A Thermoelectric Powered Quadruped Robotic System for Remote Monitoring of Geothermal Open Field Heated Gardens in Iceland

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Keywords

Thermoelectric generator, mobile robots, web security cameras, open field heating

ABSTRACT

The authors have developed and patented a thermoelectric-based point of use power system with no moving parts to produces 6 W of steady state power when attached to the outside of geothermal steam pipe. This system used has powered LED lights and a web interfaced video surveillance system while simultaneously trickle charging 12 volt 7000 mAh batteries. The generator is now powering robots. Three generations of robots were successfully tested. The first was an iRobot Create Programmable Robot with a Tekkotsu Calliope2SP platform. The second setup was highly maneuverable four wheeled robot that utilized a beacon positioning system. The last robot was a quadruped robot controlled by an Ardunio, which was designed and constructed by the authors to monitor their open field geothermal heated gardens in Iceland.

Introduction

Heated Gardens

The authors have developed an intensive open field heating system [3] in Iceland and New York City for green roofs using waste heat. The use of waste geothermal steam and steam condensate create longer growing seasons, greater growth, and harvestable out of region crops. Cotton has been grown in New York City and tomatoes, zucchinis, and oregano have had documented growth in Iceland using this system [9]. This system has the potential of reducing the need for green houses in some cases.

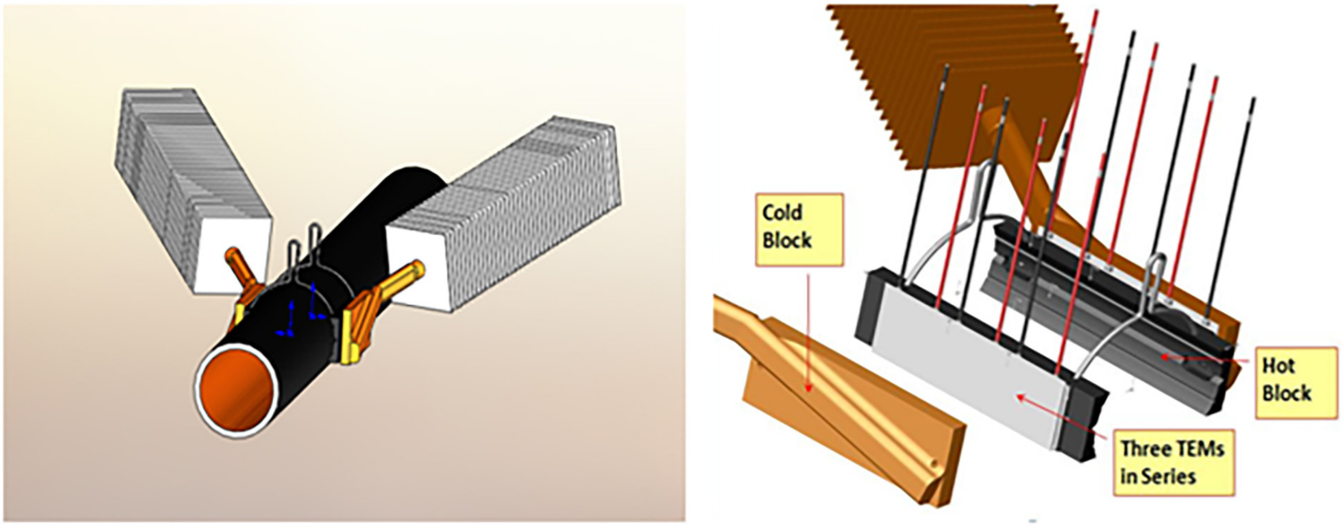
Data collection to determine the effects of these heated gardens and green roofs on plant growth is labor intensive. Constant monitoring is required to prevent damage from vermin and vandalism. The heated gardens and green roofs are also in relatively remote locations. A central monitoring hub with mobile robots provides many advantages.

The remoteness of these locations may present challenges for traditional power grid access. The authors have solved this problem by developing a thermoelectric generator. The thermoelectric generator is a standalone power source that can use geothermal and waste municipal steam sources to generate more than 6 watts of power at steady state.

Thermoelectric Generator

A test bed at the Cooper Union in New York City was used to evaluate different ambient and working fluid temperatures. The thermoelectric generator was attached to a steam pipe at 160°C and was used to power two microcontroller based security cameras, one with wireless LAN and another with cellular connectivity [8]. Additional testing of the PV voltage controller and the generator occurred in Iceland using a 100-120°C geothermal waste steam condensate pipe.

The authors' thermoelectric power generation system, shown in Figure 1, is a point of use power generation system. It produces power through the use of the Seebeck Effect, thereby eliminating the need for moving parts. No moving parts allows for a greater operational period for the generator. The Thermoelectric Power Generation Device is protected by European Patent No. EP 2 095 440 B1, United States Patent No. US 8,829,326 B2, and Canadian Patent No. CA 2671995.



b)The complete thermoelectric power system assembled on a pipe

a)An exploded view of the Thermoelectric Power Generator

Figure 1. CAD renderings of the thermoelectric power generation system.

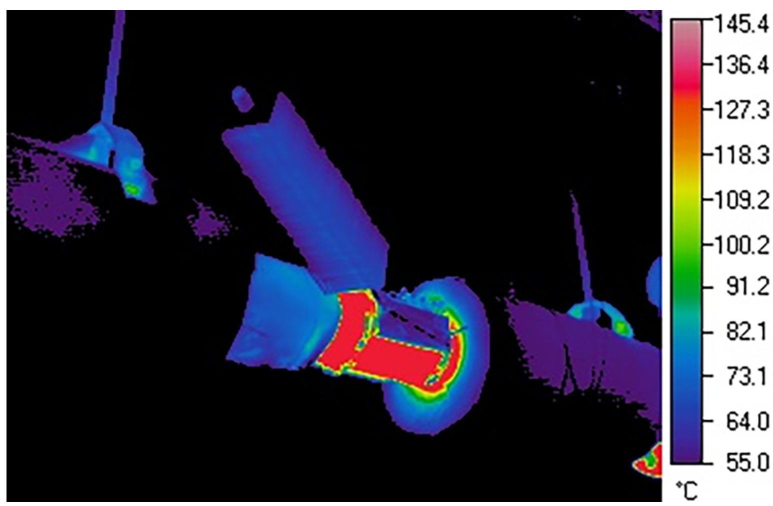


Figure 2. Infrared image of the thermoelectric generator installed on a steam pipe.

The generator consists of a mirrored assembly mounted on opposite sides of a pipe. Each assembly consists of three thermoelectric modules wired in series, a steel hot block, and a copper heat pipe system as a cold block.

The ThermaTEC modules (Laird PB23 Series, HT8, 12) have a high temperature range to accommodate typical steam temperatures [1, 2]. Thermoelectric modules are traditionally used as solid state heat pumps for cooling computers. When electricity is supplied to the thermoelectric module, heat is moved from one surface to its opposite side, creating a temperature difference. In a thermoelectric generator, the modules are used in reverse. When a temperature difference is created between the opposing sides, electricity is produced [5, 6]. Figure 2 graphically illustrates the temperature difference between the steam pipe (red) and the heat sink (blue).

A steady state 6.9 W was produced by the generator when placed on a 160 °C steam pipe in an ambient environment of 30 °C. A photovoltaic (PV) charge controller was used to facilitate the charging of 12 volt 7000 mAh lead acid batteries [1, 2].

Robots

The authors previously developed a patented thermoelectric-based point of use power generation system with no moving parts that has powered a web interfaced video surveillance system using cellular and wireless LAN security cameras [1,2].

The authors have also demonstrated the feasibility of using this system to power robots. These robots have enhanced the authors' previous stationary web accessible security and monitoring cameras [2] by providing the cameras mobility. The added mobility of the cameras and robotic arms mounted to the robots enable the remote physical access and manipulation of the environment. Routine maintenance tasks as well as emergency tasks in potentially hazardous environments can also be accomplished.

This implementation requires the use of trickle charged batteries to store the surplus energy from the thermoelectric generator. It enables tasks that require a higher power levels than the generator's current capabilities.

The first generation robot used was a Tekotsu Calliope2SP robotic platform with an iRobot Create Programmable Robot [paper citation needed]. It was selected due to its features including wireless communication, movable zoom cameras, mobility, and a variety of gripper arm features [3, 4]. The 2SP robot has a Home Base docking port for recharging.

The second generation robot was recently designed and developed by Research Assistants at the Center for Innovation and Applied Technology (CIAT) at the Cooper Union. This small robot had a higher ground clearance and was more maneuverable than the 2SP. It also used kinematic models and a beacon system.

The third generation robot is a quadruped robot designed and constructed by the authors at CIAT. It adds greater mobility because it can maneuver around the plants with minimal ground disturbance. Its main frame also has a much higher clearance that enables the robot to be directly over the plants. This can simplify future monitoring and potential harvesting tasks.

Methods and Materials

A controllable steam test bed was developed at the Cooper Union's Center for Innovation and Applied Technology is shown in Figure 3. It has an ESG Corporation 240 volt 3 phase SPEEDYELECTRIC 15A-2 electrode steam generator and an array of different diameter steam pipes in both horizontal and vertical orientations. This enables data collection over long periods of time with varying steam temperatures for steady state and transitory experimentation.

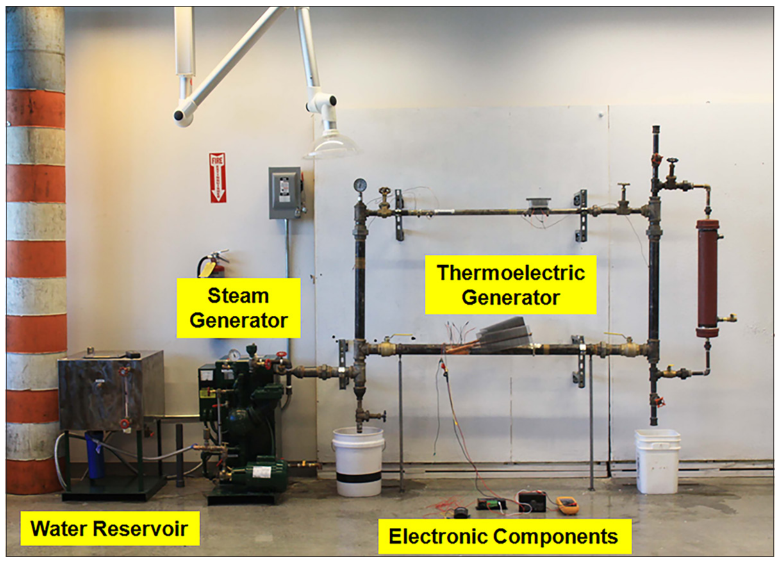


Figure 3. Steam test bed at CIAT.

In Iceland the authors have installed three thermoelectric generators. The first unit is shown on the left side of Figure 4 was installed at the Agricultural University of Iceland in Hveragerdi inside an old style unheated greenhouse. A steam condensate line with an average temperature of 100 °C is the heat source and the ambient temperature is often 15 °C and below.

The second unit shown on the right side of Figure 4 is at the Keilir Institute of Technology in Reykjanesbaer. It is attached to the building's geothermal hot water system. The hot water is usually between 70 and 80 °C. The ambient temperature near the generator is often 30°C and higher.

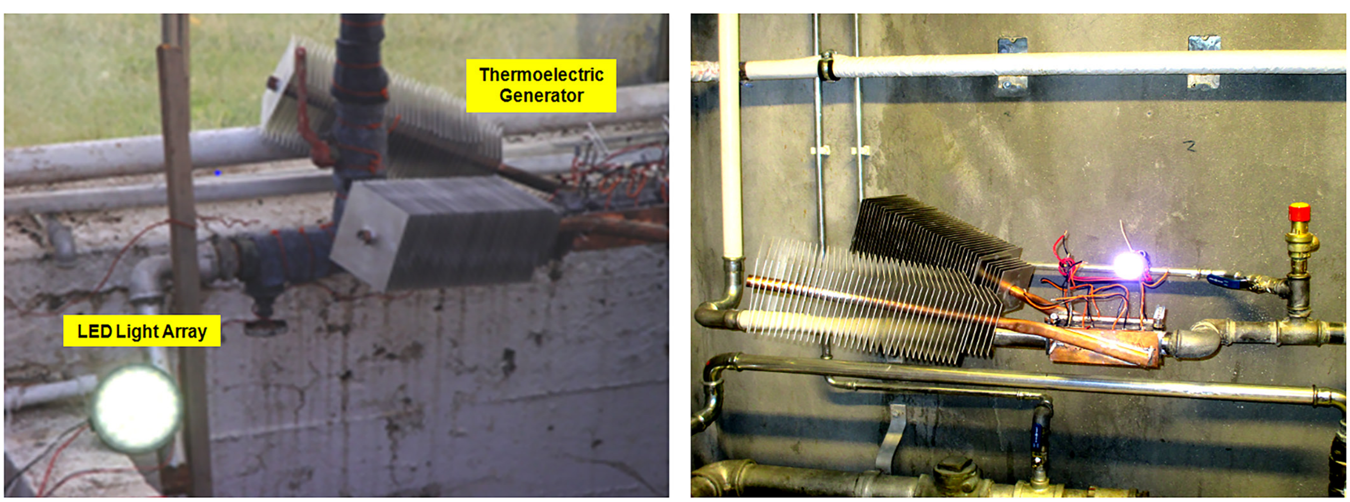


Figure 4. Hveragerdi greenhouse thermoelectric generator (left) and Keilir Institute of Technology thermoelectric generator (right).

The third thermoelectric generator is near the outside wall of the Hveragerdi greenhouse. It is attached to a geothermal steam pipe with a temperature of 140°C. The ambient temperature for this outdoor installation is obviously controlled by the weather. The generator as shown in Figure 5 was placed in a protective shed to prevent vandalism and to shield it from direct sunlight and precipitation.

The generator has been functioning since June 20, 2015. Figure 6 shows the steady state performance with a steam pipe temperature of 140°C and an ambient temperature of 25°C. The power produced is approximately 6 W using the calculations established in the authors' previous papers [1, 2, 5].

This power production is very close to that of the CIAT thermoelectric generator. Since both generators produce approximately 6 W, the potential applications are mirrored. The power available can obviously be increased by adding additional thermoelectric generators to the location. It should be noted that the thermoelectric modules are voltage sources like photovoltaic cells. Therefore, the voltage is additive, but the amperage remains fixed when wired in series. When wired in parallel the amperage does increase, but the overall power decreases [1, 2, 5].

Figure 5. Thermoelectric generator protective shed.

Charging System and Robots

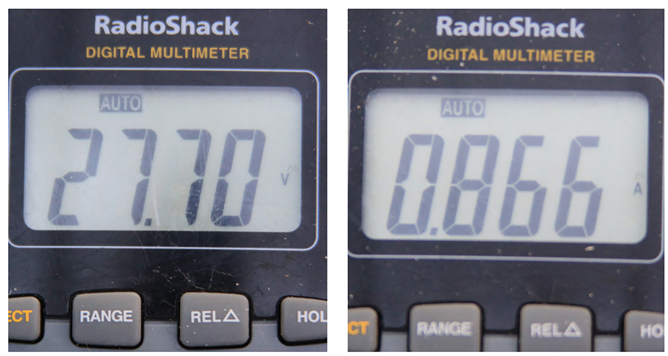


Figure 6. Hveragerdi outdoor thermoelectric generator short circuit voltage (left) and open circuit current (right).

A Photo Voltaic charge controller was used to stabilize the voltage. The Manson Engineering Industrial Ltd SBC – 7112 enabled a trickle charging of a Radio Shack Enercell sealed lead acid 12V 7000 mAh battery. Power stability was attained and the battery can also provide emergency power and a higher peak and stable voltage for a rapid recharging of the robots.

The voltage was regulated by an Arduino microcontroller. The 100W laptop universal adaptor steps up the DC12V supply from the battery to the 14V requirement to charge the Calliope2SP.

The Tekkotsu Calliope2SP robotic platform, as shown in Figure 8, is open source and written in C++. It runs the Ubuntu operating system.

The iRobot Create Programmable Robot is the 2SP's base. The robot base is fitted with a bump sensor to detect walls and four IR cliff sensors to detect the ground. An omni-directional infrared receiver detects IR signals and boundaries. An accelerometer detects if the robot is unstable and can potentially be used for positioning.

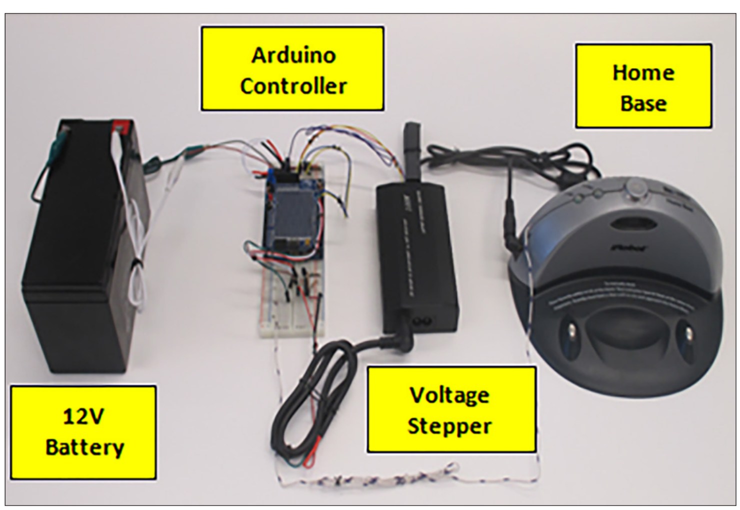


Figure 7. Charging System.

Figure 8. Callip2SP.

The 2SP's rechargeable battery is charged using the iRobot Self Charging Home Base. The robot's omnidirectional IR receiver detects the three infrared transmitters on the Home Base. The robot returns to the Home Base when the battery level is low. The 2SP is charged using a 12 V 7000 mAh lead acid battery that is trickle charged by the thermoelectric generator.

The 2SP has a Sony PlayStation Eye camera. It also comes with a gripper arm with two degrees of freedom. CIAT has developed a five degree of freedom arm that is more energy efficient. The 2SP also has a mounted portable router. The communication protocols allow the robot to be remotely accessed. A previous paper by the authors [9] discusses this robotic system.

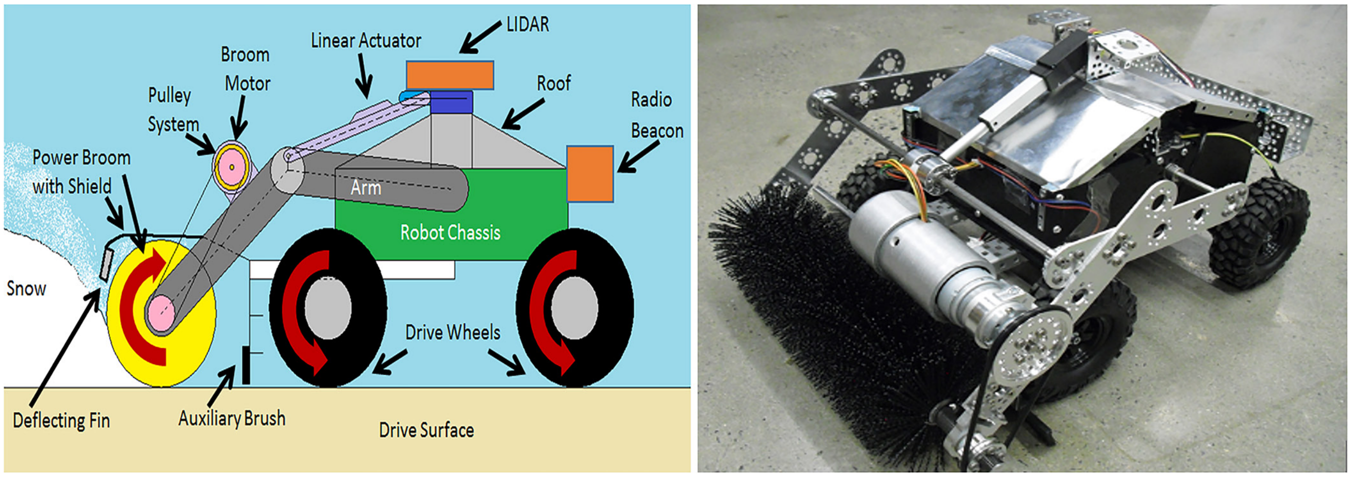


Figure 9. Second generation robot schematic (left) and operational prototype (right).

The second generation robot designed and developed by Research Assistants at CIAT is pictured in Figure 9. The robot has four wheels and an arm controlled by a linear actuator. The figure shows the robot equipped with an optional snow brush.

This robot has greater ground clearance, which allows it to go over small plants and obstacles while keeping soil disturbance to a minimum. It also has a beacon positioning system. A LIDAR collision detection system is being developed.

A kinematics model was created to control for position and orientation of the robot that uses three fixed ultrawideband ranging beacons. This positioning system, when combined with the camera, provides a level of redundancy and permits visual positioning refinements as needed. The operator can also rely solely on the beacon system to enable the automation of certain tasks.

The authors' two previous robotic generations provided a basic system that solved many of the initial design challenges. They also provided a basic proof of concept for a thermoelectric powered robot. The positive attributes of both systems can be incorporated in a quadruped robot that can ultimately be deployed in geothermal environments such as Iceland.

A quadruped robot, as stated, reduces garden damage and permits operations above low growing out of region plants that the authors have successfully grown outdoors in Iceland using their enhanced system of geothermal open field heating. A quadruped could also be used in a variety of applications where remote human access is difficult due to either geography or safety concerns.

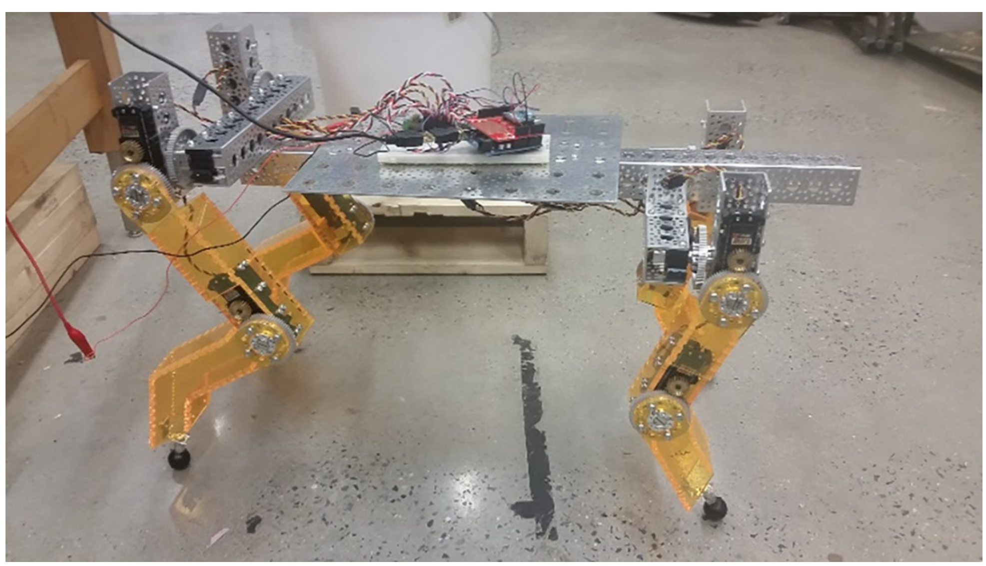


Figure 10. Quadruped robot.

CIAT Research Associate and co-author Nicholas Mitchell has led our team of researchers in designing a low power quadruped robot that can function using the thermoelectric generator.

Due to the specific design and power limitations and the required agricultural tasks, a robot specific algorithm was developed to accommodate the precarious problem of balancing and the need to protect the plants from damage. The quadruped was specifically designed with an inordinately slow gait to allow for the remote manipulation of the robot through the authors web-accessible communications systems that are powered by the thermoelectric generator.

Although obviously concerned with power consumption, traditional quadrupeds are not usually designed to move about small plants without inflicting damage. These unique challenges have resulted in this first generation quadruped as seen in Figure 10.

The body of the robot was constructed out of a 0.09 inch aluminum plate and aluminum channels. The channels give the body rigidity while the plate gives space to place the electronics. Aluminum was chosen because of its low weight and machining advantages.

The legs were made out of ¼ inch translucent acrylic. Acrylic was chosen to allow for rapid prototyping and easier electrical debugging by exposing wires and servos. Each leg has three HS-5685MH Hitec servos. The top leg joint rotates parallel to the ground and the next two rotate parallel to the plane that divides the robot in right and half planes.

The author's calculations for walking with the three joint legs that allows each leg to move independently throughout 3D space. The problems associated with lower number of degrees of freedom than a living quadruped required spherical ball feet. This ensures that the feet will maintain the desired direct contact with the ground regardless of the orientation.

To control all twelve servos, a Pololu 24-channel servo controller was used in conjunction with an Arduino Duemilanove. The Arduino calculates the positions necessary for each foot to reach while the servo controller handles the power consumption and servo communication. This isolates the power supply of the servos from that of the electronics to increase the quadraped's robustness.

The quadruped's servos are currently supplied with constant 7.2 V from a variable power supply (GW Instek SPD-3606). The electronics are powered separately by four AA batteries to provide the necessary 6 volts. Based on the performance of the 2SP and the power data for this robot, the thermoelectric generator will provide enough power to charge the battery packs and operate the robot.

To develop a walking algorithm, Denavit-Hartenberg parameters (DH parameters) and center of masses in local coordinate frames of each component was calculated. To allow for the greatest range of motion while maintaining a constant height, a standing height of 33 cm was used during testing. This is sufficient ground clearance to allow the robot to walk over most of the heated garden test cultivars.

Using the DH parameters, center of masses, and joint angle constraints, a walking algorithm was designed that always supports the weight of the robot on at least three legs. The robot's gait was designed to only shift weight from side to side. This simplifies and expedites the gait choosing process. The center of mass should always be some distance "d_{safe}" from the edge of the support polygon formed by the standing legs. For testing, a d_{safe} of 3 cm was chosen to ensure balance while stepping and to provide the longest stride.

Two algorithms were then computed in MATLAB and transferred to the Arduino using 4 cm and 8 cm step sizes respectively. For both gaits, the robot was successful in maintaining balance and in moving forward.

For this robot, a cycle is defined as the completion of a step by every foot. After 5 cycles, the 4 cm gait caused the robot to travel 26 cm while the 8 cm step gait resulted in 35.5 cm. Each cycle took 80 seconds, meaning that five cycles took six minutes and forty seconds to complete. The steps formed a straight line as desired.

The average energy consumption of the 4 cm gait was 183 J (0.0508 Wh) per cycle and the average energy consumption of the 8 cm gait was 213 J (0.0592 Wh) per cycle. As a comparison, holding the starting standing position for 20 seconds consumes 16.8 J.

The 8 cm gait travels 36.5% faster than the 4 cm gait at a cost of 6.4% more energy required. The 4 cm gait consumes 703 J/meter traveled and travels at a rate of 19.5 cm/minute whereas the 8 cm gait consumes 600 J/meter traveled and travels at a rate of 26.6 cm/minute.

Results

The 2SP robot established the thermoelectric generator as a reliable power source for recharging its batteries. The more efficient five degree of freedom arm provides the opportunity for a variety of agricultural maintenance tasks.

The beacon system of the CIAT robot enables automatic tasks and provides a backup system for positioning when the robot is remotely controlled.

The quadruped robot has greater mobility than the two earlier iterations. The Iceland gardens measure 10 m x 10 m. When the quadruped makes 5 round trips down the rows of the garden, it travels 100 m. This would take the quadruped robot approximately 8.5 hours using a 4 cm stepping gait. An 8 cm stepping gait would take about 6.25 hours.

Assuming that the battery used for the servos was a 3000 mAh battery with a 7.2 voltage, the robot would have enough energy to move for 9.4 hours which is a distance of 110 m using the 4 cm gait. The 8 cm gait would have 8.1 hours or 129 m of travel. The charge time for the robot batteries would be 3 to 5 hours based on data from the 2SP robot.

Conclusions

The research has demonstrated that the thermoelectric generator can power surveillance systems without a grid access. Unlike battery systems the thermoelectric generator's efficiency improves rather than degrades with decreasing ambient temperatures. This makes the thermoelectric generator an excellent option as a power source in colder climates such as Iceland. The system presented in this paper thrives in colder climates that can severely impede the performance of traditional battery systems.

The 2SP and the CIAT robots provide basic operational platforms that can successfully complete a variety of generic tasks. The quadruped was specifically designed for the authors' open field heated geothermal gardens. The new outdoor thermoelectric generator in Hveragerdi provides sufficient power for monitoring, communicating, and powering robots.

The quadruped needs additional research and design refinements before it can be fully functional in field conditions. It does provide a reliable platform for further experimentation.

When the needed refinements and specific task definitions are determined, the robot's design should be more robust. The robot and its charger could be shielded from the environment using an enclosure resembling a typical dog house. The authors will continue developing the systems and would welcome assistance in commercializing this interesting solution.

A quadruped robot powered by the thermoelectric generator could be adapted for a variety of applications and tasks where remote human access is difficult due to either geography or safety concerns.

Acknowledgements

The authors acknowledge the support extended by the following organizations: The Cooper Union for the Advancement of Science and Art, Center for Innovation and Applied Technology, The C.V. Starr Research Foundation, Agricultural University of Iceland, University of Iceland, Keilir Institute of Technology, NLFI clinic, Hveragerdi, GRUND nursing home, Garðheimar Gróðurvörur ehf, Hveragerdi, Town of Reykjanesbaer, C.V. Starr Research Foundation, SET ehf, Reykjanesbaer and Metropolitan Building Consulting Group.

Special thanks: to Mark Epstein Teresa Dahlberg, George Delagrammatikas, Yash Risbud, , Willaim King, Robert Hawks, Thomas Francullo, Ken Kaplan, Courtney Meaney, Joe Donnelly, Gudridur Helgadottir, Sverrir Gudmundsson, Elias Oskarsson, Orn Einarsson, Stefan Sigurdsson, Gísli Páll Pálsson, Tryggvi Thordarson, Gudridur Helgadottir, Haukur Ingi Jonasson, Fridrik Brekkan, Magnus Thor Jonsson, Paul Shepard, Olafur Petur Palsson, Tryggvi Thordarson, Krista Hannesdottir, Orn Einarsson, Josephine Aramando, Ed Ecock, Gerry Posner, Mary Lynch, George Sidebothham, Kevin Bone, Scott Bondi, Christina Stadler, Björg Árnadóttir, Lisa Frigand, Ken Kaplan, Alex Bronfman, Kelly Smolar, Beatrix Erler, Carmelo Pizzuto, and Julio Santillana.

The authors appreciate the contributions of Center for Innovation and Applied Technology and Laboratory for Energy Reclamation and Innovation Research Assistants: Hou Chong Chan,Issei Abraham Yamada, Wei Yan Tin, Chengyin Jiang, Yueyue Li, TaeKoung Lee, Harrison Milne, Romaniya Voloshchuk, Monica Chen, Jordan Selig, Ashish Pokharel, Matthew Cavallaro, Tina Elias, Karan Singh Gill, Ben Greenberg, Aman Grewal, Gisel Orzondo, Jainqin Wang, HaKyung Yoon, Mengxi Shi, Rose Carla Guerrier, Nicolas Mitchell, Peter Ascoli, Judy Wu, Mimosa Miller, Malcolm Dell, Russel Sternlicht, Subashis Paul, Jake Presky, Kemi Adeyeba, Brian Theodor, Anthony Morris, Diana H. Lee, Franklin Chu, Lukman Osi, Gene Tabach, Rohan Chauhan, Rene N. Makrinos, Natalie Mayslich, Cathy Hagan, Chrystina Sorrentino, Alice Yang, Anthony Sanfilippo, Leticia Lew, Carolina Condraco- Quesada,Victor Chen, Bobby Yankou, Nicholas Powel, Kyle Ng, Jessica Chu, Daniel Gologorskiy, Eric Ginzberg, Taylor Knoblock, Melody Ma, Sara Nodroff, Subashis Paul, Nick Rotella, Matthew Schoen,Yelena Ilin, Samantha Massengill, Takuya Otani, Gina Magnotti, Samantha Massengill, James Baker, Kimberly Wong, Chrystina Sorrentini, Michael David, Wo Chen, and Constantine Georgantzas.

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