Miniature Wire Boom System for Nano Satellites

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ABSTRACT
An overview of a 10 meter (tip-to-tip) system for deploying four 1-cm spherical sensors is presented. These sensors permit the measurement of the two-dimensional DC-electric field. The mechanism which deploys the sensors consists of a spool of wire with a small, non-magnetic, piezoelectric motor for deployment control. The entire wire boom system is 1.25 cm high and can fit in a standard CubeSat.

A mockup satellite has been developed that mimics the dynamics of a spinning CubeSat as the booms are deployed. This platform contains a 3-axis magnetometer and a set of accelerometers for studying the dynamics of the deployment. Deployment tests in a 1-g field are presented. This mechanism will be flown on the NSF sponsored DICE mission.

INTRODUCTION
The viability of nano-satellites as meaningful platforms for observing the space environment depends upon the development of suitable scientific instrumentation. One of the most fundamental parameters to observe in the space environment is the electric field which drives the motion of the plasma in the Earth’s ionosphere and magnetosphere. The electric field double-probe is a well known technique for observing electric fields, in which the potential of pairs of sensors, deployed several meters from the space vehicle, are monitored. The potential difference between sensors divided by the separation distance gives an estimate of the electric field in the direction of the boom. The dynamics of spinning spacecraft with flexible wire booms were first studied in the early. The flexible wire booms are deployed and held in the extended position by the centripetal force of the spinning satellite. A number of satellite mission have made use of flexible wire booms since these first studies. Recently wire boom double probes for measuring electric fields have flown on the NASA FAST and THEMIS missions.

A team of students from Utah State University have developed a miniature wire boom system that allows the double probe technique to be used on nano-satellites or Cubesats.

DICE Mission
The miniature wire boom system will fly on the National Science Foundation (NSF) sponsored Dynamic Ionosphere CubeSat Experiment (DICE) mission. The DICE consists of two 1.5U CubeSats deployed simultaneously into the same orbit. Over time the satellites will, due to differences in the ejection velocity, separate relative to each other. The use of two identical satellites permits the de-convolution of spatial and temporal ambiguities in the observations of the ionosphere from a moving platform. The science objective of DICE is to understand the Storm Enhanced Density (SED) features which occur frequently in the US in the late afternoon during geomagnetic disturbances. The cause of this phenomenon is currently unknown, and is a topic of great scientific and practical interest. Ionospheric variability has a dramatic effect on Radio Frequency (RF) systems; for example, large gradients in ionospheric electron density can impact communications, surveillance and navigation systems. Some of the largest gradients are found on the edges of Storm Enhanced Density (SED) features. SEDs have been known to disrupt the Federal Aviation Administration’s Wide Area Augmentation System navigation aid in aircraft.

The DICE spacecraft is shown in Figure 1. Each satellite will have a Langmuir Probe (LP) to measure ionospheric plasma densities and an Electric Field Probe (EFP) to measure DC and AC electric fields. Weighted extensions are added to the turnstile telemetry antennas to insure that the DICE spacecraft is a stable major axis spinner.
Each of the two DICE spacecraft is identical in design and function. The four EFP’s each extend 5 meters away from the spacecraft with 1 cm diameter spheres on the ends of the wire booms. The DICE spacecraft are passively stable. The DICE Attitude Determination and Control System (ADCS) will geodetically align and maintain the spacecraft spin rate through the use of torque coils.

Figure 2 shows the instrumentation layout of the DICE spacecraft. Both DICE spacecraft will be inserted jointly into orbit from a Poly-Picosatellite Orbital Deployer (PPOD). The wire booms will be slowly deployed over time with periodic spin-up stabilization event controlled by the spacecraft ADCS system. When the deployment is complete, the spacecraft will be maintained in a 0.2 to 0.1 Hz spin stabilization state.

DESIGN OVERVIEW

Design Concept

The design of this miniature boom deployment system allows for a point-to-point contact from the spherical sensors at the end of the wire to the instrumentation housed in the spacecraft. The spool design uses a passive deployment system by using centripetal force induced from a spinning spacecraft. As the force on the EFP’s becomes greater than the static friction force on the wire boom deployment system, there is a relative motion between the boom deployment system and the spacecraft, allowing the wire booms to deploy. The booms are deployed to a 5 meter distance to increase signal amplitude, which provides the ability to differentiate between electric field measurements, and noise due to the spacecraft and instrumentation limitations.

One of the goals of this design was to develop a non magnetic modular wire boom deployment system with some flexibility that was useful to the entire Cubesat community. The boom deployment system has a modular design that allows it to fit in a standard CubeSat bus. The size of wire can easily be changed by modifying the thickness of spacers used in the system. It is magnetically clean such that it is compatible with sensitive scientific magnetometers.

Top Assembly

Figure 3 shows the complete miniature wire boom system.

Figure 3: Miniature Wire Boom System

The system can be divided into many sub-assemblies for ease of design and explanation. There are four probe mount assemblies, the spool, the braking mechanism, and the interface with the rest of the spacecraft (science electronics board). The system sub-assemblies are mounted on a deck plate (shown in Figure 3 in red) which also serves as an interface to the science electronics board. The four probe mount assemblies are located on the corners of the deck plate. The spool assembly sits in the center of the deck plate. On the
bottom of the deck plate is a brake assembly (not shown in Figure 3).

**Spool Assembly**

The spool assembly is the center of the design concept. It plays an important role in the ability of the system to passively deploy the wire booms. It allows four separate wire booms to be deployed simultaneously and symmetrically from the spacecraft. Because of its compact design, it is able to fit in a relatively small space, which is an important aspect of being compatible with a Cubesat.

The spool is an assembly of thin disks machined out of aluminum and delrin, and is shown in Figure 4. These disks make up an outer spool which provides the rotating motion for the EFP deployment. The top of the outer spool is attached to the inner (non-rotating) portion of the spool. A bushing is used to allow rotational motion.

In order to make valid measurements and minimize noise from electronics, a point to point electrical contact from the probes to the science board electronics is necessary. As wire is deployed from the spool, a proportional amount of wire must be unwound from the inner spool as well. The solution is to wrap the boom wire around the outer spools, and then use the same wire to counter-wrap the inner spool. The wire wrapped around the inner spool is connected directly to the science board electronics, avoiding any intermediate connectors.

For the DICE science mission, Teflon coated 29 gauge copper stranded wire is wrapped in between each aluminum disk. Delrin spacers that accommodate the wire diameter are used. The wire is wrapped outward in a counter-clockwise loop around the delrin disk. Each delrin disk has an opening which allows the wire to be attached to the inner spool. Each wire from the outer spool is joined together in the center of the spool on a single ribbon. The ribbon cable is wrapped in the opposite (clockwise) direction. The internal ribbon cable attaches to the science electronics, where the potential across respective sensors can be measured and stored. This allows for a point to point contact from the EFP to science electronics, which significantly decreases noise that is inherent with additional connection points.

As the DICE spacecraft achieves its spin stabilization, the force on the EFP’s is sufficient to overcome the static friction in the wire boom deployment system. As the wire boom deploys, the outer spool spins counter-clockwise. As the outer wire deploys from the spool, the internal ribbon cable unwinds in the opposite direction. Figure 5 shows the motion of the spool during deployment.

In order to actively control and monitor the deployment of the wire booms, it is necessary to be able to quantify the amount of wire that has been released from the spool. An optical encoder and encoder ring is used in this design to accomplish this.

![Figure 4: Exploded view of the spool assembly](image)

![Figure 5: Illustration of spool motion](image)

**Sphere to Wire Boom Interface**

The surface finish of the sphere, the electrical and mechanical connection to the wire boom, and the mounting of the sphere during launch is critical. The sensor not only takes electric field measurements, but also contributes to the stability of the spacecraft. As the
sensors are deployed, the moment arm exerted by the sensor becomes greater, and the major axis moment of inertia increases. This directly relates not only to the ability of the miniature wire boom system to deploy the sensors, but also to the spacecraft’s ability to maintain a stable spin.

The sensor is a gold plated 1 cm diameter solid sphere. The spheres are gold plated to provide an optimal surface for charges to transfer from the ionosphere to the sensor. By using solid aluminum spheres, a greater moment of inertia about the spinning axis is induced because of the greater mass at a higher moment arm. In order to directly attach the sensor to the wire boom both electrically and mechanically, the sphere has a small hole drilled into it, and a hollow needle is press fit into the hole. Press fitting the needle eliminates the need for fasteners. The end of the wire boom inserts into the hollow needle, and is attached using high temperature solder. High temperature solder is used because the temperature of the gold plated spheres reaches steady state at approximately 170°C. By using the hollow needle, a longer length of wire is able to be fixed to the sensor. The hollow needle will have an outside diameter of approximately 0.762 mm. The sphere and needle are shown in Figure 6.

![Figure 6: Electric Field Probe sensor](image)

Each sensor is mounted in a corner mount, shown in Figure 7. The corner mount has a semi-sphere that cups the electric field probe sensor. The spherical surface on the corner mount that will contact the probe sphere is also gold plated. This ensures that the surface of the probe will retain the integrity of the surface finish, restricts translation of the sphere in lateral directions, and grounds the sensor to the boom release system.

![Figure 7: Corner mount geometry](image)

As the booms deploy, the wires may oscillate as the rotational kinetic energy of the satellite is dissipated in the motion of the boom deployment. These oscillations, if significant, may cause the spacecraft to become unstable about its spinning axis. This would result in the wire booms becoming tangled, wrapping around the spacecraft, and other undesirable effects. Because the wire has negligible hysteretic damping, an additional form of active damping is necessary. This additional damping decreases the time required to wait for the excess energy in the wire booms to reach its lowest energy state. A simple method to increase the damping involves the use of a motion damping washer.

The side of the corner mount opposite the sphere houses the motion damping washer, and is shown in Figure 8. As the wire oscillates, the washer contacts the sides of the mount in which it is housed. This provides frictional damping in the system, and aids in dissipating energy from the boom deployment more rapidly. The washer has a protective nylon insert that minimizes rubbing on the wires during and after deployment.

![Figure 8: Motion damping washer](image)
Motor and Brake Assembly

In order to dissipate the excess energy in the system as the booms are deployed, it is important to maintain active control of the rate of deployment. While the rate of deployment is quantified using the encoder ring, the active control is applied using a braking mechanism. The braking mechanism is shown in Figure 9.

The design of the braking mechanism incorporates the use of a small piezoelectric Squiggle Motor from Newscale Technologies that acts as an actuator on a lever brake housed on the underside of the deckplate. The motor is stepped forward in a linear motion to apply a force on a lever arm. The rotation of the lever rotates a brake spool with a Dynema string attached at different points. When the spool rotates, the string is constricted about the circumference of a brake ring, applying a friction force opposing the motion of the spool. This braking mechanism allows the wire boom system to deploy the booms in a controlled manner.

Figure 9: Boom Deployment System brake assembly

The point on the brake lever arm where the piezoelectric motor applies a linear force is isolated from the rest of the lever arm, so that the resulting reaction force from the lever arm on the motor remains linear. This prevents damage to the tiny motor that could result from any lateral forces induced from the motion of the lever arm. A perspective on the relative size of the squiggle motor is shown in Figure 10. Used in conjunction with the lever arm, this motor allows the braking assembly to exert approximately 1 N of holding force on the spool.

Figure 10: Piezoelectric Squiggle Motor

Magnetic Cleanliness

In order to eliminate sources of noise while taking measurements of the Earth’s electric field, it is important to have a magnetically clean (non-magnetic) system. Delrin is used for many of the parts, as well as Aluminum 6061. Non-magnetic Stainless 300 series was also used where necessary.

TESTING

Vibration

Vibration testing has yet to be carried out. DICE still does not have a specific launch provider. If no launch provider has been selected before testing is carried out, the wire boom deployment mechanism will be tested at the levels defined in GSFC-STD-7000-1.

Deployment

Currently, only small scale deployment tests have been conducted. These tests have resulted in successful 1 meter deployments in a 1-g field. While space restrictions prohibited the deployment of more than 1 meter of wire boom, the deployment still provided a proof-of-concept for the miniature wire boom system.

Each deployment included a disassembly and reassembly of the system. The assembly included the deployment spool build, the brake mechanisms setup, and the electronics setup. This process proved to be helpful in better understanding what assembly parameters the miniature wire boom system was most sensitive to.
The deployment tests were conducted in four different ways. Figure 11 illustrates the different tests.

**Figure 11: Deployment test diagram**

The first set of tests was conducted on a custom-built, air-powered spin table. This spin table (shown in Figure 12) was designed to simulate the spin-up of the spacecraft with very little friction damping. A sapphire ring jewel and endstone along with a polished stainless steel spindle were used to create a low friction interface between the base of the table and the spacecraft mock-up. This low friction spinning allowed the electronics to sense the change in energy more accurately as the booms deployed.

The test conducted with the inner spool wire was used to see how the whole system would behave. The inner spool wire added significant friction to the outer spool, thus creating a more controlled and even deployment.

However, the air powered system did not provide the necessary functionality needed for complete testing. One of the most significant problems with this setup was the rapid transfer of energy from the spinning table to the miniature wire boom system causing the spin table to slow down to the point where centripetal force could no longer maintain the EFP’s in a planar motion. The wires would become tangled, and in many cases break. The air powered system also consumed so much compressed air that it was difficult to sustain a powered spin for more than a few seconds. These problems were addressed by developing a new test setup which provided the ability to control the spin rate.

The second spinning test setup was built from a common electric hand drill and an aluminum base fixture. This test setup is shown in Figure 13. Energy transfer from the drill to the spin table happened via a stainless steel shaft with a roller bearing interface. The bearing allowed for continued motion after the drill turns off.

The second spinning test setup presented another advantage over the air powered setup. Being able to control and maintain the spin rate of the table allowed further testing of the braking mechanism since the brake could be turned on and off during deployment.

The same two tests, with and without the inner spool wire, were conducted in a similar manner to the air powered spin table tests.

The test without the inner spool wire was conducted to quantify how rapidly the booms would deploy. It also made troubleshooting the design and resetting the system easier.
and the deployment could be delayed to observe the holding force of the brake.

The testing results allowed cognizant engineers to evaluate the deployment process, dynamics, and system stability. These deployment tests were monitored using a 3-axis magnetometer and 3-axis accelerometer. These measurements were used to monitor the energy of the spinning system and the deployment of the spool. The collected data was transmitted from the spin table to a computer using a wireless USB hub and plotted in real-time using MATLAB.

The magnetometer allowed the observation of the stability of the system. Since the deployed booms have such dominating affects on a Cubesat the system needs to be well balanced. The magnetometer measurements showed the perturbations in the x and y directions and helped to quantify how stable the spinning system was.

To track the speed of the spinning system a 3-axis accelerometer was integrated into the spin table. The accelerometer was used for observation of the system energy and quantification of forces in the system.

The amount of wire being deployed from the spool was tracked using the encoder system which consists of an optical encoder and high resolution encoder wheel. This information was used to determine the length of the wire booms as well as track the points during deployment where anomalies occur. One of these anomalies is the maximum in centripetal force that occurs during deployment.

Examples of measurements taken while testing deployments are illustrated in Figure 14. The acceleration in the y-axis shows the deployment of the sensors. It can be seen that the y-acceleration reaches a maximum just after deployment. This maximum acceleration correlates to the maximum force during deployment seen in the analysis plot in Figure 15 at about 25cm.

![Figure 15: Theoretical centripetal force on the miniature wire boom system during deployment](image)

![Figure 14: Deployment data from miniature wire boom system](image)
CONCLUSION
The development and design by Utah State University students of a meaningful scientific instrument for use on nano satellites has been presented. Testing has verified the feasibility of the design. The success of the DICE mission will give the miniature wire boom system flight heritage. It becomes clear that suitable scientific instrumentation can indeed be developed and used on nano satellites.

The design presented here can be adapted for other meaningful space environment science instrumentation. Cost savings are significant for this sophisticated instrumentation because of its compact size and the size of the spacecraft on which it is integrated. This cost savings allows funds to be used on developing further technology for making science observations and measurements.

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REFERENCES