/product/spiral-strand/

Appendix A – Maximum Cable Tension Matrix Calculations and Assumptions

Calculation spreadsheet can be accessed here: https://studentutsedu-my.sharepoint.com/:x:/g/personal/12562601_student_uts_edu_au/EUt89ab1_5ZGrElYTMqmE20B-_z2hL-HX3Nv339tFIl0Ng?e=awxQFa

NOTE: 3 cable solution was calculated with the assumption that top winch was always positioned directly on top of Wallbot. This could potentially be optimized as future works.



Calculating force on wallbot due to wind

*Assume wallbot is a $1m^3$ cube

$A = 1 \times 1 = 1m^2$

Dynamic pressure due to wind...

$P_d \sim \frac{1}{2} \rho V^2$

Average wind speed Australia: 6-30.9 km/h

↳ Take upper average: $V = 30.9 km/h \times \frac{1000}{60^2} = 8.58 m/s$

ρ = air density = $1.225 kg/m^3$

$P_d = \frac{1}{2} \times 1.225 \times 8.58 = 5.26 Pa$

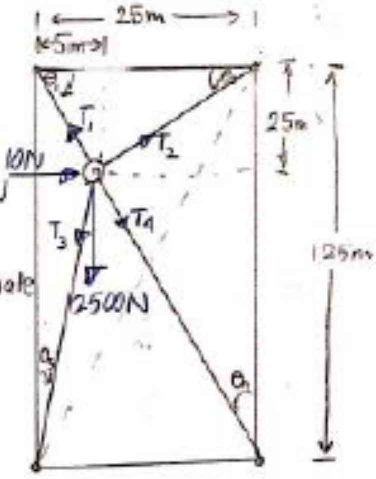
$P_d \approx 10 Pa$

$F_w = P_d \times A = 10 \times 1 = 10N$

Calculating Tension in cables

- Assume 125 x 25m building facade
- Assume wind force = 10N →
- Assume Wallbot mass = 250kg (Max window washing cradle weight)

Wallbot weight, W = 250 x 9.81 ≈ 2500N



↳ This system is statically indeterminate

↳ The following assumptions have been made inorder to give a baseline indication of tension with in cables:

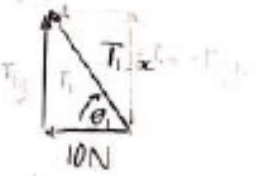
- Each cable is considered individually to support entire weight (top cables only) and entire wind force
- Tension in the cable is assumed to be the sum of wind + weight components acting along the cable.

Tension in cable 1...

$\theta_1 = \tan^{-1}\left(\frac{25}{5}\right) = 78.7^\circ$

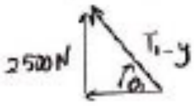
component of tension due to wind force:

$T_{1-x} = \frac{10}{\cos 78.7} = 51.03\,N$



component of tension due to wallbot weight

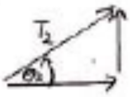
$T_{1-y} = \frac{2500}{\sin 76.7} = 2549.42\,N$



$T_1 = 51.03 + 2549.42 = 2600.45$

Tension in cable 2... (assume opp wind force for max tension ←10N)

$\theta_2 = \tan^{-1}\left(\frac{25}{20}\right) = 51.34^\circ$



$T_{2-x} = \frac{10}{\cos(51.34)} = 16\,N$

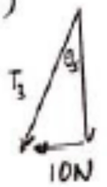
$T_{2-y} = \frac{2500}{\sin(51.34)} = 3201.57\,N$

$T_2 = 16 + 3201.57 = 3217.6\,N$

Tension in Cable 3... (Cannot hold weight force)

$\theta_3 = \tan^{-1}\left(\frac{5}{400}\right) = 2.86°$

$T_3 = \frac{10}{\sin(2.86)} = 200.42N$



Tension in cable 4...

$\theta_4 = \tan^{-1}\left(\frac{20}{100}\right) = 11.31°$

$T_4 = \frac{10}{\sin(11.31)} = 50.99N$

$\therefore$ Max Cable tension in location (5, -25) is in Cable 2 with $T_2 = 3.2kN$

Appendix B – NDVI Sensor Overview and Supplier Summary

What is NDVI & How does it work?

Normalized Difference Vegetation Index (NDVI) measures the health of a plant by seeing how green the leaves are in real-time and allows for monitoring of healthy or dying plants easily, quickly and efficiently. Since 1992 the Bureau of Meteorology has been using satellite NDVI to produce a nationwide image for those in agriculture.

The Chlorophyll in a leaf absorbs nearly all visible light except for the green section which gives leaves their distinctive colour. The structure or frame of the leaf strongly reflects near-infrared (NIR) light. A spongy layer on the bottom of the leaf determines the ratio of red visible light to near-infrared light. As the leaves become unhealthy by dehydration or disease, this spongy reflective layer deteriorates. This results in the plant absorbing more near-infrared light rather than reflecting it. The ratio of the reflected near-infrared light against the reflected red light produces the NDVI value.

NDVI Readings:

All NDVI values will range between -1 and +1.
The NDVI values need to be compared against tests of the same plant in a known healthy state.

- **-1 and 0** is dead or an inanimate object
- **0 and 0.33** is unhealthy
- **0.33 to 0.66** is moderately healthy
- **0.66 to 1** is very healthy

$$NDVI = \frac{Near\ Infrared - Red\ Reflectivity}{Near\ Infrared + Red\ Reflectivity} = -1 < x < 1$$

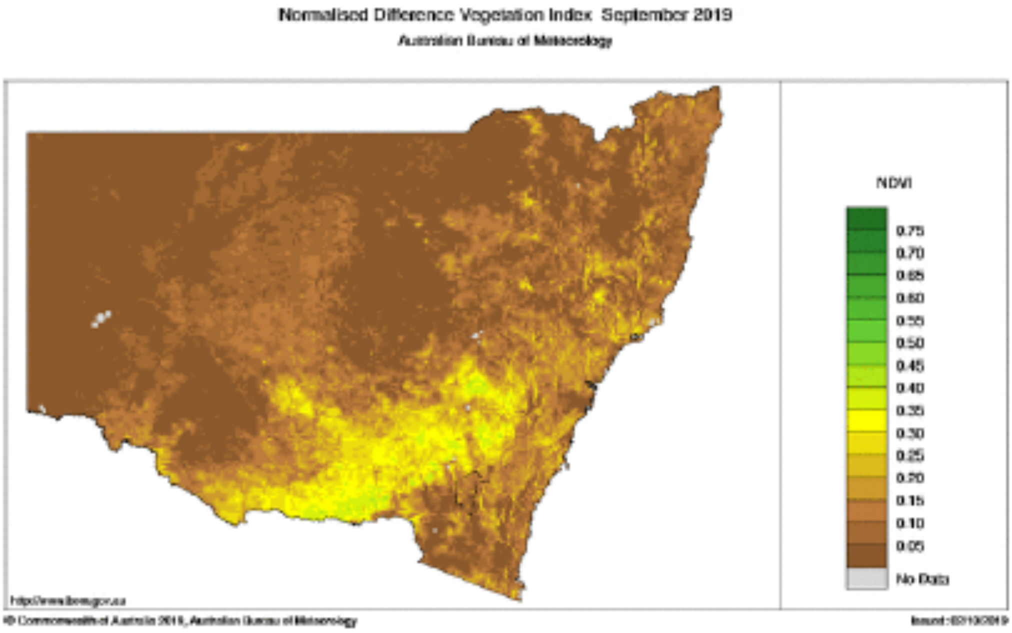
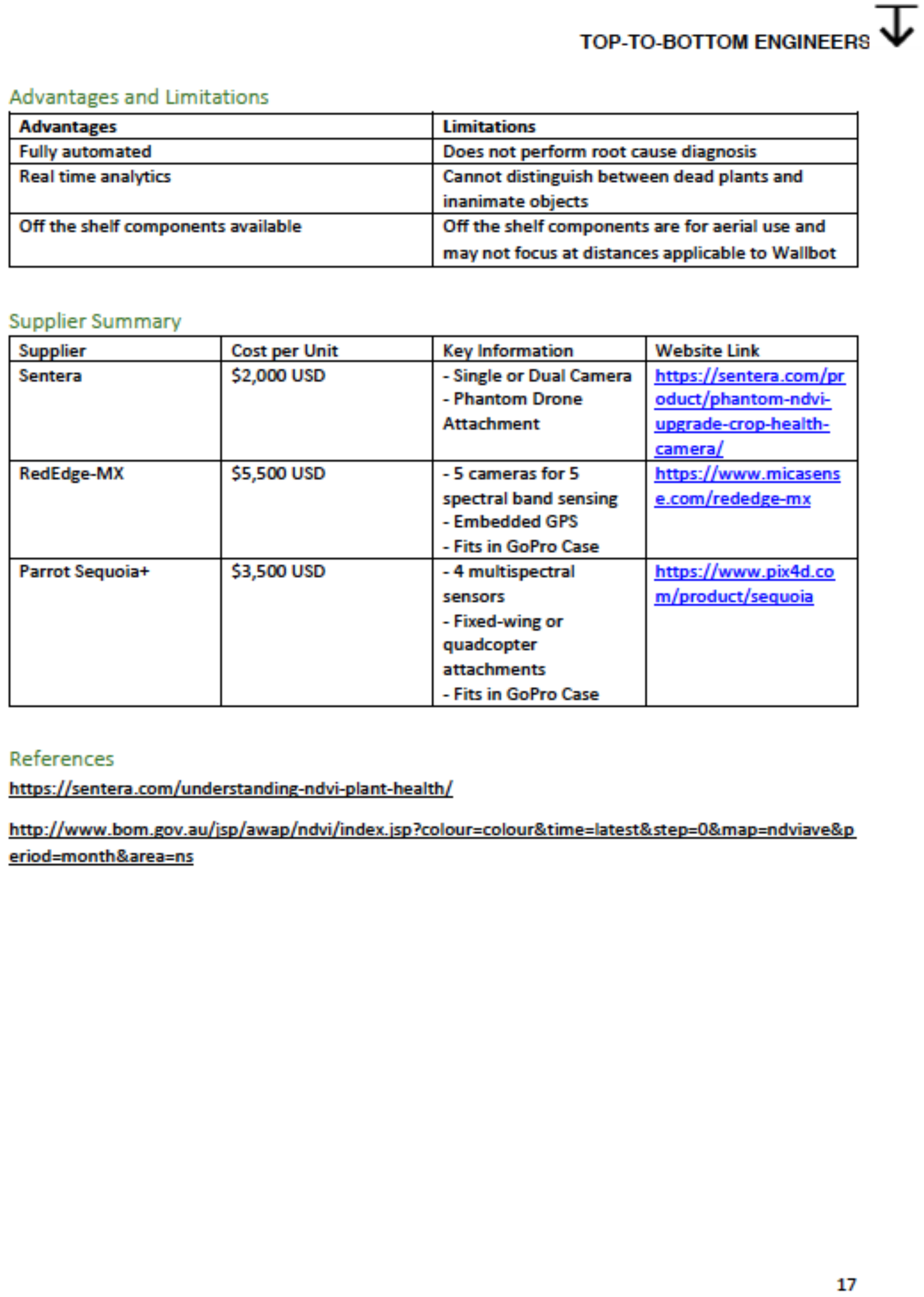


Figure 1: Satellite NDVI of New South Wales



Advantages and Limitations

Advantages	**Limitations**
Fully automated	Does not perform root cause diagnosis
Real time analytics	Cannot distinguish between dead plants and inanimate objects
Off the shelf components available	Off the shelf components are for aerial use and may not focus at distances applicable to Wallbot

Supplier Summary

Supplier	Cost per Unit	Key Information	Website Link
Sentera	$2,000 USD	- Single or Dual Camera - Phantom Drone Attachment	https://sentera.com/product/phantom-ndvi-upgrade-crop-health-camera/
RedEdge-MX	$5,500 USD	- 5 cameras for 5 spectral band sensing - Embedded GPS - Fits in GoPro Case	https://www.micasense.com/rededge-mx
Parrot Sequoia+	$3,500 USD	- 4 multispectral sensors - Fixed-wing or quadcopter attachments - Fits in GoPro Case	https://www.pix4d.com/product/sequoia

References

https://sentera.com/understanding-ndvi-plant-health/

http://www.bom.gov.au/jsp/awap/ndvi/index.jsp?colour=colour&time=latest&step=0&map=ndviave&period=month&area=ns

End of report