

Investigation of Power Sources for the Polar Seismic TETwalker

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Abstract—The TETwalker robot was created by NASA Goddard Space Flight Center for space exploration. The goal for this project was to merge the TETwalker platform and technology with seismic surveying to acquire polar seismic data in an innovative fashion. The first objective of this project was to identify reliable power sources for a swarm of TETwalkers. By integrating multiple power sources like solar, wind, and vibration with the TETwalker design, this would make an excellent polar seismic data acquisition robot. The second objective was to adjust the design to accommodate the necessary power sources, along with their size and weight requirements.

I. INTRODUCTION

For the past five decades, many scientists have been interested to learn about the changes occurring with the ice sheets. Ice sheets have become an important factor in predicting sea level rise. Extensive research and exploration of polar regions enables scientists to validate the various changes of the ice sheets, but human participation is limited due to the extreme wind and harsh conditions. Collecting data is exceptionally difficult in polar environments. Human involvement can be reduced by using robots to assist them with the dangerous task of collecting data in harsh, polar environments. Collecting data takes many hours of work and, with the aid of robots, data could be collected in a more efficient and safe manner. There are many unique challenges for robots in polar regions, including the low temperatures, high winds, hazardous terrain, and extensive distances.

This paper describes the various renewable power sources that could be used for the Seismic TETwalker. Renewable power sources are important because discovering an adequate power source will increase the TETwalker's lifetime, mobility, and functionality by having self-sufficient power sources. One or more power sources can be utilized on the TETwalker to provide ample power. Some power sources can utilize the polar environment, such as solar and wind, for increased survival. Many power sources **may** be combined to harvest energy from the polar environment as well as from toppling.

II. BACKGROUND

The Center for Remote Sensing of Ice Sheets (CReSIS) is an organization focused on studying ice sheets **and** investigating the effect of **climate change** on sea level rise [1]. Together with NASA Goddard Space Flight Center (GSFC), CReSIS is proposing to develop and test a Seismic TETwalker robot capable of recording polar seismic data. **Another proposal is to develop a swarm of TETwalkers that could form a seismic array and record data.**

A. TETwalker Robot

The TETwalker is a tetrahedral-shaped robot, developed at NASA GSFC, capable of climbing over rough terrain [2]. Fig. 1 shows a simulation image of a 4-TETwalker, composed of spheres for nodes and adjustable-length struts. Compared to other wheeled and tracked robots, the TETwalker has a major advantage since its abilities include toppling, climbing, and scaling up variable terrain [8][9]. The TETwalker is flexible and changes shape by altering its center of gravity. The TETwalker can be a valuable asset to the field of seismic serving by autonomously deploying seismic sensors in rough terrain. It allows collection of high resolution data from a broadband seismometer or from several inexpensive geophones.

The TETwalker eliminates some of the challenges robots encounter in cold regions due to its structure. Its main deficiency is the need for self-fueling and power redundancy for long-term survival.

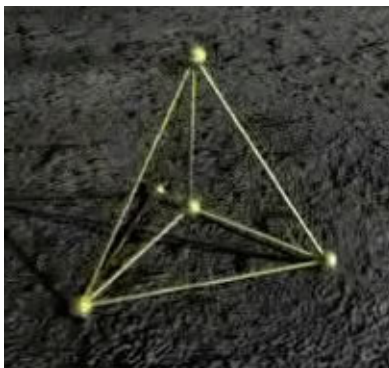


Fig. 1: A simulation image of the tetrahedral-shaped 4-TETwalker with center payload node [2].

B. Seismic Sensors

Seismic sensors are devices that can detect vibration echoes from the Earth [3]. These vibrations can be natural (passive) or artificial (active). Artificial vibrations are created by using small **explosive** charges are drilled into the ice causing a burst of vibration. Seismic sensors are very sensitive and can detect different levels of movement and wave frequencies based on their specifications. They are available in different styles and models which are used for snow, sea, and land exploration. The velocity of the **subsurface of the ice sheet** is measured by the echo response time to the geophone. Seismic sensors use echo strength to recognize how strong and weak the subsurface material is. They can acquire subglacial data, give readings on ice sheet flow, and show potential melting at the base of an ice sheet. This assists in creating an accurate graphical representation of the Earth's subsurface geologic structure.

Geophones are a type of seismic sensor that are used on hard surfaces such as ice, concrete, or land. These sensors are aligned in a grid and buried slightly, inserted into the ground, or rest on the Earth's surface [15]. Geophones are active seismic, which requires a primary vibration source to detect wave frequencies. They are typically used for oil exploration and **subsurface imaging**. However, broadband seismometers use passive seismic, meaning that they constantly monitor and record vibrations. These are typically used for monitoring earthquakes and acquiring geological data. Seismic sensors can detect vibrations from water, ice, and rocks.

C. Polar Seismic Acquisitions using the TETwalker

The TETwalker's architecture allows it the ability to travel over many different obstacles and terrain, which can assist in seismic surveying in polar environments. Most current wheeled and tracked rovers are semi-autonomous in terms of robotic control; however, the TETwalker could be fully autonomous using no human intervention [10]. The TETwalker robot allows recording in previously unreachable terrain where wheeled and tracked robots would not be able to **reach**. By integrating seismic sensors into the TETwalker, this will enable a swarm of TETwalkers to gather seismic images of the polar subsurface.

D. Energy Harvesting

Energy harvesting plays a major role in converting environmental resources into useable energy, and occurs when energy is captured and then stored. **The common sources of energy harvesting are mechanical energy, thermal energy, light energy, electromagnetic energy, and natural energy.** The first example of energy harvesting is utilizing energy from wind, which is converted from kinetic energy into electrical energy. The second example of energy harvesting is extracting energy from vibrations and then converting this mechanical energy into electrical energy. These energy sources may be possible solutions for finding an adequate power supply for the TETwalker. Energy harvesting will improve the use of a limited battery system in the TETwalker design.

III. POWER SOURCE TYPES

This section contains discussions on utilizing solar power, wind power, and vibration power in the Seismic TETwalker design to increase its lifetime and power supply for polar seismic surveying.

A. Solar Power

Solar power is gathered using the radiation from the sun, and can be converted into other forms of energy such as heat and electricity. Photovoltaic cells are devices that convert solar energy into electricity. By using photovoltaic material such as silicon, the TETwalker can directly convert sunlight into electricity. When sunlight beams on the photovoltaic panel, electrons scatter, and this creates an electric current that can be captured and stored. There are two major challenges with using solar energy: (1) how solar energy reaches the Earth's surface and, (2) the area needed to collect it at an adequate rate.

As incoming solar radiation travels through the Earth's atmosphere, approximately 6% of the incoming radiation is reflected and another 16% is absorbed into the Earth's surface [4]. Atmospheric conditions like clouds also reduce the incoming solar radiation by 23%, also causing the light to scatter [4]. One of the disadvantages of using solar power is not being able to gather energy at night or on very cloudy days when the sunrays are being blocked. Polar environments are characterized by long periods of complete darkness (six months) and weather that can affect visible sunlight. The polar regions have a higher level of albedo (reflectivity) due to the predominantly white environment and snowy/icy surface. Experiments on a similar polar solar-powered robot (1 cubic meter in size) showed that it could operate most efficiently when the sun's elevation was above 16° and under clear skies in a polar environment [11]. Assuming each face of the TETwalker is a 1 meter equilateral triangle, the surface area of each face is $\sqrt{3}/4 \text{ m}^2$, for a total solar surface area of $3\sqrt{3}/4 \text{ m}^2$ for the 3 solar faces (one face is left open for geophone deployment). However, not all faces will be exposed to direct sunlight **due to the orientation of the TETwalker with respect to the angle of direct sunlight**, which would reduce the amount of possible solar energy that can be gathered during deployment.

Durability is another challenge that solar panels might encounter on rough terrains and in extreme cold. The solar panels have to be durable and flexible enough to travel across rocks, sastrugi (wind sculpted snow and ice), and other variable polar terrain. PowerFilm Solar is one solar panel option that is rollable, flexible, sheet-like, and lightweight to undergo this task [5]. Fig. 2 shows an image of a PowerFilm solar panel.

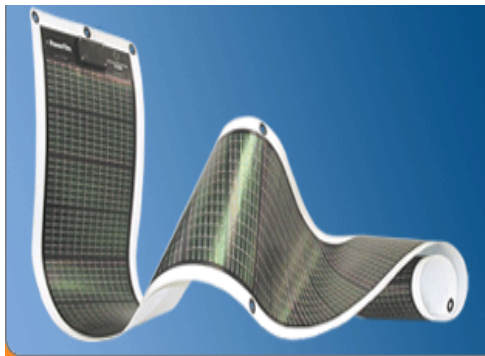


Fig. 2: Flexible and rollable PowerFilm solar panel [5].

PowerFilm solar panels can function in diverse conditions, and cloudy environments. For example, a laptop can be powered for $2\frac{1}{2}$ hours with an operating voltage of 15.4V and an operating current of 1.2A with just 5 hours of direct sunlight using the PowerFilm solar panel.

Energy storage is a challenge that can be solved by using a battery for storage. When storage capacity is

at a maximum, the TETwalker can be directly powered by solar panels. If the solar panels cannot supply enough power in the time needed, the battery can be used. Small batteries will be located in each of the nodes adjacent to the solar panels. This gives the TETwalker a back-up source of power at all times. Solar panels have will have two different purposes: 1) provide power and, 2) act as an environmental chamber to provide wind protection for the internal sensors and components. **The photovoltaic material will be placed on all three sides of the TETwalker, but the side with the geophone deployment will be left uncovered to reduce complexity.** The protection of the sensors is significant due to wind noise interference causing data corruption. Fig. 3 shows how solar power can be applied to the TETwalker and also act as wind protection.

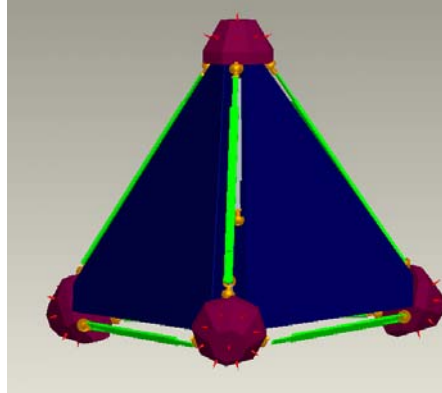


Fig. 3: TETwalker with solar panels (blue), ground nodes (maroon), and struts (green).

B. Wind Power

Wind energy has several characteristics that make it attractive as a power source. It is abundant, inexpensive, and widely distributed in polar environments. Wind energy can be sustained over a long period of time because wind can be collected during any season or time of the day. Wind power has a big advantage over solar power because solar power needs a direct source of sunlight. Wind energy can possibly give the TETwalker a sufficient amount of power and be used for recharging the TETwalker's power supply. Utilizing both solar and wind power would be another focus for the TETwalker to be operational in all polar seasons. This is just one of the preliminary ideas of an adequate power source.

Exact power specifications for the Seismic TETwalker are not yet fully determined. We are currently investigating different power sources for the TETwalker's unique architecture. Utilizing a wind power turbine is a strategy for this power option. The design of the wind turbine can be either horizontal or vertical. The vertical wind turbine appears to be the most beneficial design for the TETwalker as it doesn't need to be aligned with wind direction. Fig. 4 shows an image of a vertical and a horizontal wind turbine.

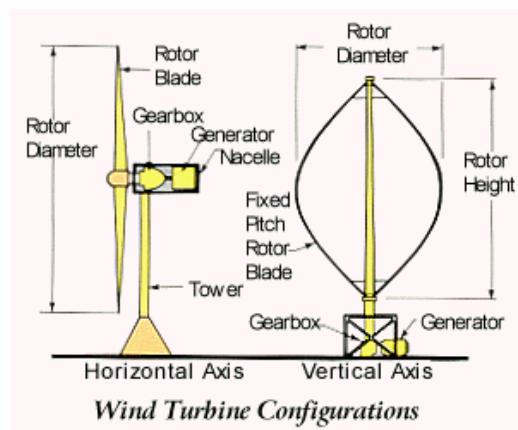


Fig. 4: Detailed diagram of vertical and horizontal wind turbines [6].

The wind turbine blades could be flexible enough to allow it to be pulled down into the top node or strut. The turbine shaft could be placed into a strut with the same lowering and raising capabilities. The wind turbine's electrical storage would be located in the top node along with the turbine blades. The generator would be small enough to be placed into the top node or center node of the TETwalker. Fig. 5 displays the wind turbine applied to the TETwalker, which is only extended during deployment and put away during mobility. The large challenge with this design is the need for the wind turbine to be flexible, which may become brittle and unreliable in extreme cold.

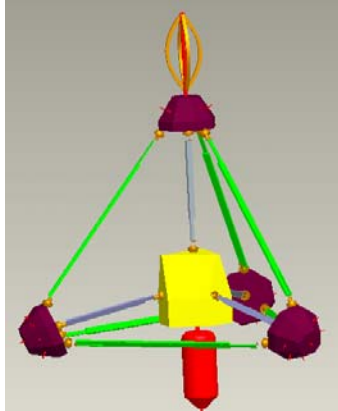


Fig. 5: TETwalker with the wind turbine concept applied to top node (red and gold), along with the science node (yellow) and deployed broadband seismometer (red)

Wind is controlled by many different factors like tides, atmospheric pressures, and temperatures. Wind energy has two disadvantages: 1) not having a constant high wind velocity and, 2) an efficient way of collecting the wind energy at all times. Wind is not always predictable and there could be a chance of slow, weak, and inadequate wind speeds occurring. Even though wind is a renewable source of energy, we are still researching on how to collect wind energy more efficiently with smaller devices.

For instance, we can calculate the wattage of a vertical wind turbine will produce under certain conditions. **Wind speeds can typical reach a maximum of 50 mph in polar environments. We conducted the trade study using the maximum wind speed and divide the maximum wind speed to obtain a minimum wind speed for a comparison.** This example assumes a constant wind speed of 50 mph. A vertical wind turbine with a rotor radius of 3 inches should produce 127.5 Watts of power [6] according to its equation [16]. Table 1 displays the trade study of rotor radius versus resulting power at two wind speeds.

25 MPH Wind		
Rotor Diameter (ft)	Power (Watts)	Two Week Period (Kilowatts)
0.5	63.78125	21.4305
0.41	42.8865125	14.4098682
0.33	27.7831125	9.3351258
0.25	15.9453125	5.357625
0.167	7.115181125	2.390700858
0.0833	1.770284311	0.594815529

50 MPH Wind		
Rotor Radius (ft)	Power (Watts)	Two Week Period (Kilowatts)
0.5	510.25	171.444
0.41	343.0921	115.2789456
0.33	222.2649	74.6810064
0.25	127.5625	42.861
0.167	56.921449	19.12560686
0.0833	14.16227449	4.758524229

Table 1: Trade study of rotor radius versus resulting power

for vertical wind turbine at 25 and 50 MPH.

Another challenge with using wind power is the space, height, and weight of the wind turbine. The TETwalker has only a limited amount of space in each node and strut to accommodate a wind turbine. Due to the challenge of freezing and damage, another location for the vertical wind turbine is on the deployment strut itself. Fig. 7 shows two wind turbine designs for the deployment strut of the TETwalker.

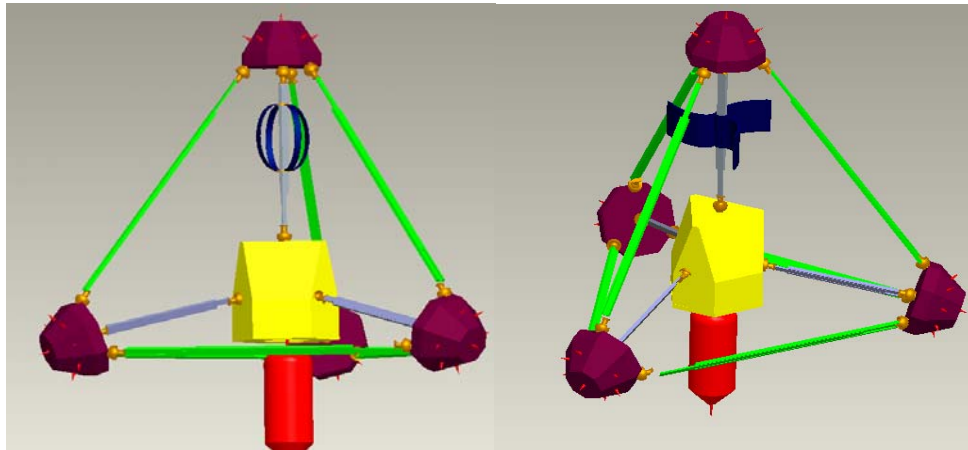


Fig. 7: Two wind turbine designs for the deployment strut: vertical (left) and horizontal (right).

C. Vibration Power

As the TETwalker topples for mobility, it can harness energy from the resulting vibrations. Wind is another natural vibration source that contributes a small amount of vibration frequencies depending on wind speed. There are two types of vibration: 1) free vibration and, 2) force vibration. Free vibration occurs when there is an original contact and the mechanical system is triggered. Vibration frequencies start from one and continue to increase until the frequencies begin to decrease down to zero. Force vibration occurs when a mechanical system has an altering force or motion applied. The frequency of vibration is solely dependent on the frequency of the initial motion or force. The magnitude of the vibration depends on the behavior of the mechanical system.

The TETwalker will be using force vibration since it has the capabilities of altering its center of gravity to topple and hit the ground. Another strategy is to use a micro-machined electromagnetic generator [12][13][14]. As the coil vibrates between four magnets, the magnetic circuit takes the given vibrations and amplifies them to produce power. For example, the electromagnetic generator produces 120 nW of power from frequencies between 1.3 and 9.5 kHz [7]. Individual micro-machined electromagnetic generators only provide a small amount of energy which may not be enough for the TETwalker. Fig. 8 shows the initial design of the micro-machined electromagnetic generator.

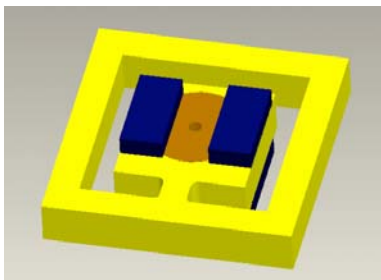


Fig. 8: Detailed design of the electromagnetic generator, including a coil (brown) placed between four magnets (blue) surrounded by a silicon structure (yellow) [7].

The electromagnetic generator is 100 mm^3 and is able to fit inside one of the nodes of the TETwalker. Fig. 9 shows several micro-machined electromagnetic generators in the same node, which can be repeated for all ground nodes of the TETwalker for increased power.

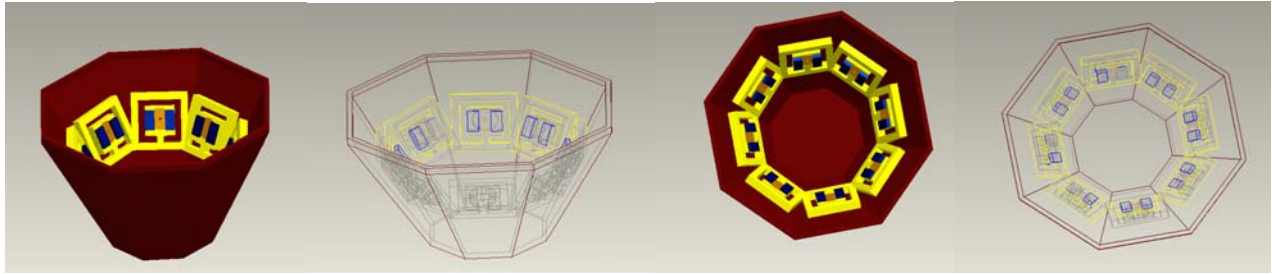


Fig. 9: Views of a ground node with several micro-machined electromagnetic generators mounted inside.

Surface texture contributes **to the amount of vibration that the TETwalker topples**. Hard surfaces that contain more ice rather than snow will generate stronger vibrations compared to soft surfaces. In order for vibration power to be valuable to the TETwalker, it requires hard surfaces. Inconstancies surface texture may cause insufficient source of vibration energy. Surface temperature has major effects on the micromachined electromagnetic generators in the bottom nodes of the TETwalker. As the surface is extremely cold, the nodes and internal components may freeze and cause failure of the micro-machined electromagnetic generator. Thus, temperature regulation may be necessary.

IV. COMBINATION OF POWER SOURCES

One or more power sources can be used on the same platform for the TETwalker design. The first design was to use only vibration energy as a power source. By using all three power sources (solar, wind, and vibration) at the same time, we conclude that these power sources would give the TETwalker enough power to perform the majority of its actions. Vibration power will be in the ground nodes, wind power will be located in-between the top node and the center node (part of the deployment strut), and solar power will be located on all 3 faces of the TETwalker by using flexible solar panels excluding the surface that is used during deployment. Fig. 10 shows a diagram of the TETwalker with all three power sources being used during deployment.

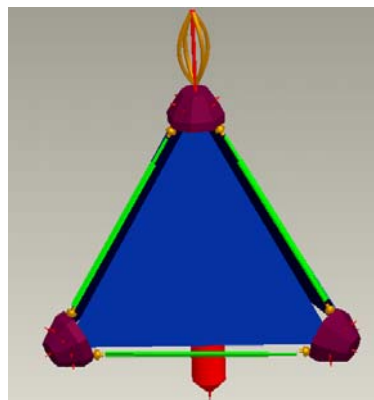


Fig. 10. TETwalker model with all three power sources being used during deployment.

V. CONCLUSIONS

Power sources provide the TETwalker with necessary energy to be mobile and survive longer in the polar environment. Some of the investigations of power sources have proven that they are insufficient to use in the TETwalker's architecture. All three power sources must be able to withstand temperatures below -40°C and contact vibration. Solar panels are likely too brittle and could break under freezing temperatures. The

vertical wind turbine has a possibility of encountering damage from harsh wind and freezing temperatures. Vibration power has the most potential of being an adequate power source out of the three studied based on the architecture of the TETwalker and its unique form of mobility. As the TETwalker topples, it can gain energy to power itself. To prevent freezing, rugged and durable materials must be used in the ground nodes. Placing generators in the ground nodes can help reduce the chance of failure by exposure to the harsh environment.

Further investigations will take place with respect to finding other adequate power sources such as hydrogen extraction, use of ferroelectric materials, and future wireless power. A trade study will be conducted of the various power sources with respect to the polar environment. In this trade study, the power gain and the loss will be compared. Each power source should be adequate to function in three different types of scenarios: high winds, extreme cold, and variable sunlight.

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