Property Manag

Towards Smart Green Wall Maintenance and Wallbot Technology.

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Introduction

The UN forecast of a 3 degree Celsius global temperature increase by 2100, will further intensify excessive heat (Collins et al, 2013). Population growth, urban densification, climate change and global warming all contribute to heat waves, which are more intense in high-density environments (Mellick Lopes et al, 2020). With urbanisation, vegetation is replaced by impervious materials which contribute to the Urban Heat Island (UHI) effect. Concurrently, adverse health outcomes and heat related deaths are increasing where the old, young and those with reduced mobility are more severely affected. Heat stress affects labour productivity, with the number of days people can work safely outdoors in Australia set to decline (Castiglia Feitosa & Wilkinson, 2020).

How can we reduce the UHI and ameliorate the accompanying issues? The answer lies in increasing green infrastructure (GI) in cities, as it; attenuates the UHI, reduces surface temperatures during daytime and air temperature at night, improves air quality, and; enhances population health (Wilkinson et al, 2018).

GI on buildings comes in the form of green roofs (GR), green walls (GW) and green facades (GF), which can be part of an original design, or, retrofitted (Wilkinson & Dixon, 2016). Other urban forms of GI are parks and trees on streets. A Macquarie University study and 2014 UTS Institute of Sustainable Futures report showed 6 degrees Celsius heat mitigation is possible with good GI (Davis et al, 2017). 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. However, despite known benefits, uptake of GI, particularly GW has been slow. The reasons include; costs of ongoing maintenance inspections, monitoring plant health, and occupation health and safety (OH&S) issues for maintenance teams (Wilkinson et al., 2017).

Maintenance in high rise buildings, where maximum GI benefits could be delivered, is managed by Property Managers (PM). If inspection, monitoring and maintenance could be automated by a robot; a Wallbot, these arguments against adoption of GI may not hold in future. As such PMs need to appreciate the innovations and opportunities created through robotic maintenance. Furthermore, PMs have a direct opportunity to enhance sustainability throughout the building lifecycle where the biggest environmental impact is realised. Increasingly advances are being made in so called SMART cities and SMART buildings which adopt technologies to optimise operations and also, sustainability performance.

This paper describes the rationale and development of a design for a green wall maintenance robot by a transdisciplinary team of UTS researchers from Built Environment, Mechatronics and Horticultural Science disciplines. The green wall maintenance robot, or 'Wallbot' project, comprises the design and fabrication of a prototype Wallbot to monitor and maintain green walls. Two design workshops were held in 2019 to determine design criteria for Wallbot1 which is being tested in a UTS robotics lab before field (or wall) trials after 2020. The implications and benefits for property managers through the adoption of smart green wall technology and robotic maintenance that overcome the barriers identified is highlighted in this paper.

The case for green walls in the built environment

Many academics, politicians and community members refer to a climate emergency, as mounting evidence of Climate Change makes denial no longer tenable (Collins et al., 2013). The Australian summer of 2020 comprised unprecedented intensity in bushfires, followed by hailstorms, intense rainfall and flooding along the east coast (BOM, 2020). The predictions are for increases in temperatures for some years, even if extreme mitigation actions are taken (IPCC, 2018).

Another contributory factor is population growth; as a result the built environment will expand its total footprint by 100% by 2060 to accommodate the human population (Erhlich & Holdren, 1972; Bongaarts, 2009). Currently most urban growth is in the form of high density buildings typically requiring air conditioning (Steemers, 2003), where lightweight external envelopes minimise loadings on structural forms and foundations, and which historically, have not performed well thermally (Santos et al , 2014).

With increased temperatures and a growing aged population, health and heat stress issues mount (Porto Valente et al, 2020). The old and young are most affected and, if our built form does not change, we can expect more adverse, acute health issues (Porto Valente et al, 2020). These events strain health services and the economy (Porto Valente et al, 2020).

In city centres there is a spike in temperature, known as the urban heat island (UHI) effect (Castiglia Feitosa et al, 2020). The increase is caused by heat being reflected from materials, such as concrete used in built forms, and being expelled from air conditioning systems typically into narrow streets, where heat can be trapped below tree canopies exacerbating the problem. However green walls on high rise buildings have thermal benefits and lower building energy use was found in a study of sub-tropical residential property (Wong & Baldwin, 2016).

Plants photosynthesise; absorbing carbon dioxide and emitting oxygen. As such, they attenuate some pollutants emitted from buildings and vehicles and improve air quality (Wilkinson & Torpy, 2019). With high density built forms covering large areas, air flow can be impaired and; having green walls improves air quality (Pettit et al, 2017).

In high density built environments, habitats for biodiversity; for the bugs and the birds are not typically provided, despite these creatures pollinating plants that are essential for life on earth (Davis et al, 2017). Further, with a changing climate, many species need to migrate to new areas to survive (Davis et al, 2017) and therefore, pathways across dense built environments are needed.

Finally, humans have an innate need to experience the natural world and spending time in natural environments, we experience feelings of well-being, known as biophilia (Wilkinson & Orr, 2017). Proximity to nature and green infrastructure enhances calmness and reduces anxiety and is a good reason to have green walls on buildings especially in densely developed urban environments.

All of the issues above can be mitigated through increasing GI and the case for adoption is strong. Overall there were seven positive economic, social and environmental reasons found for Property Managers to consider adopting green walls on new and existing buildings. Table 1 summarises the issues and ways that green walls can mitigate adverse impacts and improve the environment.

Table 1 Critical Urban Issues and Green Wall Benefits

Critical Urban Issues	**Green Wall Benefits**
Climate change	Improves thermal performance of buildings reducing Greenhouse Gas emissions.
Urban Heat Island	Widespread uptake reduces energy loads and amount of hot air discharged from buildings.
Population growth	Improved thermal performance and attenuation of UHI will enable us to accommodate more people comfortably in cities.
Health and aging populations	Attenuation of UHI mitigates heat stress for young and aged populations.
Biodiversity habitat	Habitat is provided for species which ensure pollination of plants
Air quality	Absorb carbon dioxide and emit oxygen.
Biophilia	Provide opportunity for people to experience wellbeing.

(Source: Authors).

Barriers to adoption of green walls

Whilst the technology for green walls exists, adoption rates are slow, and a reason frequently cited is the ongoing costs of maintenance (Mullen et al, 2013). Typically maintenance is undertaken manually by workers operating from window cleaning cradles suspended from the top of a building. During high winds or wet weather maintenance is suspended. This leads to another perceived barrier which is Occupational Health and Safety (OH&S) issues for the maintenance workers. Risk averse owners and Property Managers prefer not to have people working at heights unless it is absolutely necessary (Porteous, 2011).

Another perception is that green walls constitute a fire hazard (Wood et al, 2014; Solecki, and Welch, 1995) and whilst the actual evidence of fires and green walls is minimal, nevertheless the perception remains and this affects uptake. Some question the amount of improvements to air quality that derive from the technology and some quantification is useful (Pettit et al, 2017). The overall result is that despite the significance of the benefits of green walls, uptake in cities, especially Australian cities, has been slow (Wilkinson et al, 2018).

Having seen robots that farm and maintain plants horizontally (Brown et al, 2017. Moscoso et al, 2018) the authors considered the potential to design, fabricate and test a vertical wallbot that would inspect, monitor and maintain green walls. The short and long term benefits being development of a safe maintenance technology for Property Managers to adopt where green walls are provided, with lower maintenance costs over the building lifecycle.

Wallbot design and maintenance issues

Wallbot is the name given to the green wall robot that was the focus of this research. No green robot exists and the idea came about when the researchers saw a farmbot, which is a robot used on horizontal beds to maintain the plants. The wallbot is a robot which travels vertically and laterally across a green wall to inspect, monitor and maintain plants.

Property Managers and Facility Managers require a bot to be able to move laterally and vertically across a green wall and to measure plant health and to perform maintenance of plants. A critical review of vertical climbing mechanisms, pruning, waste collection, power systems was undertaken to create a list of the functions required of a Wallbot.

As no other Wallbot exists the researchers had to review other technologies which might generate ideas for the movement, sensors and control systems for the wallbot. Various wall climbing technologies and their respective advantages and disadvantages are reviewed in Schmidt and Berns (2013) and; Nansai and Mohan (2016). The review of climbing mechanisms included cable, gantry, single cable, inbuilt rail system, drone propeller systems, hooks and sliding frame, telescopic legs, passive walking legs, and propeller stabilisation technology. For each climbing mechanism; power supply and façade connection and gravity resist and movement technologies were assessed (Wilkinson et al, 2020). Window cleaning robots were reviewed, such as Skyboy, Roboclimber and SIRIUSc, as they traverse entire façades to perform a cleaning maintenance function; as such they shared some similarities with the proposed Wallbot (Wang et al, 2010. Cepolina et al. 2006. Elkman et al, 2005). Propellor type wall climbing robots, capable of independent flying (Nishi & Miyagi, 1994) along with rope ride technology (Kin et al 2104), and a cable system called Kite Bot (Kite Robotics 2019) were critiqued. Some systems were permanently installed, whereas others are set up when maintenance is performed. In addition, some technologies required more labour to set up and manoeuvre than others.

The pruning and plant maintenance functions can be performed using shearing motorised blades and mounted secateurs (plant cutting sissors). To record and measure plant health, the literature review analysed a range of sensors which measure temperature, humidity, heat levels, wind speed, wind direction and soil moisture. Not only do they measure plant health, but also environmental conditions. The sensors may either be onboard and mounted on the robotic maintenance system, or located externally to the robot and mounted on the green wall itself. Their respective characteristics and advantages and disadvantages are summarised in Tables 2 and 3 below.

Table 2 Onboard sensor characteristics

Advantages	Disadvantages
• Consolidates sensors to one device • Can measure various gardening measures • No probes needed on wall	• Robot has to be active for sensors to operate • Cannot get simultaneous readings from multiple wall locations.

(Source: Wilkinson et al, 2020).

External sensors, on the other hand, position probes at desired points on a wall, and can accommodate sensors to correspond with the type of measurement needed. A moving arm is necessary in this system, however this detects all key green wall elements, and; is able to perform electrical conductivity testing to collect data on soil health.

Table 3 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, cannot be relocated easily

(Source: Wilkinson et al, 2020).

Currently, green waste collection is undertaken using bags on cradle access platforms. Waste, such as plant clippings are collected, rather than letting the waste fall to the streets below. For the Wallbot a similar catchment system may be used. An onboard shredder may be utilised to reduce volume. The issue of power supply varied from using batteries with charging station to mains cables connected via gantries (Elkman et al, 2005) and winches (Cepolina et al. 2006).

The literature review showed that with each of the technologies, evaluation criteria are; flexibility, costs, safety issues, maintenance functions and the capacity for waste collection. Furthermore, six design criteria derived from the literature include;

a) Maintenance activities – frequency.
b) Legal / regulatory and OHS issues.
c) Use of existing building infrastructure (window cleaning cradle tracks).
d) Control systems.
e) Sensors required.
f) Integration with BMS or BIM.

Research design and methodology

This part of the research is qualitative, as it sought to identify the key design criteria the prototype Wallbot should encompass (Yin, 2015. Silverman, 2016). As such, it was decided that workshops, with a group of expert key stakeholders would produce good insights on essential criteria and result in valid and reliable data (Yin, 2015). Following submission of an Ethics Application, two key stakeholders workshops were hosted in August and October 2019 with 11 participants (listed in Table 4). Workshop participants included stakeholders actively engaged in sustainable urban development, robotics and green infrastructure. They included green wall installers and designers, Indigenous elders, landscape architects, building certifiers, urban planners, policy makers, construction companies, property developers, robot designers, IoT professionals and horticultural scientists. These experts have direct experiential knowledge and understanding of the variables involved in designing, installing and maintaining greens walls and properties in New South Wales (NSW), Australia.

Workshop 1 focussed on identifying the tasks/issues involved in green wall maintenance and design in respect of;

a) Maintenance activities
b) Legal / regulatory and OHS issues
c) Use of existing building infrastructure (window cleaning cradle tracks)
d) Control systems
e) Sensors required
f) Integration with BMS or BIM
g) Any other tasks / issues relevant.

The workshop participants identified their issues and then ranked the tasks/issues as either; essential, desirable, infrequent or, unnecessary. A group discussion followed, focussed on all the tasks/issues identified and was debated until a consensus regarding the priorities for green wallbot was achieved. This approach is recommended as best practice by research methods experts (Yin, 2015) as it ensures all issues are discussed, openly, in real time and a consensus is reached across different stakeholder groups.

In the second Workshop, one task was to prioritise the design criteria and develop a method to critique a prototype wallbot. This required participants to;

1. List the most important design criteria and identify how we can evaluate the wallbot design
2. Review the prototype wallbot
3. Confirm the key design criteria and map way forward
4. Identify next steps.

The second workshop summarised options in respect of; wall climbing mechanisms, hedging/pruning, sensor systems, waste collection and power supply. The workshop participants who had all attended workshop 1, reviewed all the options and determined the prototype design features that would be adopted to create a prototype green wall robotic maintenance system.

Potential attributes of the green wall robotic maintenance design were debated along with the advantages and disadvantages in respect of social, economic, environmental, regulatory, legal and technological factors. Key technical considerations were how to facilitate motion across the side of buildings, and how maintenance such as planting, pruning, waste collection and plant health monitoring could be performed.

Research Findings

Workshop 1 outcomes

An outcome from the workshops with the stakeholders was the understanding that the form of the system would require different embodiments depending on the type of GW installation being maintained. For example, large buildings with significant GI requiring frequent maintenance, could be best maintained by a permanent installation integrated into the building, with the capital cost offset by savings on maintenance over time. Whereas, smaller green walls may be maintained better by a system installed temporarily when maintenance is required, allowing costs to be shared across multiple green wall installations.

Another discussion point was the functional capabilities of the robotic maintenance system. A system physically interacting with the plants for operations such as; planting and pruning is significantly more complex than a system solely performing non-contact health monitoring. The advantage of this extra complexity again depends on the type of installation.

After the workshops, the scope was agreed for the prototype robotic maintenance system, labelled; 'Wallbot' . The participants concurred the focus should be to develop a system that can be transported site to site, which has plant health monitoring capabilities. This reduced the complexity of development at this early stage, whilst resulting in a design that could be beneficial for the stakeholders.

Workshop 1 comprised 11 participants from engineering, green wall design, installers, maintenance, horticultural science and project management. This was a good cross section of expertise and knowledge of key stakeholders involved in maintenance and green wall design and installation. The rank order of importance of the green wall robot design issues for each participant is shown in Table 4, and followed a lengthy debate on each of the six criteria.

Table 4: Workshop 1 Wallbot workshop participants and ranking data

Participant (scores 1 = most important)	Maintenance	Legal, regulations, OH&S.	Using existing building infrastructure	Control systems	Sensors required	Integration with BMS / BIM.
Engineer 1	1	4	6	2	3	5
Engineer 2	1	4	5	3	2	6
GW Installer 1	2	1	4	3	5	6
GW Maintenance 1	1	2	3	5	4	5
Engineer PM	2	1	3			
GW Installer 2	2	1	6	4	3	5
GW Designers	2	1	5	3	4	6
Hort Scientist 1	2	1	5	4	3	6
Hort Scientist 2	2	1	4	5	3	6
GW Maintenance 2	1	2	5	4	3	6
Engineer 3	4	1	5	2	3	6

Total scores	20	19	51	35	33	57

(Source: Authors).

Table 5 shows the final agreed rank order list of importance of design issues.

Table 5: Rank Order of Importance of Wallbot design issues.

1. Legal, regulations, OHS
2. Maintenance
3. Sensors required
4. Control systems
5. Using existing building infrastructure
6. Integration with BMS / BIM

(Source: Authors).

This information confirms a robust, safety first approach is undertaken which is essential for effective property maintenance and management. Participants felt adoption of these criteria would result in a robust robot design that property managers can have confidence in.

Workshop 2 outcomes

Having evaluated the various options and ranked according to the flexibility, cost, safety, maintenance and waste collection criteria. Seven criteria relating to the mechanisms were proposed for participants to review and included;

- gravity resist and lateral movement design (either via 4 independently actuated cables, use of window cleaning gantry equipment or two cables and a rail),
- distance control mechanism, pruning components (a choice of scissors, blades or shears),
- power source (battery or mains power),
- waste disposal (via a shredder, chute and/or a bag),
- inclusion of sensors (including normalized difference vegetation index (NDVI) which measures the amount of vegetation present, or probes on controllable arms), and finally;
- face transmission (one robot per façade or, use of rails as part of window cleaning cradle provision).

Factors taken into account with the proposed designs were cost, level of automation and complexity, flexibility and degree of permanence. Three different green wall robot options were proposed to the Workshop 2 participants as follows;

1. High cost – high automation and complexity (Table 6).
2. Low cost – flexible and non-permanent (Table 7).
3. Medium cost – semi autonomous and medium complexity (Table 8).

Table 6- High cost – high automation and complexity

Mechanism	Component
Gravity Resist and Lateral Movement	Four independently actuated Cables
Distance Control	Multiple insect legs
Pruning	Shearing motorized blades and pruning system
Power	Mains Power Supply
Waste	Shredder & Bag
Sensors	NDVI sensors
Face Transition	One robot for each facade

(Source: Authors).

Table 7 - Low cost – flexible and non-permanent

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	Shearing Motorized blade
Power	Mains Power Supply
Waste	Shredder & Bag
Sensors	Probe on controllable arm
Face Transition	Rail (as part of window cradle assembly)

(Source: Authors).

Table 8 - Medium cost – semi autonomous and medium complexity

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

(Source: Authors).

The workshop discussion sought to answer which is the best option to pursue? (Low/medium or high cost) and why? Secondly, given the budget, what aspects of this option are priorities? Finally, what is best option for testing a prototype? Following extensive group discussion, consensus determined that the priority was to avoid people working at heights on buildings, reduce costs of maintenance for green walls, and to avoid OHS issues with current systems, as these factor deter clients from procuring large green walls currently. It was noted newly installed green walls require a major service after 3 months. The project scope was considered to be very big and thus a need to focus on the most important initial aspects was agreed.

Workshop 2 participants concluded the first priority is to design a non-contact inspection / plant monitoring component to assess pest and disease (typically undertaken every 3 months). The second priority is to design a climbing mechanism for walls up to 6-7 m height (approx. 2 stories).

The Wallbot prototype

Following the two workshops, a prototype green wall robot was designed and fabricated (Plate 1). A concept using actuated ropes to manoeuvre the Wallbot's body across the green wall was chosen, which aligns with Wallbot being a system that is transported and installed on site. Four computer-controlled winches operate in unison to control the length and tension of the ropes, and the Wallbot is moved across the green wall to perform plant inspection.

To measure plant health, the Wallbot body is fitted with three vision-based sensors. An optical tracking camera (Intel RealSense T265) tracks the motions of the Wallbot body as it manoeuvres across the wall. A second camera (Intel RealSense D425) uses stereo infrared sensors to build a 3D map of the scene it detects. Combined, these cameras allow a high-fidelity 3D map of the green wall to be constructed. A third sensor, a multi-spectral survey camera (MAPIR Survey 3), calculates the normalised difference vegetation index (NDVI) of the plants and allows the general health of the green wall to be measured.

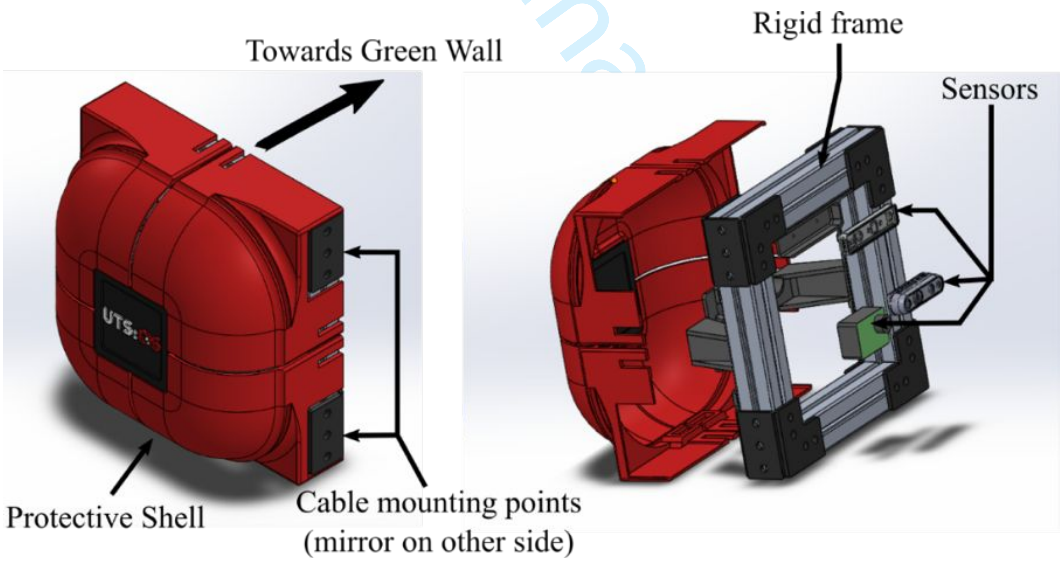

Plate 1 The Wallbot main body (Source: Authors).

Initial tests were performed at UTS, Sydney Australia on a green wall containing five Junglefy planter boxes, four of which were populated with plants (Plate 2). Combining measurements from different Wallbot positions allowed a 3D map of the plants to be generated (Plate 3). The tests demonstrated the ability of the Wallbot to traverse the wall whilst collecting data from the plants for processing.

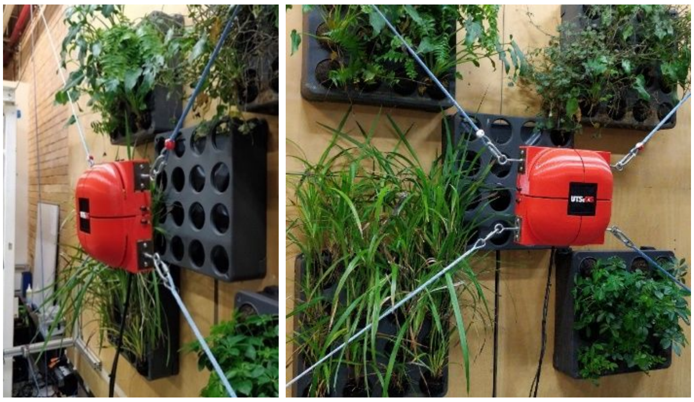

Plate 2: The Wallbot installation at the University of Technology Sydney (UTS) (Source: Authors).

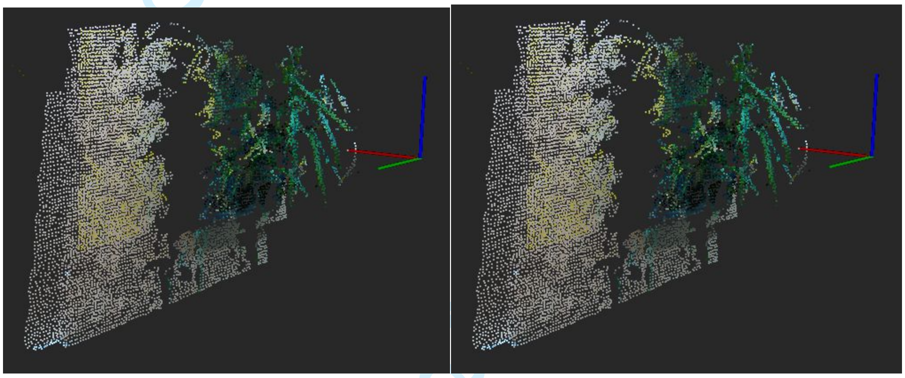

Plate 3 Reconstruction of the vertical garden by the Wallbot (Source: Authors).

Based on the workshops data, six key design issues formed the basis of a prototype design based on a 4-cable climbing mechanism.

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 collection of data on plant health and an initial appraisal of the Wallbot sensors ability to assess plant health. Preliminary test results are encouraging, however further work is needed before Wallbot is ready to deliver full maintain green walls. The Wallbot prototype has successfully created a 3D map of the GW to assist regular inspections. Once the system is installed plants can be monitored automatically and regularly without need for manual inspections.

Maintenance functions, such as pruning requires further development, and a potential solution is to combine regular Wallbot GW monitoring, with people performing targeted maintenance tasks. This paradigm reduces requirements for human maintenance, OH&S risk and human maintenance costs. Additionally, with regular inspection the demise of plants could be detected early and potentially remedied if corrective action is performed in time.

Future versions of Wallbot are under development with additional sensors for collecting temperature, humidity, wind and soil moisture data, providing maintenance teams with rich information about the health of green walls. Additionally, attachments to allow pruning or spraying nutrients may be added. Further work will extend the range of functions to include pruning, waste collection and power sources.

Conclusions

The case for robotic technology to encourage greater uptake of green walls and facades, whilst reducing OHS and maintenance costs, is strong. The benefits of urban GI 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 GI. A robotic installation to inspect, monitor and maintain green walls gives property managers the option to commission green walls with reduced OHS issues and maintenance costs.

The 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. The initial focus being on climbing mechanisms and sensor technology. The research design comprised the review of secondary data such as research reports, peer reviewed journal papers and technical guidelines. Empirical data was collected when all options were proposed and discussed in two Sydney workshops with key stakeholders and experts in delivering GI in cities.

The benefits for property management will be a more cost effective, lower risk maintenance strategy for ensuring optimum condition and health of green walls. Greater uptake of green infrastructure will enable our urban environments provide healthy, attractive buildings that mitigate the effects of the urban heat island and enable property managers to contribute to greater sustainability. Globally there is greater adoption and integration of smart technologies into cities, precincts and buildings. This research posits the innovation of smart green walls and the Wallbot that facilitates the maintenance and inspection of green walls remotely, as well as the collection of data on air quality and biodiversity.

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Introduction

The UN forecast of a 3 degree Celsius global temperature increase by 2100, will further intensify excessive heat (Collins et al, 2013). Population growth, urban densification, climate change and global warming all contribute to heat waves, which are more intense in high-density environments (Mellick Lopes et al, 2020). With urbanisation, vegetation is replaced by impervious materials which contribute to the Urban Heat Island (UHI) effect. Concurrently, adverse health outcomes and heat related deaths are increasing where the old, young and those with reduced mobility are more severely affected. Heat stress affects labour productivity, with the number of days people can work safely outdoors in Australia set to decline (Castiglia Feitosa & Wilkinson, 2020).

How can we reduce the UHI and ameliorate the accompanying issues? The answer lies in increasing green infrastructure (GI) in cities, as it; attenuates the UHI, reduces surface temperatures during daytime and air temperature at night, improves air quality, and; enhances population health (Wilkinson et al, 2018).

GI on buildings comes in the form of green roofs (GR), green walls (GW) and green facades (GF), which can be part of an original design, or, retrofitted (Wilkinson & Dixon, 2016). Other urban forms of GI are parks and trees on streets. A Macquarie University study and 2014 UTS Institute of Sustainable Futures report showed 6 degrees Celsius heat mitigation is possible with good GI (Davis et al, 2017). 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. However, despite known benefits, uptake of GI, particularly GW has been slow. The reasons include; costs of ongoing maintenance inspections, monitoring plant health, and occupation health and safety (OH&S) issues for maintenance teams (Wilkinson et al., 2017).

Maintenance in high rise buildings, where maximum GI benefits could be delivered, is managed by Property Managers (PM). If inspection, monitoring and maintenance could be automated by a robot; a Wallbot, these arguments against adoption of GI may not hold in future. As such PMs need to appreciate the innovations and opportunities created through robotic maintenance. Furthermore, PMs have a direct opportunity to enhance sustainability throughout the building lifecycle where the biggest environmental impact is realised. Increasingly advances are being made in so called SMART cities and SMART buildings which adopt technologies to optimise operations and also, sustainability performance.

This paper describes the rationale and development of a design for a green wall maintenance robot ~~Green Wallbot~~ by a transdisciplinary team of UTS researchers from Built Environment, Mechatronics and Horticultural Science disciplines. The green wall maintenance robot, or~~UTS~~ 'Wallbot' project, comprises the design and fabrication of a prototype Wallbot to monitor and maintain green walls. Two design workshops were held in 2019 to determine design criteria for Wallbot1 which is being tested in a UTS robotics lab before field (or wall) trials after 2020. The implications and benefits for property managers~~ment~~ through the adoption of smart green wall technology and robotic maintenance that overcome the barriers identified is highlighted in this paper.

The case for green walls in the built environment

Many academics, politicians and community members refer to a climate emergency, as mounting evidence of Climate C~~c~~hange makes denial no longer tenable (Collins et al., 2013). The Australian summer of 2020 comprised unprecedented intensity in bushfires, followed by hailstorms, intense rainfall and flooding along the east coast (BOM, 2020). The predictions are for increases in temperatures for some years, even if extreme mitigation actions are taken (IPCC, 2018).

Another contributory factor is population growth; as a result the built environment will expand its total footprint by 100% by 2060 to accommodate the human population (Erhlich & Holdren, 1972;~~,~~ Bongaarts, 2009). Currently most urban growth is in the form of high density buildings typically requiring air conditioning (Steemers, 2003), where lightweight external envelopes minimise loadings on structural forms and foundations, and which historically, have not performed well thermally (Santos et al , 2014).

With increased temperatures and a growing aged population, health and heat stress issues mount (Porto Valente et al, 2020). The old and young are most affected and, if our built form does not change, we can expect more adverse, acute health issues (Porto Valente et al, 2020). These events strain health services and the economy (Porto Valente et al, 2020).

In city centres there is a spike in temperature, known as the urban heat island (UHI) effect (Castiglia Feitosa et al, 2020). The increase is caused by heat being reflected from materials, such as concrete used in built forms, and being expelled from air conditioning systems typically into narrow streets, where heat can be trapped below tree canopies exacerbating the problem. However green walls on high rise buildings have thermal benefits and lower building energy use~~ as~~ was found in a study of sub-tropical residential property (Wong & Baldwin, 2016).

Plants photosynthesise; absorbing carbon dioxide and emitting oxygen. As such, they attenuate some pollutants emitted from buildings and vehicles and improve air quality (Wilkinson & Torpy, 2019). With high density built forms covering large areas, air flow can be impaired and; having green walls improves air quality (Pettit et al, 2017).

In high density built environments, habitats for biodiversity; for the bugs and the birds are not typically provided, ~~(Davis et al, 2017),~~ despite~~ that~~ these creatures pollinating~~e~~ plants ~~and~~ that are essential for life on earth (Davis et al, 2017). Further, with a changing climate, many species need to migrate to new areas to survive (Davis et al, 2017) and therefore, pathways across dense built environments are needed.

Finally, humans have an innate need to experience the natural world and spending time in natural environments, we experience feelings of well-being, ~~labelled~~known as~~;~~ biophilia (Wilkinson & Orr, 2017). Proximit~~These feelings~~y to nature and green infrastructure enhances calmness and reduces anxiety and is a good reason to have green walls on buildings especially in densely developed urban environments.

All of the issues above can be mitigated through increasing GI and the case for adoption is strong. Overall there were seven positive economic, social and environmental reasons found for Property Managers to consider adopting green walls on new and existing buildings. Table 1 summarises the issues and ways that green walls can mitigate adverse impacts and improve the environment.

Table 1 Critical Urban Issues and Green Wall Benefits

Critical Urban Issues	Green Wall Benefits
Climate change	Improves thermal performance of buildings reducing Greenhouse Gas emissions.
Urban Heat Island	Widespread uptake reduces energy loads and amount of hot air discharged from buildings.
Population growth	Improved thermal performance and attenuation of UHI will enable us to accommodate more people comfortably in cities.
Health and aging populations	Attenuation of UHI mitigates heat stress for young and aged populations.
Biodiversity habitat	Habitat is provided for species which ensure pollination of plants
Air quality	Absorb carbon dioxide and emit oxygen.
Biophilia	Provide opportunity for people to experience wellbeing.

(Source: Authors).

Barriers to adoption of green walls

Whilst the technology for green walls exists, adoption rates are slow, and a reason frequently cited is the ongoing costs of maintenance (Mullen et al, 2013). Typically maintenance is undertaken manually by workers operating from window cleaning cradles suspended from the top of a building. During high winds or wet weather maintenance is suspended. This leads to another perceived barrier which is Occupational Health and Safety (OH&S) issues for the maintenance workers. Risk averse owners and Property Managers prefer not to have people working at heights unless it is absolutely necessary (Porteous, 2011).

Another perception is that green walls constitute a fire hazard (Wood et al, 2014; Solecki, and Welch, 1995) and whilst the actual evidence of fires and green walls is minimal, nevertheless the perception remains and this affects uptake. Some question the amount of improvements to air quality that derive from the technology and some quantification is useful (Pettit et al, 2017). The overall result is that despite the significance of the benefits of green walls, uptake in cities, especially Australian cities, has been slow (Wilkinson et al, 2018).

Having seen robots that farm and maintain plants horizontally (Brown et al, 2017. Moscoso et al, 2018~~.~~) the authors considered the potential to design, fabricate and test a vertical wallbot that would inspect, monitor and maintain green walls. The short and long term benefits being development of a safe maintenance technology for Property Managers to adopt where green walls are provided, with lower maintenance costs over the building lifecycle.

Wallbot design and maintenance issues

Wallbot is the name given to the green wall robot that was the focus of this research. No green robot exists and the idea came about when the researchers saw a farmbot, which is a robot used on horizontal beds to maintain the plants. The wallbot is a robot which travels vertically and laterally across a green wall to inspect, monitor and maintain plants.

Property Managers and Facility Managers require a bot to be able to move laterally and vertically across a green wall and to measure plant health and to perform maintenance of plants. A ~~list of the functions required of the Wallbot, a~~ critical review of vertical climbing mechanisms, pruning, waste collection, power systems was undertaken to create a list of the functions required of a Wallbot.

As no other Wallbot exists the researchers had to review other technologies which might generate ideas for the movement, sensors and control systems for the wallbot. Various wall climbing technologies and their respective advantages and disadvantages are reviewed in Schmidt and Berns (2013) and; Nansai and Mohan (2016). The review of climbing mechanisms included cable, gantry, single cable~~ with onboard ascension~~, inbuilt rail system, drone propeller systems, hooks and sliding frame, telescopic legs, passive walking legs, and propeller stabilisation technology. For each climbing mechanism; power supply and façade connection and gravity resist and movement technologies were assessed (Wilkinson et al, 2020). Window cleaning robots were reviewed, such as Skyboy, Roboclimber and SIRIUSc, as they traverse entire façades ~~and~~ to perform a cleaning maintenance function; as such they shared some similarities with the proposed Wallbot (Wang et al, 2010. Cepolina et al. 2006. Elkman et al, 2005). Propellor type wall climbing robots, capable of independent flying (Nishi & Miyagi, 1994) along with rope ride technology (Kin et al 2104), and a cable system called Kite Bot (Kite Robotics 2019) were ~~reviewed~~critiqued. Some systems were permanently installed, whereas others are set up when maintenance is performed. In addition, s~~S~~ome technologies required more labour to set up and manoeuvre than others.

The p~~P~~runing and plant maintenance functions can be performed using shearing motorised blades and mounted secateurs (plant cutting sissors).

To record and measure plant health, the literature review analysed a range of s~~S~~ensors which measure temperature, humidity, heat levels, wind speed, wind direction and soil moisture. Not only ~~are needed to measure~~do they measure plant health, but also ~~and~~ environmental conditions~~ and also, to determine maintenance required were researched~~. These sensors may either be onboard and mounted on the robotic maintenance system~~Wallbot~~, or located externally to the robot and mounted on the green wall itself. Their respective characteristics and advantages and disadvantages are ~~noted~~ summarised in T~~t~~ables 2 and 3 below.

Table 2 Onboard sensor characteristics

Advantages	Disadvantages
• Consolidates sensors to one device • Can measure various gardening measures • No probes needed on wall	• Robot has to be active for sensors to operate • Cannot get simultaneous readings from multiple wall locations.

(Source: Wilkinson et al, 2020).

External sensors, on the other hand, position probes at desired points on a wall, and can accommodate sensors to correspond with the type of measurement needed. A moving arm is necessary in this system, however this detects all key green wall elements, and; is able to perform electrical conductivity testing to collect data on soil health.

Table 3 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, cannot be relocated easily

(Source: Wilkinson et al, 2020).

Currently, green waste collection is undertaken using~~via~~ bags on cradle access platforms. Waste, such as plant clippings are collected, rather than letting the waste fall to the streets below. For the Wallbot a similar catchment system may be used. An onboard shredder may be utilised to reduce volume.

The issue of power supply varied from using batteries with charging station to mains cables connected via gantries (Elkman et al, 2005) and winches (Cepolina et al. 2006).

The literature review showed that w~~W~~ith each of the technologies, evaluation criteria are; flexibility, costs~~-~~, safety issues, maintenance functions and the capacity for waste collection. Furthermore, six design criteria ~~were~~ derived from the literature ~~as follows~~include;

a) Maintenance activities – frequency.
b) Legal / regulatory and OHS issues.
c) Use of existing building infrastructure (window cleaning cradle tracks).

d) Control systems.
e) Sensors required.
f) Integration with BMS or BIM.

Research design and methodology

This part of the research is qualitative, as it research which seekssought to identify the key design criteria the prototype Wallbot should encompass (Yin, 2015. Silverman, 2016). As such, it was decided that workshops, with a group of expert key stakeholders would produce good insights on essential criteria and result in valid and reliable data (Yin, 2015). Following submission of an Ethics Application, two key stakeholders workshops were hosted in August and October 2019 with 11 participants (as(listed in Table 4). Workshop participants included stakeholders actively engaged in sustainable urban development, robotics and green infrastructure. They included green wall installers and designers, Indigenous elders, landscape architects, building certifiers, urban planners, policy makers, construction companies, property developers, robot designers, IoT professionals and horticultural scientists. These experts have direct experiential knowledge and understanding of the variables involved in designing, installing and maintaining greens walls and properties in New South Wales (NSW), Australia.

Workshop 1 was focussed on identifying the tasks/issues involved in green wall maintenance and design in respect of;

a) Maintenance activities
b) Legal / regulatory and OHS issues
c) Use of existing building infrastructure (window cleaning cradle tracks)
d) Control systems
e) Sensors required
f) Integration with BMS or BIM
g) Any other tasks / issues relevant.

The workshop participants identified their issues and then ranked the tasks/issues as either; essential, desirable, infrequent or, unnecessary. A group discussiondiscussion followed, focussed on all the tasks/issues identified and was debated until a consensus regarding the priorities for green wallbot was achieved. This approach is recommended as best practice by research methods experts (Yin, 2015) as it ensures all issues are discussed, openly, in real time and a consensus is reached across different stakeholder groups.

In the second Workshop, one task was to prioritise the design criteria and develop a method to critique a prototype wallbot. This required participants to;

1. List the most important design criteria and identify how we can evaluate the wallbot design
2. Review the prototype wallbot
3. Confirm the key design criteria and map way forward
4. Identify next steps.

The second workshop summarised options in respect of; wall climbing mechanisms, hedging/pruning, sensor systems, waste collection and power supply. The workshop participants who had all attended workshop 1, reviewed all the options and determined the prototype ~~Wallbot~~ design features that would be adopted to create a prototype ~~Wallbot~~ green wall robotic maintenance system. ~~Two key stakeholders workshops were hosted, which included green wall installers and designers, Indigenous elders, landscape architects, building certifiers, urban planners, policy makers, construction companies, property developers, robot designers, IoT professionals and horticultural scientists.~~

Potential ~~embodiments~~ attributes of the green wall robotic maintenance~~Wallbot~~ design were debated along with the advantages and disadvantages in respect of social, economic, environmental, regulatory, legal and technological factors. Key technical considerations were how to facilitate motion across the side of buildings, and how maintenance such as planting, pruning, waste collection and plant health monitoring could be performed.

~~Two key stakeholders workshops were hosted, which included green wall installers and designers, Indigenous elders, landscape architects, building certifiers, urban planners, policy makers, construction companies, property developers, robot designers, IoT professionals and horticultural scientists.~~

Research Findings

Workshop 1 outcomes

An outcome from the workshops with the ~~GW~~ stakeholders was the understanding that the form of the system would require different embodiments depending on the type of GW installation being maintained. For example, large buildings with significant GI requiring frequent maintenance, could be best maintained by a permanent installation integrated into the building, with the capital cost offset by savings on maintenance over time. ~~Alternatively~~Whereas, smaller green walls~~GW~~ may be ~~better~~ maintained better by a system installed temporarily when maintenance is required, allowing costs to be shared across multiple ~~GW~~ green wall installations.

Another discussion point was the functional capabilities of the ~~Wallbot~~robotic maintenance system. A system physically interacting with the plants for operations such as; planting and pruning is significantly more complex than a system solely performing non-contact health monitoring. The advantage of this extra complexity again depends on the type of installation.

After the workshops, the scope was agreed for the prototype robotic maintenance system, labelled; 'Wallbot' ~~prototyp. e scope was agreed~~The participants concurred the ~~, with a~~ focus should be to~~on~~ develop~~ing~~ a system that can be transported site to site, ~~and with~~which has plant health monitoring capabilities. This reduced the complexity of development at this early stage, whilst resulting in a design that could be beneficial for the stakeholders.

Workshop 1 comprised 11 participants from engineering, green wall design, installers, maintenance, horticultural science and project management. This was a good cross section of expertise and knowledge of key stakeholders involved in maintenance and green wall design and installation. The rank order of importance of the green wall robot design issues for each participant is shown in Table 4, and followeding a lengthy debate on each off the six criteria.

Table 4: Workshop 1 Wallbot workshop participants and ranking data

Participanterson (scores 1 = most important)	Maintenance	Legal, regulations, OH&S.	Using existing building infrastructure	Control systems	Sensors required	Integration with BMS / BIM.
Engineer 1	1	4	6	2	3	5
Engineer 2	1	4	5	3	2	6
GW Installer 1	2	1	4	3	5	6
GW Maintenance 1	1	2	3	5	4	5
Engineer PM	2	1	3			
GW Installer 2	2	1	6	4	3	5
GW Designers	2	1	5	3	4	6
Hort Scientist 1	2	1	5	4	3	6
Hort Scientist 2	2	1	4	5	3	6
GW Maintenance 2	1	2	5	4	3	6
Engineer 3	4	1	5	2	3	6
Total scores	20	19	51	35	33	57

(Source: Authors).

Table 5 shows the final agreed rank order list of importance of design issues.

Table 5: Rank Order of Importance of Wallbot design issues.

1. Legal, regulations, OHS
2. Maintenance
3. Sensors required
4. Control systems
5. Using existing building infrastructure
6. Integration with BMS / BIM

(Source: Authors).

This information confirms a robust, safety first approach is undertaken which is essential for effective property maintenance and management. Participants felt adoption of these criteria would result in a robust robot design that property managers can have confidence in.

Workshop 2 outcomes

Having evaluated the various options and ranked according to the flexibility, cost, safety, maintenance and waste collection criteria. Seven criteria relating to the mechanisms were proposed for participants to review and included;

- gravity resist and lateral movement design (either via 4 independently actuated cables, use of window cleaning gantry equipment or two cables and a rail),
- distance control mechanism, pruning components (a choice of scissors, blades or shears),
- power source (battery or mains power),
- waste disposal (via a shredder, chute and/or a bag),
- inclusion of sensors (including normalized difference vegetation index (NDVI) which measures the amount of vegetation present, or probes on controllable arms), and finally;
- face transmission (one robot per façade or, use of rails as part of window cleaning cradle provision).

Factors taken into account with the proposed designs were cost, level of automation and complexity, flexibility and degree of permanence. T~~t~~hree different ~~wallbot~~ green wall robot options were proposed to the W~~w~~orkshop 2 participants as follows;

1. High cost – high automation and complexity (T~~t~~able 6).
2. Low cost – flexible and non-permanent (T~~t~~able 7).
3. Medium cost – semi autonomous and medium complexity (T~~t~~able 8).

Table 6- High cost – high automation and complexity

Mechanism	Component
Gravity Resist and Lateral Movement	Four independently actuated Cables
Distance Control	Multiple insect legs
Pruning	Shearing motorized blades and pruning system
Power	Mains Power Supply
Waste	Shredder & Bag
Sensors	NDVI sensors
Face Transition	One robot for each facade

(Source: Authors).

Table 7 - Low cost – flexible and non-permanent

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	Shearing Motorized blade
Power	Mains Power Supply
Waste	Shredder & Bag
Sensors	Probe on controllable arm
Face Transition	Rail (as part of window cradle assembly)

(Source: Authors).

Table 8 - Medium cost – semi autonomous and medium complexity

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

(Source: Authors).

The workshop discussion sought to answer~~;~~ which is the best option ~~is best~~ to pursue? (Low/medium or high cost) and w~~W~~hy? Secondly, given the budget, what aspects of this option are priorities? Finally, what is best option for testing a prototype?

Following extensive group discussion, consensus determined that the priority was to avoid people working at heights on buildings, reduce costs of maintenance for green walls, and to avoid OHS issues with current systems, as these factor deter clients from procuring large green walls currently. It was noted newly installed green walls require a major service after 3 months.~~-~~ The project scope was considered to be very big and thus a need to focus on the most important initial aspects was agreed.

~~After an extensive discussion~~Workshop 2 participants ~~agreed~~ concluded the first priority is to design a non-contact inspection / plant monitoring component to assess pest and disease (typically undertaken every 3 months).

The second priority is to design a climbing mechanism for walls up to 6-7 m height (approx. 2 stories).

The Wallbot prototype

Following the two workshops, a prototype ~~Wallbot~~ green wall robot was designed and fabricated (Plate 1). A concept using actuated ropes to manoeuvre the Wallbot's body across the ~~GW~~ green wall was chosen, which aligns with Wallbot being a system that is transported and installed on site. Four computer-controlled winches operate in unison to control the length and tension of the ropes, and the Wallbot is moved across the ~~GW~~ green wall to perform plant inspection.

To measure plant health, the Wallbot body is fitted with three vision-based sensors. An optical tracking camera (Intel RealSense T265) tracks the motions of the Wallbot body as it manoeuvres across the wall. A second camera (Intel RealSense D425) uses stereo infrared sensors to build a 3D map of the scene it detects. Combined, these cameras allow a high-fidelity 3D map of the ~~GW~~ green wall to be constructed. A third sensor, a multi-spectral survey camera (MAPIR Survey 3), calculates the normalised difference vegetation index (NDVI) of the plants and allows the general health of the green wall~~GW~~ to be measured.

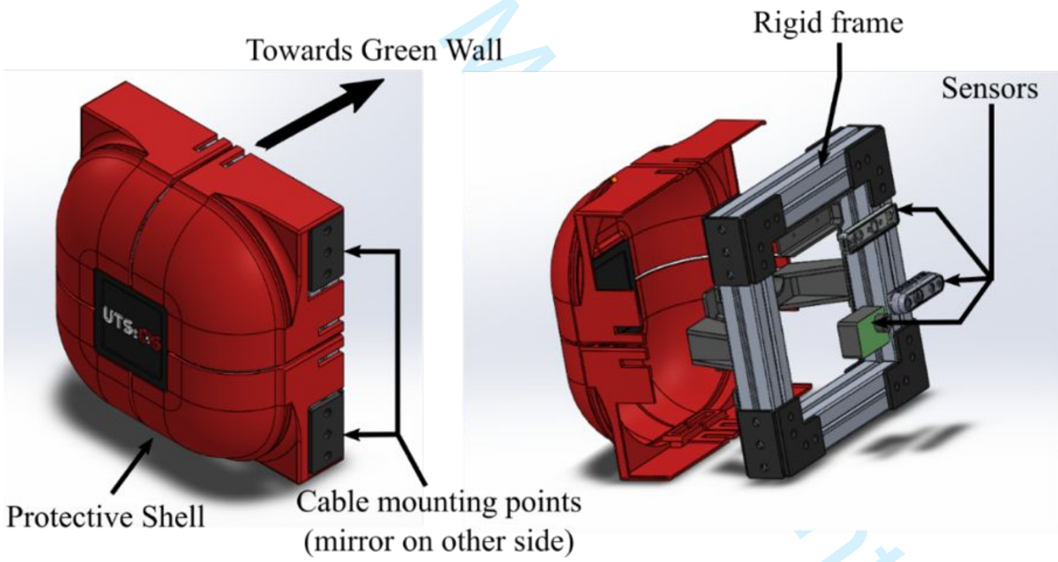

Plate 1 The Wallbot main body (Source: Authors).

Initial tests were performed at UTS, Sydney Australia on a ~~GW~~ green wall containing five Junglefy planter boxes, four of which were populated with plants (P~~p~~late 2). Combining measurements from different Wallbot positions allowed a 3D map of the plants to be generated (P~~p~~late 3). The tests demonstrated the ability of the Wallbot to traverse the wall whilst collecting data from the plants for processing.

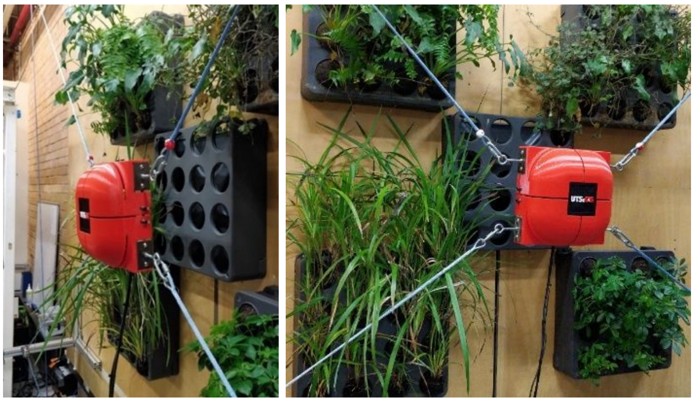

Plate 2: The Wallbot installation at the University of Technology Sydney (UTS) (Source: Authors).

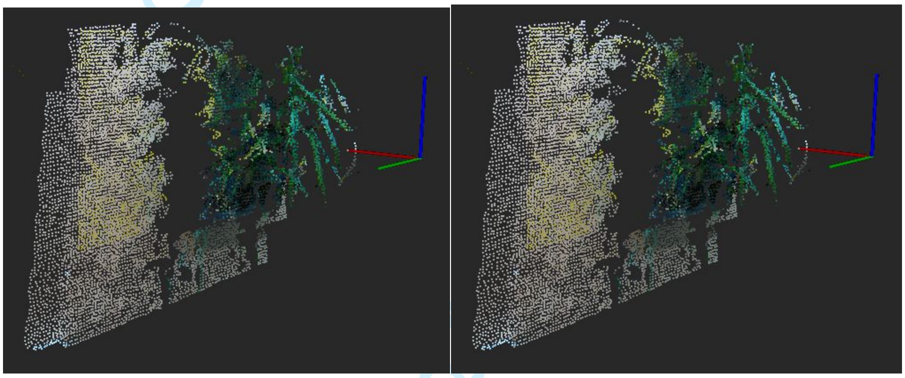

Plate 3 Reconstruction of the vertical garden by the Wallbot (Source: Authors).

Based on the workshops data, six key design issues formed the basis of a prototype design based on a 4-cable climbing mechanism.

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 collection of data on plant health and an initial appraisal of the Wallbot sensors ability to assess plant health. Preliminary test results are encouraging, however further work is needed before Wallbot is ready to deliver full maintain green walls. The Wallbot prototype has successfully created a 3D map of the GW to assist regular inspections. Once the system is installed plants can be monitored automatically and regularly without need for manual inspections.

Maintenance functions, such as pruning requires further development, and a potential solution is to combine regular Wallbot GW monitoring, with people performing targeted maintenance tasks. This paradigm reduces requirements for human maintenance, OH&S risk and human maintenance costs. Additionally, with regular inspection the demise of plants could be detected early and potentially remedied if corrective action is performed in time.

Future versions of Wallbot are under development with additional sensors for collecting temperature, humidity, wind and soil moisture data, providing maintenance teams with rich information about the health of green walls. Additionally, attachments to allow pruning or spraying nutrients may be added. Further work will extend the range of functions to include pruning, waste collection and power sources.

Conclusions

The case for robotic technology to encourage greater uptake of green walls and facades, whilst reducing OHS and maintenance costs, is strong. The benefits of urban GI 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 GI. ~~Wallbot, a~~A robotic installation to inspect, monitor and maintain green walls ~~offers~~ gives property managers the option to commission green walls with ~~the chance to~~ reduced OHS issues and maintenance costs ~~associated with green walls~~.

The 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. The initial focus being on climbing mechanisms and sensor technology.

The research design comprised the review of secondary data such as research reports, peer reviewed journal papers and ~~,~~ technical guidelines. Empirical data was collected when a~~and~~ll options~~appraisal of all options, which~~ were proposed and discussed in~~at~~ two Sydney 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 collection of data on plant health and an initial appraisal of the Wallbot sensors ability to assess plant health. Preliminary test results are encouraging, however further work is needed before Wallbot is ready to deliver full maintain Green Walls. The Wallbot prototype has successfully created a 3D map of the GW to assist regular inspections. Once the system is installed plants can be monitored automatically and regularly without need for manual inspections.~~

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The benefits for property management will be a more cost effective, lower risk maintenance strategy for ensuring optimum condition and health of green walls. Greater uptake of green infrastructure will enable our urban environments provide healthy, attractive buildings that mitigate the effects of the urban heat island and enable property managers to contribute to greater sustainability. Globally there is greater adoption and integration of smart technologies into cities, precincts and buildings. This research posits the innovation of smart green walls and the Wallbot that facilitates the maintenance and inspection of green walls remotely, as well as the collection of data on air quality and biodiversity.

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