Hardware Article

An inexpensive robotic gantry to screen and control soil moisture for plant experiments

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ABSTRACT

Controlling water content in soil is a recurrent and labor intensive operation on almost any experiment about plant physiology. Here we describe a robotic gantry to measure and control soil moisture in pots that is modular, inexpensive, easy to build, accurate, precise, and reliable. Machines can be stacked into industrial shelves, coupled with other control systems to conduct multifactorial experiments, and adjusted to accommodate numerous pots of any size allowing for experiments with limitless specimen capacity in terms of height and specimen count. The system can be assembled in up to seven hours using off the shelf components and simple tools at a total cost of $1,276, in 2019 prices. A screening cycle can be performed as fast as every six minutes reducing variations in water content due to evaporation and thus creating precise control of soil moisture. As a validation of the long-term cyclic reliability of the system, the machine was run non-stop for 4480 loops; the equivalent to running an experiment for six months controlling water content every hour. By facilitating high throughput monitoring of soil moisture in pots, reliably and at low cost, this machine can facilitate the development of large-scale experiments on plant physiology.

Hardware name	**Inexpensive Modular Gravimetric Robotic Gantry Soil Moisture Screener and Controller**
Subject area	• Engineering and Material Science • Environmental, Planetary and Agricultural Sciences • Educational Tools and Open Source Alternatives to Existing Infrastructure • General
Hardware type	• Measuring physical properties and in-lab sensors • Biological sample handling and preparation

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Hardware name	**Inexpensive Modular Gravimetric Robotic Gantry Soil Moisture Screener and Controller**
	• Electrical engineering and computer science
Open Source License	CC BY 4.0
Cost of Hardware	*$780*
Source File Repository	*DOI URL to an approved source file repository:* Mendeley Data, https://doi.org/10.17632/zp9p6sr2fk.1

1. Hardware in context

Controlling the amount of water in the soil is a repeating task for any plant physiology experiment. Unfortunately, the high labor intensity of controlling water content by hand on individual plants or the high costs of available machines that makes automatization prohibitively expensive has considerably restricted the scope of experiments that are feasible. For instance, technological limitations to perform large multifactorial experiments have been highlighted as the key reason for our poor understanding of how plants will respond to a myriad of ongoing climatic changes [1,2]. With increasing greenhouse gas emissions, patterns of droughts, floods, and heat waves are changing considerably making the understanding of plants responses to climate change increasingly relevant in the fields of agriculture, modeling, and crop production [1–6]. Such insight can help to reveal not only crop varieties that are more robust and effective agricultural technology [4], but also indicate if plants can ameliorate or aggravate climate change [6]. Unfortunately, our understanding of how plants respond to climate change is still limited, arguably by the current technical challenges for handling large numbers of plants [1,2].

This technical limitation has not gone unnoticed with solutions ranging from open source hardware to full scale industrial automated greenhouse systems by interested parties in both academia and industry [7–12]. For example, robotic arms have been deployed to tend to plants on moving platforms in greenhouses [7] a precursor to the rise in "cobots" or collaborative robots proliferating in all sorts of industries today. The need for automated high-throughput maintenance of plants has some market validation with utility patents being filed for designs such as those by Dow [8] and the Institute National de la Recherche Argronomique INRA [12]. Readily available industrial systems such as Phenoscope [10], WIWAM [11], and Phenopsis [12] provide a proof of concept of high throughput gravimetric soil sensing similar to the design that Dow has patented with the added features of phenotyping specimens, further automating the experiment. These machines, however, remain expensive for broad use, particularly when a given experimental design calls for the use of multiple replicated machines.

2. Hardware description

Here we describe a robotic gantry that screens and controls water content in soil (Fig. 1A–F) while addressing barriers of 1) technical complexity, 2) accuracy, 3) precision, 4) reliability, and 5) cost that prevents the development of large experiments on plant physiology. The machine operates using the gravimetric method, in which by knowing the weight of dry soil, the machine can add water by weight until a desired soil moisture level is reached.

The machine consists of a set of two rails that constrain and guide the motion of a carriage along what we define as the X-axis. Above the rails, a frame of perforated square tubing and angle bar holds the pots (Fig. 1A). Two steel angle bars are placed facing each other, thus creating a two-base support for the pots (Fig. 1G). The machine can be configured with several pairs of angle bars to handle numerous pots simultaneously; from here on a pair of two angle bars holding pots is referred to as a column. Along a column, pots can be arranged in rows; pots in rows can be separated at any desired distance so long as pots are not in contact. The first row of pots in the machine contain known and non-variable weights that are used to calibrate the mass sensors each loop. The carriage carries two actuators that in turn hold a horizontal gantry with as many load cells (Fig. 1B) as columns on the machine. Load cells are located in the gantry in line with each column. Between each pair of columns, the gantry holds a water spigot (Fig. 1C) that is connected to a water tank, and in between there is a solenoid (Fig. 1D) that controls the deposition of water to the pots. The carriage is moved along the x-axis by a belt drive (Fig. 1E). Controlling the actuation and data collection of the robotic gantry is an Arduino Mega and subsequent support electronics such as relays and analog to digital converters (Fig. 1F).

Magnets along one of the rails in the x-axis (Fig. 1G), in combination with a hall sensor on the carriage, allows the user to configure the position of each carriage stop to be exactly underneath a row of pots. Activation of the actuators elevates the gantry, in turn elevating all pots in a row exactly above each load cell, thus allowing the microprocessor to quantify the mass of each pot. That process of mass quantification is applied in an infinite loop that starts by calibrating the load cells using the first row of pots, then measuring the mass of each pot in each subsequent rows, adding water by turning on the solenoid if mass is lower than the stored target mass for the pot or not watering in the opposite case. The steps in a loop are described graphically in Fig. 2; a URL to a video describing the operation of the machine is also provided in Fig. 2.
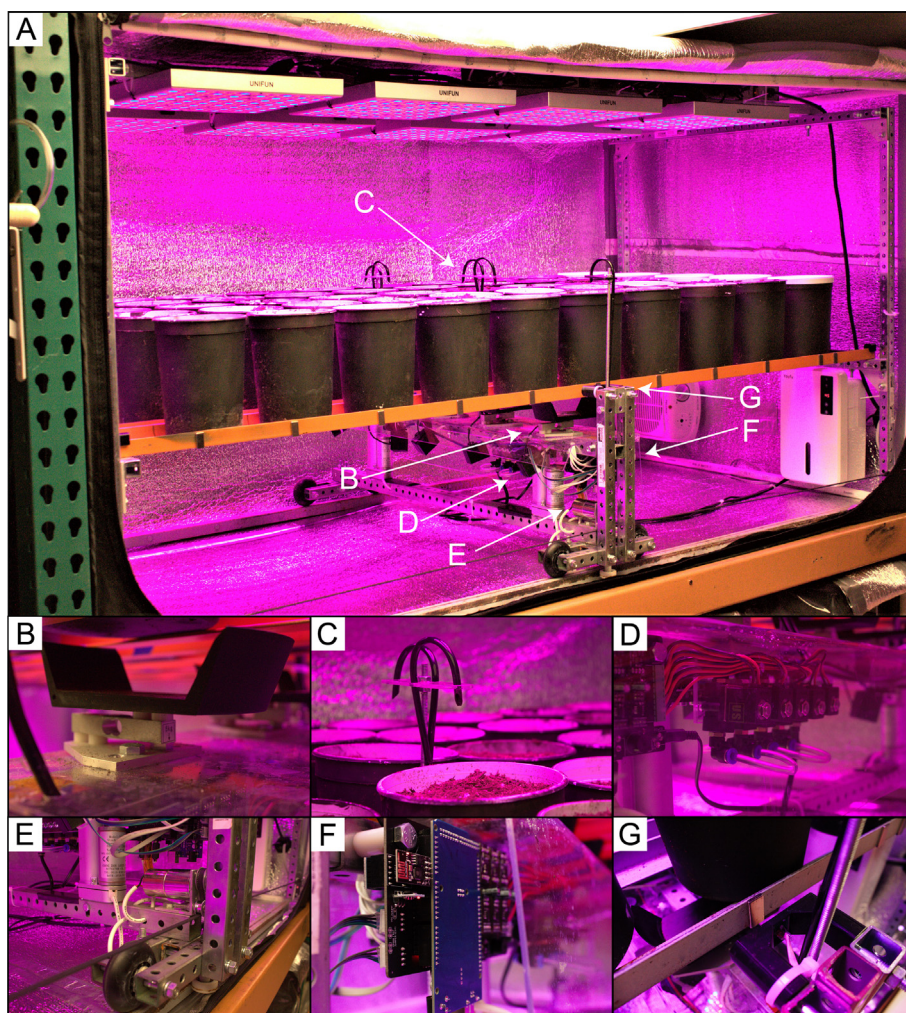
Fig. 1. The robotic gantry with subsystems called out. (A) Displays the overall system within a grow tent. (B) Displays the 5 kg strain gauges and 3D printed pot holder with a slightly inclined self-centering design to ensure pots remain separated, particularly while being weighed. (C) Demonstrates how water is piped to the specimens. Adding an angled cut to the tubing or a barbed fitting facilitates finer control of water distribution and minimizes overshoot and overall soil moisture variability. (D) Displays the solenoids for the hydraulic system. They are mounted as close to the water spigots as possible to reduce latency when depositing water. (E) Depicts the motors that raise the gantry and drive the belt. Shown in (F) are PCBs mounted to the chassis. (G) Shows the position of strong magnets on the angled steel and a Hall effect sensor that is triggered by the magnetic field of the magnets and indicates to the robot the location of a row.

3. Design files

In addition to the files listed in the table below, which provide specific illustrations to components needed to build the machine, we also provide an interactive CAD file that visualizes all the components of the machine: https://www.3dcontent-central.com/parts/download-Part.aspx?id=991185&catalogid=171

Design file name	File type	License type	Location of the file
Design File 1	*CAD, STEP*	CC BY 4.0	https://doi.org/10.17632/zp9p6sr2fk.1
Design File 2	CAD, Eagle	CC BY 4.0	https://doi.org/10.17632/zp9p6sr2fk.1
Design File 3	CAD, Eagle	CC BY 4.0	https://doi.org/10.17632/zp9p6sr2fk.1
Design File 4	Arduino	CC BY 4.0	https://doi.org/10.17632/zp9p6sr2fk.1

Design File 1 is The Robotic Gantry Assembly. This file is a 3D model STEP file. It contains all of the physical 3D modeled parts of the robotic gantry version described in this paper.
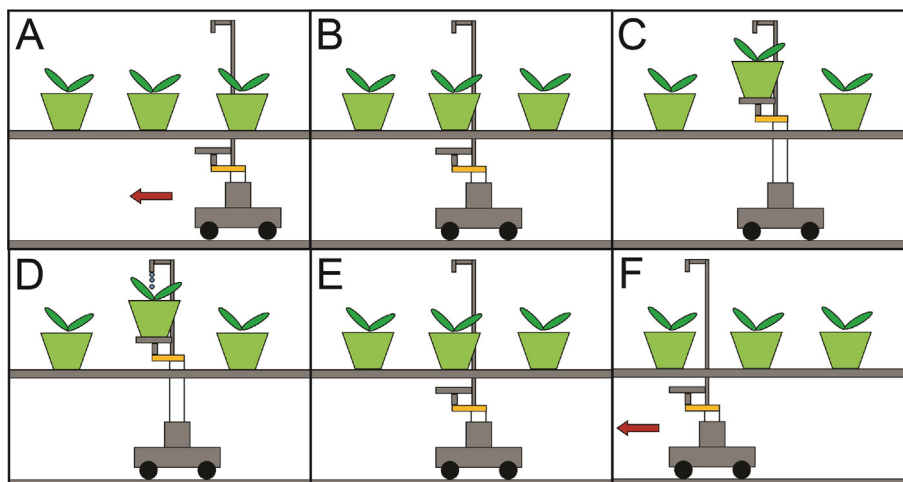
Fig. 2. Concept of operation of the robotic gantry. The water control process of the system begins with the carriage traversing on rails until a Hall effect sensor detects a magnet indicating that the machine has reached the row of specimens (A). The machine then halts allowing for vibrations to dissipate and then tares the scales (B). Two linear motor actuators then raise the gantry so that the pots are fully supported by the strain gauges (C). The mass is measured and water is deposited if the specimen's mass is below the desired value (D). The mass and time are recorded. The lift then lowers the specimens back onto the rails (E). The machine moves to the next row and the process is repeated (F). A video of the robot in operation can be viewed here https://youtu.be/eyWZc4_ce2I.

Design File 2 is The Arduino Shield PCB. This file is the PCB shield used to control the motors, the solenoids, and relays information to the Substation PCB to collect data from each strain gauge. The shield adjusts to an Arduino Mega. The file can be opened in the circuit board design software, Eagle.

Design File 3 is The Substation PCB. This is a small breakout board that houses the HX711 ADC, which amplifies the signal from the load cells, and it is connected directly to the strain gauge to minimize electrical noise due to long wires.

Design File 4 is the Arduino code. This file provides the Arduino code to operate the machine. The code is provided with comments on the margins to explain each line of command.

4. Bill of materials

The bill of materials is provided at https://doi.org/10.17632/zp9p6sr2fk.1. The estimated total cost for materials is $780. Few parts require simple machining; we estimated the cost of these custom machining at $300, while we estimated assembly labor cost at $US196 (two people times $US14 per hour times seven hours). The total cost for construction of the machine is estimated at $1,276 (Table 1).

5. Build Instructions

To fabricate the machine, we have separated its construction into four different components, each of which is described in detail in supplements 1 to 4.

They are: 1) the outer frame that holds the pots and the carriage, 2) the carriage, which carries the load cells and the water spigots, 3) the water system, which connects each water spigot to a water tank; water flow is controlled by a solenoid, and 4)

Table 1
Bill of Materials.

Category	Cost
Mechanical and Carriage	$ 233.08
Electrical	$ 141.94
Hydraulics	$ 12.59
Frame	$ 391.46
Total Hardware Cost	**$ 779.07**
Custom Machined Components	$ 300.00
Assembly ($14/hr, 7 hrs, 2 people)	$ 196.00
Potential Labor Costs	**$ 496.00**
Total Cost	**$1,275.07**

electrical system, which includes the microprocessor, which connects to the load cells to measure mass, actuators to control movement, and the solenoids to add water.

6. Cautions

The machine described here has been used in numerous trials in which occasional unforeseen mishaps occurred affecting the functionality of the machine. We have implemented corrective approaches in the machine to avoid the consequences of such mishaps:

First, on rare occasions the weight of certain pots were consistently higher or lower than their likely weight. This error occurred as a result of pots being too close to each other such that they were not fully free from contact while being weighted by the machine, thus affecting the reading by the load cell. The solution to this problem was to provide enough spacing among pots to avoid contacts, considering the growth of the plant later in the experiments such that future contact is also avoided.

Second, over time the actuators started to lean forward while lifting the pots. This was particularly pronounced when lifting heavy pots as any deviation from the center of mass forced an inclination. The problem here was that pots that were lifted with an inclination at times created contacts with neighboring pots; this being one of the reasons for the error mentioned above. To correct this problem, we attached two vertical bars on each side of the carriage that worked as guide for the gantry when it was elevated by the actuators. After this, the pots were raised vertically every time.

Third, at times all pots in a column we consistently offset from their actual mass by a certain amount. This occurred if the contacts mentioned above occurred among pots in the first row, which are the calibration pots. Basically, if the calibration was incorrect, all pots weighted by that load cell would be incorrect. To avoid this problem, we create a step in the procedure of the machine: after calibration, the carriage is brought down and raised again to measure the known load cell. In principle this works as validation of the calibration. Because the weight of the pots in the first row are known, after calibration, the weight of the pots in that row should be equal to the stored values for those pots. We implement a 1 g margin of error, as the criteria for validation. If readings of pots in the first row were smaller or larger than the stored value by 1 g, the machine will continue with the loop as described in Fig. 2. In the opposite, if the reading is larger than 1 g, an alarm is activated to call attention to the user about problems on a specific pot.

Fourth, in an early version of the machine, soil water content commonly exceeded the desired threshold. Basically, there was an overshoot of soil water content in which water was added faster than the machine was recording the mass of it. To reduce this overshoot, we added a spigot to the water outlet that deposits smaller increments of water and added a time delay to the opening and closing of the water valve to provide time for the machine to measure the mass before more water was added.

7. Operation Instructions

Once the machine has been built and the desired masses for each individual pot are set in the Arduino code (see supplement 4 for more detail), operation of the machine is relatively simple. First, all pots are filled with a known mass of dry soil, and positioned along each row indicated by a given magnet on the rail along the X-axis. The machine is then turned ON which will automatically add water to each pot until the desired water level is reached. Once the machine has completed a full cycle, the machine is turned OFF and seedlings planted in the individual pots. The machine is then turned back ON, and left running for the desired duration of the experiment. Upon culmination of the experiment the machine is turned OFF, and plants harvested to quantify specific parameters of plant performance (e.g., total plant biomass, size of stems, size of leaves, length of roots, etc.). Given the facility to manipulate numerous plants under the same conditions lends itself to harvest plants along the duration of the experiment to assess changes in specific variables of plant performance over time.

8. Validation and characterization

The extent to which our machine can be of broad use for experiments on plant physiology depends on how it compares in terms of price to readily available machines, while being easy to build, accurate, precise and reliable. Below we describe our machine in those four criteria.

8.1. Cost

Much of the limitation for automatization of monitoring and controlling soil water content in individual pots is the high cost of available machines. For instance, available machines with equal functionality to our robotic gantry to monitor soil moisture in tens to hundreds of plants, range in price from $109,000 to $204,000 (Fig. 3). Our machine went through multiple prototypes, at times to improve functionality and reliability, but also at times to reduce cost. Almost entirely the machine can be built with off the shelf materials, which considerably reduced the cost. As a result, the machine can be built for US$1,276 (Table 1). The value per plant controlled compared to other machines, for which data were available, was 7 times less than the lowest cost commercially available machines (Fig. 3). With the average grant size of organizations such as NSF being ~ 1
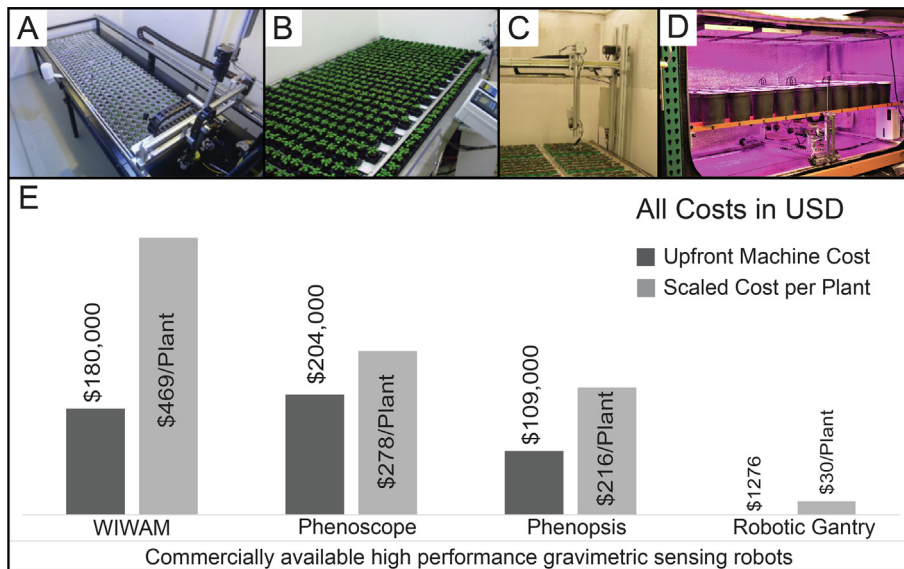
Fig. 3. Cost comparison of the robotic gantry to commercially available solutions. (A-D) Photographs of automatic plant growing machines. (A): WIWAM, (B): Phenoscope, (C):Phenopsis, (D):Robotic Gantry. (E) Prices of available machines. The cost of WIWAM was provided by S. Dhondt, Phenoscope by O. Loudet, and Phenopsis by M. Desigaux, data for 2017. Another system not showed here, PlantScreen, costs US$195,000 (S. Hunt, per. com. 2017). Cost per plant was estimated by dividing the price of a machine by the number of plants that the given machine can handle.

million dollars, the small cost of our robotic gantry suggests that high precision experiments involving soil moisture are now within reach to more organizations given available funding opportunities.

8.2. Easy to use

A common situation in biological experiments that require automated machines is that the research question is the motivation of a biologist, while the skills to build and use the machine normally rest on an engineer. This calls for projects that bring together biologists and engineers or alternatively machines that are simple to operate by people without prior experience. Our robotic gantry was developed with the later scenario in mind. To assess the complexity of assembling the machine, we asked seven groups of two to four people (children to adults), without prior experience of the machine, to assemble the robotic gantry following an already constructed version of it and measured the time it took each group to build the machine from a kit of parts until the machine was operational. Among groups, the average time of construction was 7 h (+/−30 min). Each machine constructed by the volunteers was run according to the Operation Instructions indicated above, and have operated normally for at least one year. These results indicate the easiness with which the machine can be built and the long-term reliability even when constructed by novice users.

8.3. Accuracy

As described, the machine loops through all pots, monitoring the water content of each pot and adding water to replace any evaporation or transpiration losses. As a result of this protocol, the time lapse to revisit a pot could create variations in soil water content due to evaporation or transpiration losses: the longer the time to complete a loop, the larger the likely error. This variability in water content around the given water threshold can be considered as an experimental error, which can have strong consequences for the results of a given experiment. We call this error accuracy and can be divided into two sources: 1) the capacity of the machine to measure the actual mass of a pot and 2) the capacity of the machine to sustain the same soil water content over time.

To quantify the first source of error, we performed a static mass experiment where the machine measured seven known masses ranging from 255.8 g (+/−0.1 g) to 3667.9 g (+/−0.1 g), which represents the range of pot masses our robotic gantry can handle. The seven masses were placed randomly within 42 available positions (7 rows, 6 columns) and the machine was set to measure the known masses over the course of 1024 loops. Fig. 4 is a violin plot of the results. We found that the robotic gantry yields mass measurements of known masses within + 0.3% and −0.1% error across the range of masses handled by the machine (Fig. 4). Individual masses exhibited much smaller error distributions with most distributions overwhelmingly contained in a range less than 0.1% (Fig. 4).

The period between measurements, or measurement frequency, is a critical machine parameter affecting the second source of error. During the time between measurements, soil water content can drop significantly below the desired
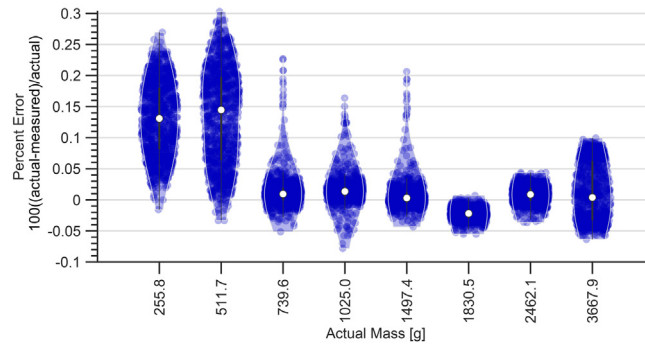
Fig. 4. Accuracy with which the robotic gantry can measure known weights. Depicted are the mass measurements of static known masses. Specifically, eight known masses that did not change in weight were measured by the robotic gantry over 200 replicated loops. The difference between actual and measured masses indicates the error in accuracy of the robotic gantry; the distribution of these errors are presented as violin plots. Across the range of masses that can be measured by the robotic gantry, accuracy error was within +0.3% and −0.1%.

threshold due to evaporation and plant transpiration. This error can be more pronounced in experimental settings with high temperature and low relative humidity that will rapidly dry out the soil. To assess the ability of the robotic gantry to accurately maintain a given soil water content over time, two soil water treatments controlled at three different time intervals were tested. The treatments were 10% and 90% soil water content controlled every 0.1, 6, and 24 h. The 10% soil treatment consisted of 15 g of water and 150 g of soil. The 90% soil treatment consisted of 135 g of water and 150 g of soil. The time periods were selected to get an insight into the errors due to water losses in cases when soil water is controlled at considerably different intervals (e.g., the robotic gantry can control soil water with periods as fast as every six minutes while available machines such as Phenoscope [10] control soil water content as frequently as every four hours and most lab experiments done by hand control water on periods of a day or more). The experiment ran continuously for 16.4 days and was held indoors at a relative humidity ranging from 47% to 61% with temperature ranging from 18.5C to 24.5C.

As expected, experimental trials in which soil water content is checked less frequently (e.g., every 24 h) resulted in considerably higher variations in water content than trials with more frequent control (e.g., every six minutes) (Fig. 5A). Fig. 5B–G illustrates the increasingly larger range of variation in soil water content with increasingly longer control intervals. This indicates the considerable experimental error of trials with long frequency intervals, as plants are exposed to water conditions considerably different from the set thresholds. By controlling water content at time intervals as low as every six minutes, our robotic gantry was able to reduce experimental errors due to water losses by up to 84% compared to trials in which water is controlled by hand or available machines. These results also enforce the importance of measurement frequency particularly during trials with high evaporation-potential treatments and environments.

8.4. Reliability

Plant physiology experiments commonly require the measurement of slow response variables such as growth, which often leads to long duration experiments. Even under the best test species, such as Arabidopsis, data on plant growth to maturity requires experiments to run for over two months. For such experiments, machines that perform without failing are critical to avoid unnecessary sources of error (due to the downtime the machine is broken, if failure is fixable) or the worst-case scenario of re-starting an experiment when the downtime is long enough to constitute a large source of variability to desired soil water levels. To test the reliability of the robotic gantry, we ran an experiment to control six different treatments of soil moisture non-stop for 4480 loops or the equivalent of running an experiment for six months if each pot was visited every hour. The machine operated without failure for the duration of the experiment. Further, by controlling water as fast as the machine can go through each loop, we found that the robotic gantry controlled any evaporation such that the desired soil water level remained virtually constant over the entire experiment (blue line in Fig. 5A). Overall, the test of reliability indicates that our machine can be operated reliably over the duration of traditional experiments on plant physiology.

9. Discussion

The scope of plant physiology experiments has been considerably limited by the lack of affordable automatization machines. In this paper, we described a robotic gantry machine capable of screening and controlling soil water content with high accuracy, precision, reliability, and low cost by comparison to analogous available machines. The capacity to modulate the amount of pots that can be handled by a single machine provides sufficient flexibility for studies with varying numbers of replicates or sizes of plants. Additionally, the machine has been designed to be easily stacked into commercial shelving (Fig. 6) and also enclosed into growing tents creating closed spaces in which variables like temperature and CO_2 can also be controlled. This isolation and control of other variables allows for the design of more complex factorial experiments. Further improvements to the machine should include the design of a water proof casing for the PCB circuits to prevent dam-
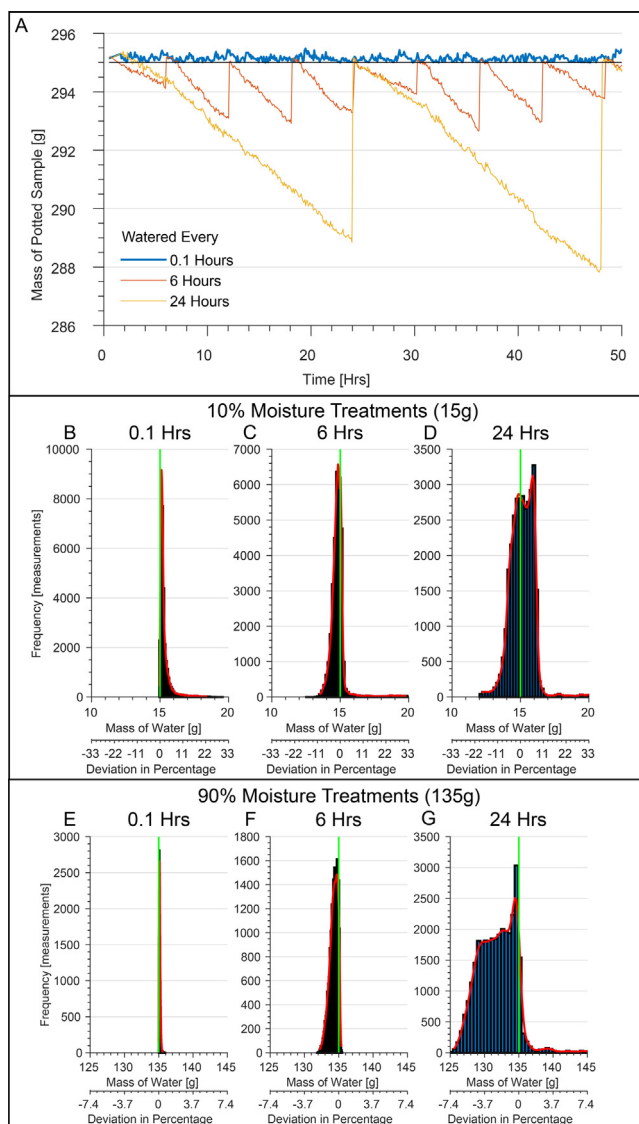
Fig. 5. The robotic gantry's accuracy over dynamic mass values. During experiments in which water content is controlled only sporadically the rate of evaporation can lead to considerable reductions in water content and exposing plants to conditions outside the desired treatment as opposed to experiments in which water is controlled more frequently. To test this experimental error, we controlled soil water content at 10% and 90% at time intervals of 0.1, 6, and 24 h. Plot (A) shows a case example of soil water content in three pots at a supposed treatment of 90% soil water content controlled every 0.1, 6, and 24 h. When water content is controlled every 0.1 h the treatment is maintained within less than 0.1% of the desired mass treatment (E). In contrast, when the water content is controlled every 24 h, evaporation reduced water content up to 7% below the target mass (G). With levels of statistical significance commonly set at 5%, errors in experimental control of water of 7% could be regarded as significant. Similar results were found when controlling lower soil water contents (B-D). These experimental errors could be considerably much larger under experimental trials including high temperature or low humidity, which can accelerate evaporation.

age if water spills or from condensation, the incorporation of photographic cameras to monitor plant growth over time, and web-connectivity for the purpose of monitoring pot measurements and functionality of the machine.

10. Human and animal rights

No animals were or will be used or handled for the building or operation of the described machine.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Fig. 6. Deployment of robotic gantries for carrying out large factorial experiments. In this setting, machines are stacked in commercial shelves, and enclosed into tents that allows for the control of temperature and CO_2 concentration.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ohx.2021.e00174.

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