An Analysis of ESD Mitigation for the *FIRST* Tech Challenge

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Introduction

In past seasons, the FTC control system has been plagued by electrostatic discharge (ESD) issues and proposed solutions have been inconsistently applied and only marginal successful at mitigating them. After extensive testing, I would like to propose a set of solutions that should drastically reduce the occurrence of ESD related problems during FTC competitions. This document will outline my proposals and tests and give some technical explanations for ESD phenomena.

Thanks to Greg Szczeszynski and Doug Chin for their research and testing, which guided many of the ideas and tests outlined here.

Theory

Before we look at proposed solutions, it is important to look at why the current problems exist and introduce a bit of theory.

What is an Electrostatic Discharge Event?

An electrostatic discharge (ESD) event is when a highly charged object (like a robot) touches an uncharged or oppositely charged object and discharges to it. Because of the high voltages involved (up to tens of kilovolts), ESD events can produce extremely high electrical currents. Although ESD current spikes are extremely brief, they can easily damage or disrupt sensitive electrical devices.

How Robots Become Charged

When two surfaces interact, there is generally a small amount of adhesion. This means that they share electrons and if they are made from different materials the electron sharing may be uneven. When the surfaces are taken apart, they can become charged. This is called the triboelectric effect.

The triboelectric effect is more pronounced if the two surfaces slide past each other because they are not perfectly smooth and tiny imperfections cause vibrations. This causes the surfaces to make and break contact very quickly. It is important to note that triboelectric charging takes charge from one object and gives it to another. In the case of an FTC robot's wheels interacting with field tiles, positive charge is given to the wheels and negative charge is given to the tiles. The triboelectric effect has been found to be more pronounced in low relative humidity.

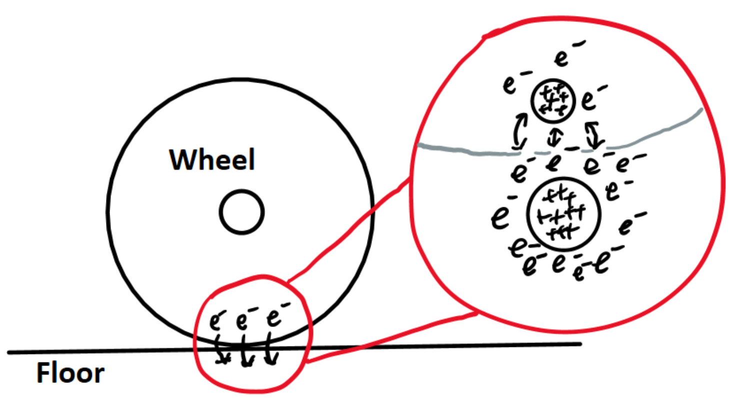


Figure 1- Triboelectric Effect

Discharging a Robot

There are two relevant ways to discharge something through the air. The first is arcing, which is when the air between two differently charged objects becomes ionized and allows current to flow from one to the other. The second is corona discharge, which involves charges on an object equalizing with ions in the air. Of these, corona discharge is more useful for mitigating static because it does not carry a hazardous amount of current.

A positively charged robot produces an electric field. Corona discharge works when a molecule ionizes in this field. The electron is pulled toward the robot and the positive ion is launched away. The electron hits other molecules causing them to ionize and eventually it runs into the robot, cancelling out a positive charge there. This process continues as a chain reaction. Because highly curved objects like sharp edges, points, and thin wires can concentrate electric fields, they tend to produce more corona discharge than smooth objects.

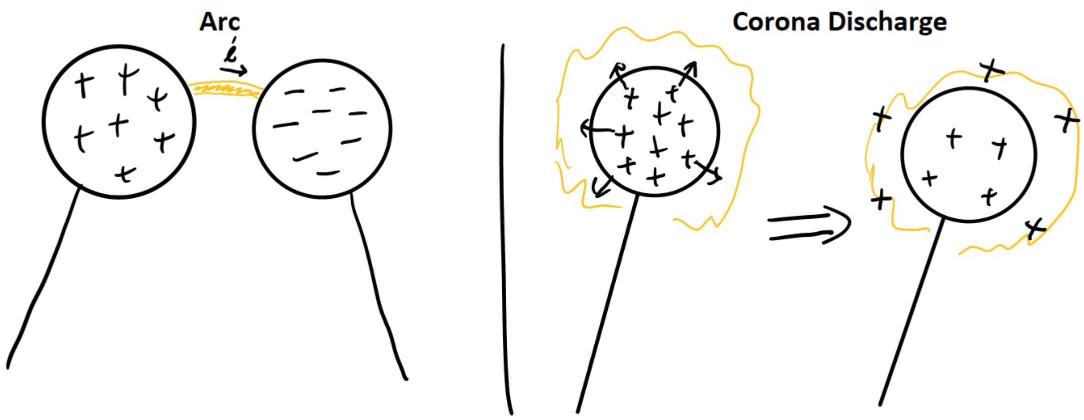


Figure 2- Arcing vs. Corona Discharge

Modeling the System

When thinking about how to safely deal with ESD, it's useful to think of a robot as a capacitor. You can store charge on its frame and the voltage relative to ground and the electrical system will increase. Likewise, the electrical system may also be considered a capacitor with capacitance to both ground and the frame. The triboelectric effect can be roughly modeled as a current source, corona discharge can be thought of as a resistor to ground, and an arc is analogous to a short. It is important to note that, just like shorting a highly charged capacitor, shorting the electrical system to ground while charged will produce extremely high currents unless there is a series resistor. This is the root cause of all ESD issues on the field. It is also important to note that neither the frame nor the electrical system can charge or discharge instantly.

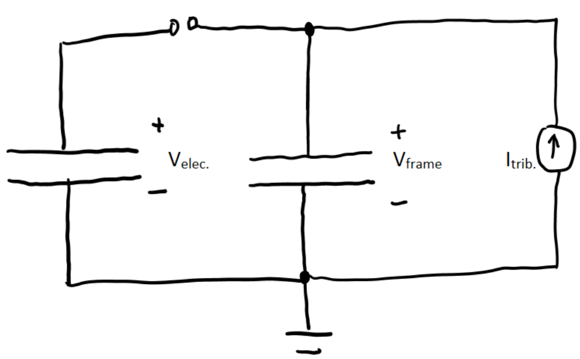


Figure 3- Electrical Model for the System

The goal of ESD mitigation is to minimize the current flowing into and out of the electrical system from the surroundings. Based on the above model, the best way to minimize current is to keep the electrical system and everything that it could possibly interact with at the same voltage. The most effective way to do this would be to ground everything in the environment to Earth ground (including the electronics) and make all surfaces conductive. In industrial settings, this is the predominant solution for ESD problems. Unfortunately, it is impractical to ground FTC robots because the requisite wires would be an entanglement hazard.

ESD String

ESD string is a specially made string that incorporates microscopic, highly curved steel wires that enhance corona discharge. Its primary use is to minimize charge on industrial conveyor belts, which is a similar case to an FTC robot for all practical purposes.

Corona discharge can be further enhanced by increasing the electric field strength even more. To do this, we need to consider the behavior of conductors in electric fields. Consider a large plane of conductive material with a localized electric field from a positively charged robot penetrating it. The conductor will collect negative charge in the region under the robot, which will produce an electric field that adds to the field produced by the robot. This increases the already concentrated electric field at the highly curved conductors in the static string, thereby increasing corona discharge. Thus, a good way to maximize corona discharge is to cover the floor underneath the tiles with a conductive sheet and use one or more pieces of static string suspended close to the ground. This will spray built up charge back onto the floor tiles.

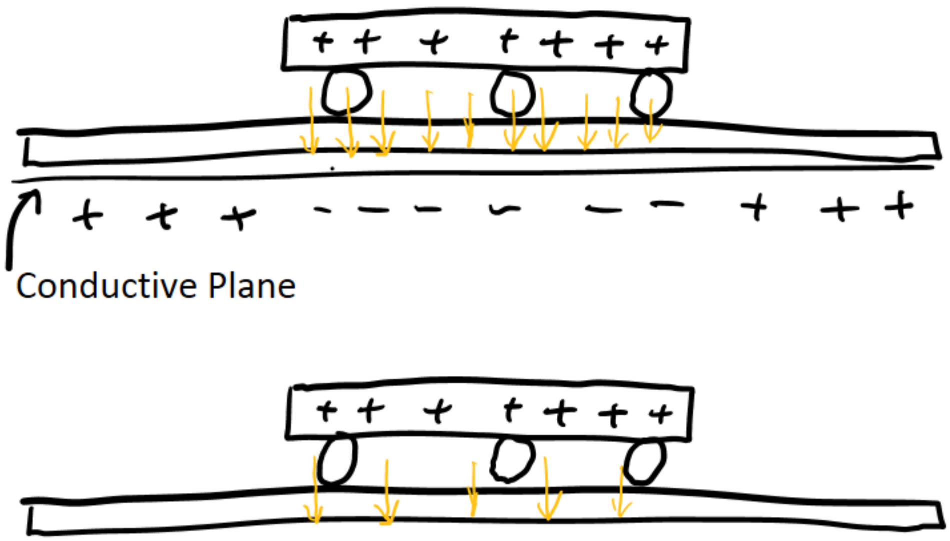


Figure 4- A ground plane amplifies electric fields

It should be noted that if the robot is stationary, the ESD string solution is less effective because positive charge builds up on the surface of the tiles and creates an opposing electric field. In practice, this does not matter because the triboelectric effect only produces current when the robot is moving, but it may affect test results.

Static Sprays

Another industrial static reduction product is static spray, which blocks triboelectric generation and allows charge to equalize across the surface it is applied to. This greatly reduces charge build up and increases the discharge rate of the robot. Tests show that static spray can be combined with static string for greater effect.

Testing

To improve our understanding of ESD problems, we conducted a series of tests, the results of which are summarized below. The primary goal of testing was to quantify the effectiveness of various proposed solutions.

Equipment

Test Robot

Unless otherwise noted, all tests involving a robot were done using a Tetrix drive base with six 4” Tetrix wheels (Figure 5).

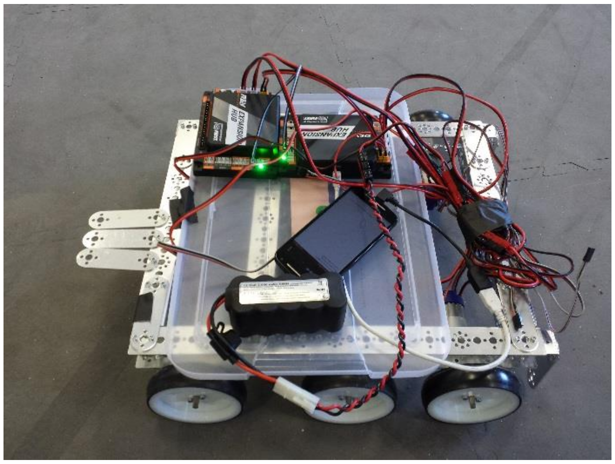


Figure 5- ESD Testing Robot

Electrostatic Field Meters

To measure the voltage on the frame of the robot, two separate electrostatic field meters were used. The first is a AlphaLab model SVM2, the second is a Munroe Electronics Stat Arc II, model 265A-1. Both are handheld units, but the Stat Arc II has an analog output, which made it possible to log the frame voltage with

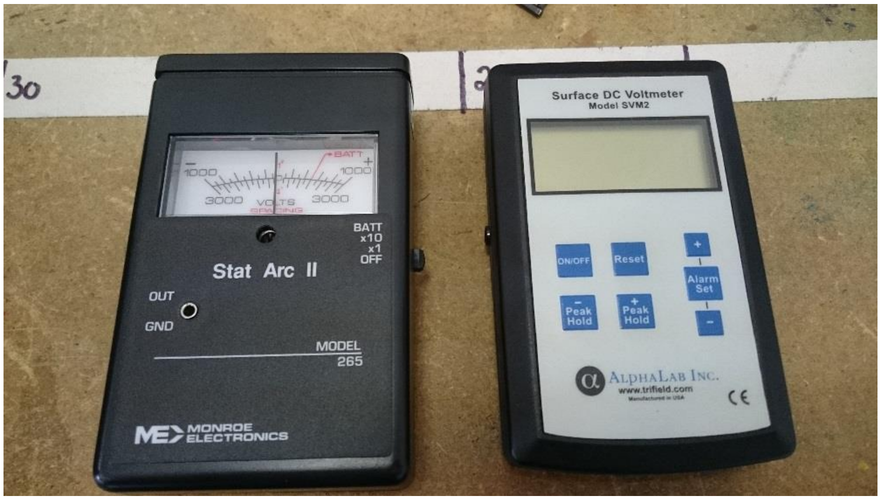


Figure 6- Electrostatic Field Meters

an oscilloscope. Electrostatic field meters sense electric field strength. By placing them a known distance from a reasonably large conductive object, they will give the voltage of the object.

For these tests, electrostatic field meters are the only effective means of measuring the frame voltage because they do not need to make physical contact with the object they are measuring. Any measurement device, with the exception of an electrostatic voltmeter (which uses the same principle as an electrostatic field meter), that required physical contact would be ineffective because it would disturb the charge on the robot, which is small enough that even a minor disturbance would be significant. Additionally, most measurement devices, including electrostatic voltmeters, are not rated for the high voltages involved in electrostatic phenomena.

It should be noted that electrostatic field meters provide only an approximation of voltage because differently sized measuring surfaces at the same voltage will produce electric fields of different strengths. Thus, all measurements in these tests assume that the first electrostatic field meter reads the correct voltage at one inch from the set of plates on the back of the test robot. The second electrostatic field meter was calibrated to the first using a scaling factor in Waveforms, the oscilloscope's computer interface program. This is almost certainly not the exact voltage of the frame, but it is perfectly fine for comparing the effectiveness of different solutions.

Van de Graaff Generators

In all tests where the robot needed to be charge to significant voltages, one of two Van de Graaff generators was used. The first Van de Graaff generator was a battery powered hand-held unit. It was only able to produce a little over 10 kV on the frame of the robot and it was very slow. After we received the second electrostatic field meter, we switched to using a much larger Van de Graaff generator powered by mains, which could produce much higher voltages on the frame.

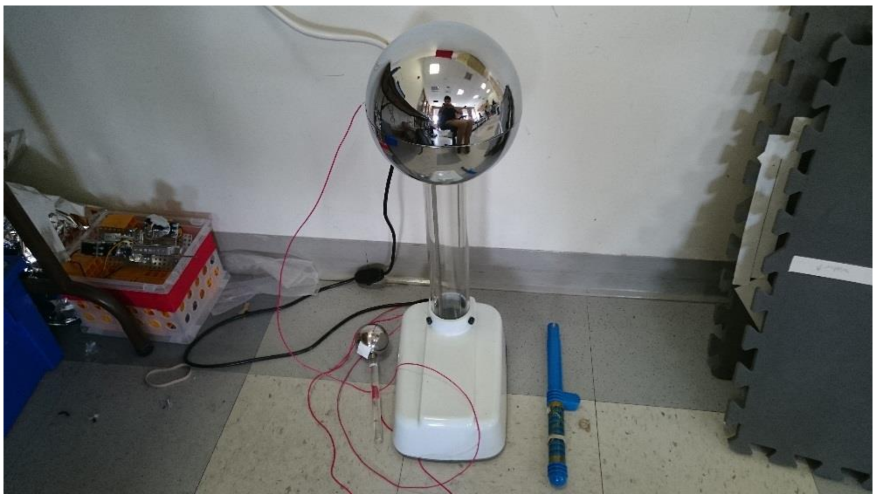


Figure 7- Van de Graaff Generators

Van de Graaff generators effectively act as small current sources, which makes them ideal for building a lot of charge on capacitive systems, like the robot.

Humidity Sensing

Because triboelectric charging is humidity dependent, we wanted to have a way to measure the relative humidity in the testing room and we bought a hygrometer from Home Depot. To test this device, we placed it in a sealed plastic bag with a saturated table salt solution and left it overnight. Saturated salt solutions maintain constant humidity (75%, in the case of NaCl), which makes them useful for calibrating hygrometers. The hygrometer read 69%, which is 6% lower than the expected value. When it was later checked against a hygrometer known to be accurate, it was shown to be uniformly 6% low. All humidity measurements reported in this document have been corrected by this amount.

Test 1: Characterizing Stationary Discharge

Before doing anything else, I wanted to test the simplest possible case. I charged the robot with a hand-held Van de Graaff generator while it was sitting at rest on the tiles and measured the frame voltage every minute using an electrostatic field meter. Out of curiosity, I repeated this procedure with a long string of ESD tinsel draped over the top of the robot, which did not have an appreciable effect. The non-tinsel test started at 17 kV and decayed to 5 kV in 20 minutes. The tinsel test started at around 10 kV and also ended at around 5 kV.

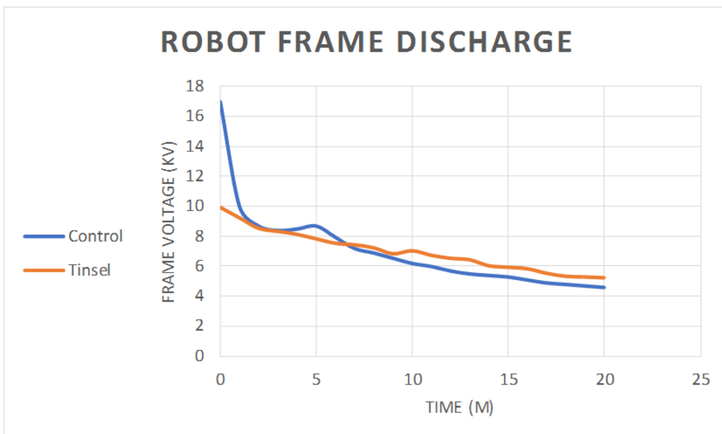


Figure 8- Discharge of a stationary robot

It is important to note the non-linearity of the control. It shows how corona discharge drops off dramatically below the threshold electric field strength needed to sustain the chain reaction.

Test 3: Spinning in Circles

While the Van de Graaff generator is useful for testing discharge, it is important to know how much charge the robot can develop on its own. I tested this by grounding the frame to get rid of any charge, then driving around on the field and measuring the voltage of the frame afterward. I tried three different driving styles: Driving straight forward and backward, driving forward and backward and turning, and spinning in circles. Driving straight produced roughly .5kV, driving and turning produced around 1kV, and spinning in circles produced 2kV. I also tried removing the two center wheels of the robot, which produced 1kV in the spinning test.

The voltages developed in these tests are far lower than I expected based on descriptions of extremely charged robots. I suspect this is the result of the relatively high humidity in our testing room. After looking at historical weather data from winter 2018, I think that the likely minimum humidity in winter in New England is around 25% outside. It would certainly be lower inside of a heated building. The humidity in the testing room was around 45%.

Test 4: Driving Discharge

To test the effectiveness of the static string, I added a set of forks to the front of the robot and stretched the static string across such that the string was approximately 3/8" off of the floor. I then charged up the robot to 10 kV and drove it across the field and back. This dropped the voltage on the frame to 2.5 kV. I repeated this test without the static string and the voltage dropped to 5.5 kV. I repeated this test again with the static tinsel. As expected, it was slightly less effective than the string. I tried this test again with the tinsel brushing on the ground. This was just as effective as the static string.

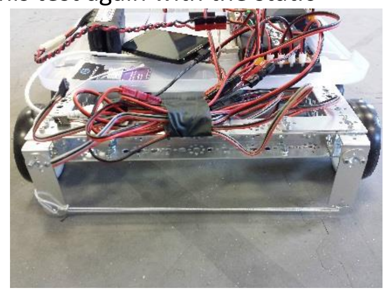


Figure 9- Robot with static string

After discharging the robot and switching back to the static string, I tried spinning the robot in circles. Unlike in the previous spinning tests, this produced no significant voltage on the frame. Running the same test with the tinsel produced .5 kV.

Test 5: Charge on the Field

During normal driving, the field will pick up an equal and opposite charge to that on the robot. Because the charge on the robot does not come from the field while testing with the Van de Graaff generator, any charge that the robot transfers to the field increases the net charge of the field. After testing the static string, I measured voltages on the field greater than 5 kV. This likely reduced the effectiveness of the static string in tests done using the Van de Graaff generator.

In an attempt to provide a uniform charge for static string tests, I decided to slide a long metal bar across the surface of the field. Interestingly, this produced significant negative charge on the field, even when the metal bar was grounded to Earth ground. This is likely another manifestation of the triboelectric effect.

Test 6: Charging off the field

To reduce the charge built up on the field, Tom suggested that we try charging the robot off the field and then moving it onto the field. I added some zip tie handles to the frame to move the robot onto the field without discharging it. After charging the robot and moving it onto the field, it seemed to discharge normally. I then attempted the same experiment with the static string attached to the forks as before. After charging up the frame for a long time, I moved the robot onto the field and measured the charge. It was under 2 kV. Assuming that the batteries in the Van de Graaff generator might be dying, I replaced them and tried to move the robot again with the same result. I then charged up the robot while grounding myself and observing the voltage with the field meter. The robot took a long time to charge up to 10 kV. After it was charged, I moved it to the field again and measured the voltage, which was again sitting under 2 kV. Thinking that I may have inadvertently brought the robot too close to me or the field wall and discharged it, I repeated the test and made sure to keep a large air gap between the robot and all other objects while moving it. The frame was under 2 kV again. From this, I concluded that the robot discharged extremely quickly to the air while it was not resting on the mats.

This made me curious to see the discharge on the floor outside of the field, so I charged up the robot to 10 kV and watched it discharge. This was much faster than the discharge while the robot was sitting on the field. It is possible that the floor is more conductive than the field tiles.

Test 7: Tile Charge equalization

In order to test the static string effectively, it is important to minimize the charge on the floor tiles. In one of my earlier tests, I noticed that when the tiles were highly negatively charged, the robot would also become negatively charged when driving around with the static string attached. This led me to believe that I could ground the robot frame and use the robot as a sort of static vacuum. I tried this and could bring a tile down from 6 kV to 2.5 in a few passes. It was inconvenient to drive the robot around to clear charges, so I made a hand-held device to hold the static string at the correct height. With this, I could bring the charge down to +/- 1 kV everywhere on the mat. I found that holding the device provided a sufficient charge reservoir and I did not need to connect it to earth ground.

Figure 10- Electron Vacuum

Test 8: Aluminized Mylar

With a method to equalize the charge on the field, it became possible to effectively test the static string. I placed a folded space blanket under one row of mats and connected the static string to the robot. I ran tests with the following procedure using different combinations of string and ground plane:

1. Charge the robot with the hand-held Van de Graaff generator for one minute
2. Measure the voltage
3. Drive the robot out and back the length of three tiles
4. Measure the final voltage.
5. Clear tile charge

The results were as follows:

Test	**Start**	**End**	**% Decrease**
String, Ground Plane	9.5 kV	2.5 kV	74%
	9 kV	2.3 kV	74%
String, No Ground Plane	9.5 kV	4.4 kV	54%
	10 kV	3.6 kV	64%
No String, Ground Plane	12 kV	7.2 kV	40%
	10.8 kV	6.2 kV	43%
No String, No Ground Plane	12.7 kV	7.5 kV	41%
	13 kV	6.9 kV	47%
String at 1", Ground Plane	11.8	4.4	63%
	11.8	4.3	64%
String Parallel to Primary	12.6	5.3	58%
Direction of Motion, Ground Plane	13.3	5.6	58%

Humidity was between 40 and 50%.

As shown by both the starting voltage and % decrease for each test, the static string significantly improved charge dissipation. The blanket had an insignificant effect when used without the static string, but drastically improved performance with it. It should be noted that the effect of the string is probably even more pronounced than it first appears because the higher starting voltages of the non-string tests may have increased the rate of corona discharge in those tests.

After running each of these tests, I checked the charge of the floor tiles. Though the tile charge was non-uniform, I observed that the tiles picked up far more positive charge (the voltage reached ~5 kV in places) in the tests with the string than without. The regions of high charge were concentrated around the robot's starting position, which leads me to believe that either most of the charge was dissipated very early in the movement or that the robot leaked a significant amount of charge while still in contact with the Van de Graaff generator, which explains the lower starting voltages. A combination of the two is perhaps more accurate.

Test 9: Mecanum with Static String

Tom noted that a mecanum robot might produce more charge than a tank drive robot, so I drove one around on the tiles for a minute or so and measured the voltage on its frame. It went up to 3 kV, which was higher than I had seen on the 6-wheel robot. We determined that this would be a more effective testing platform for the static string. I mounted a line of static string diagonally across the robot and drove it around over the aluminized blanket section of the field and checked the voltage. It was slightly negative instead of positive, which implies that the robot acquired some of the field's negative charge. Repeating the same test on the non-aluminized blanket section of the field resulted in a charge of roughly 1 kV.

The procedure was as follows:

1. Discharge the robot
2. Drive the robot around on the field for 1 minute
3. Measure the frame voltage and record it
4. Repeat at various times with different humidity

Description	Ending kV	Humidity	Date & Time	Notes
No Ground Plane, String	0.6	52%	5/23/2018 13:10	
No Ground Plane, String	0.3	51%	5/23/2018 13:15	
No Ground Plane, No String	2.9	51%	5/23/2018 13:17	
No Ground Plane, No String	2.3	52%	5/23/2018 13:19	
Ground Plane, String	1	52%	5/23/2018 13:35	This test and the next were done primarily with the robot strafing back and forth in place
Ground Plane, String	1	52%	5/23/2018 13:40	
Ground Plane, String	0.2	52%	5/23/2018 13:50	This test and the next were done with the robot primarily driving and turning (not in place)
Ground Plane, String	0	52%	5/23/2018 13:52	
Ground Plane, String	1.3	52%	5/23/2018 14:00	Primarily Strafing
Ground Plane, String	1.2	52%	5/23/2018 14:05	Primarily Strafing, video
Ground Plane, String	-0.3	52%	5/23/2018 14:10	Driving in an oval, video
Ground Plane, No String	2	52%		Primarily Strafing
Ground Plane, No String	0	52%		Driving in an oval
No Ground Plane, No String	3.3	52%		Primarily Strafing
No Ground Plane, No String	0.4	52%		Driving in an oval
No Ground Plane, String	2.7	52%		Primarily Strafing
No Ground Plane, String	-0.5	52%		Driving in an oval
No Ground Plane, String	-1	52%		Strafing for 30 seconds, then driving back and forward the length of 2 tiles
No Ground Plane, No String	-0.2	52%		Strafing for 30 seconds, then driving back and forward the length of 2 tiles

This test leads to some conclusions that contradict previous tests. In particular, the 12th run and the 16th run indicate that the grounding plane alone has a significant effect on the amount of charge build up. This effect is much more pronounced than it appeared to be in test 8. Perhaps that is because this test operated at much lower potentials.

While I am encouraged by the reduction in steady state voltage with the static string and blanket, I am concerned that the robot still built charge. I think that in lower humidity, the steady state voltage may be higher. This implies that the static string alone is not a complete solution.

Test 10: Mecanum Robot Discharge

In this test, I wanted to characterize the discharge of the mecanum bot. For the first four runs, the robot was charged off the field while sitting on a large pile of mats for 1 minute and then moved onto the field, driven back and forth the length of three tiles once, and measured. For the last two tests, the robot was charged on the field.

Run	Start	End	% Difference
No Static String	7.7	4.6	40%
	6.8	5.2	24%
Static String	2.5	1.6	36%
	3.3	1.8	45%
	8.4	3.5	58%
	13.5	7	48%

This test is interesting because it shows the large drop in potential as the robot is moved from the charging position to the field with the string. Assuming that the robot started at around 10 kV immediately after being charged, the static string is able to dump nearly 4 kV more than the robot alone in just a few seconds.

It should be noted that this test should produce a less dramatic increase in charge reduction between the non-static string and static string runs than might be accurate because in the case where the robot was charged off the field, the robot started at a much lower potential, which would have decreased the rate of corona discharge and in the case where the robot was charged on the field, it would have deposited charge on the field while being charged, which would also decrease the rate of corona discharge.

Test 11: Grounding Cable

The next phase of testing was to determine the usefulness of grounding the electronics to the frame. I built a grounding wire using a 4.7 Mega Ohm resistor, a ring connector, and an Anderson Power Pole connector. The ring connector is screwed into the frame and the Anderson connector is connected to the ground terminal of the battery through the Expansion Hub power port.

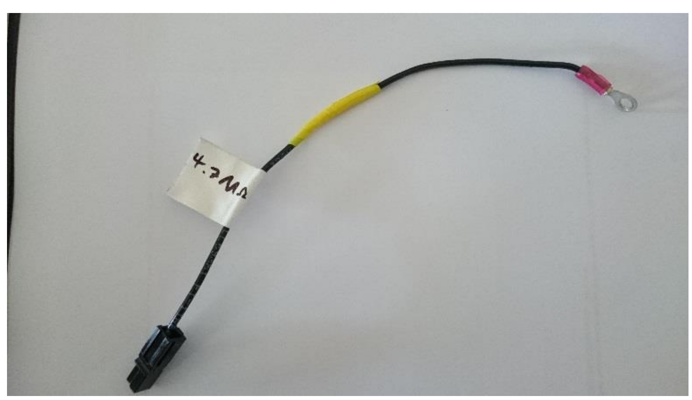


Figure 11- Grounding Cable

The most important initial test was to ensure that a large discharge from the frame would not knock out the electrical system with the grounding shunt connected, which could be a potential side effect if the value of the shunt resistor was too small. I charged up the robot frame to between 10kV and 25kV ten times and discharged it to earth ground. This had no visible effect on the electrical system. I repeated this test without the grounding shunt and likewise, the discharges had no visible effect.

Test 12: Color Sensor over I2C

The next test was to connect an I2C color sensor to the expansion hub and attempt to cause errors on the I2C bus. I mounted the color sensor face down on the frame with the hope that current would arc from the frame into the color sensor at high voltages and followed the same procedure as in test 11. There were no visible effects after any of the grounded or ungrounded runs in this configuration.

Figure 12- Color sensor mounting

This was a surprising result. I assumed that the voltage was not high enough to arc to the color sensor and decided that it might be more effective to place the back of the connector on the color sensor close to the frame. This also did not seem to do anything under tests up to 25 kV. In this case, I think that it is possible current was arcing at such a low voltage that it did not cause any issues. Essentially, the small air gap could have acted as a large resistor.

I next tried charging the frame while holding the color sensor at the base of the connector. I could feel a series of arcs from my finger into the color sensor, but it initially did not seem to do anything. After a short while, the controller showed a problem with the color sensor. I stopped shocking it and power cycled the expansion hubs. When power was reconnected, the expansion hub connected to the color sensor seemed to be dead. Its LED was off and the phone did not detect it. I concluded that the Expansion Hub was bricked and after testing it, Tom agreed.

With the goal of creating a more controlled method for shocking the I2C bus, I added a servo to move the back of the color sensor wire near the frame of the robot. This would allow the robot to build up a large charge before discharging to the electrical system at a controllable point. Without the grounding shunt attached, I charged the robot up to around 10 kV and started the servo movement. This caused a "problem with the color sensor" error when the color sensor got close to the frame. After some testing, I realized that I had killed the I2C port, which manifested itself as the entire system being unable to initialize when a sensor was plugged into that port.

Test 13: Color Sensor with Grounding

In this test, I repeated the same experiment as in test 12 but used the grounding shunt. I was able to move the servo to the shocking position many times at frame voltages ranging from 10 to 16 kV with no apparent effect. After the test, I noticed that the servo would twitch upon discharging the frame. I presume this was the result of the rapid change in voltage on the expansion hub.

Test 14: Better Instrumentation

We acquired a second electrostatic field meter, which is a handheld unit with analog output from Monroe Electronics. I mounted it 4" above a metal plate on the robot and hooked up the Analog Discovery and used a multiplying factor of 255000 to get kV, which I obtained by comparing the new field meter against the reading of the original hand-held unit. This allowed me to use the wall powered Van de Graaff generator because I could more easily watch the voltage and avoid letting it get too high. The graphs in all later tests were produced with this device.

Test 15: More Destructive I2C Testing

This was a continuation of tests 12 and 13. I took the expansion hub with the damaged I2C 0 port and connected the color sensor to I2C 1. I first charged the bot up to increasingly high voltages with the grounding cable and moved sensor close to the frame repeatedly. This had no effect on the control system.

I ran a similar test without the grounding shunt, charging the frame up to increasingly high voltages and moving the color sensor close to the frame. The following screen shot is of the frame voltage during this test.

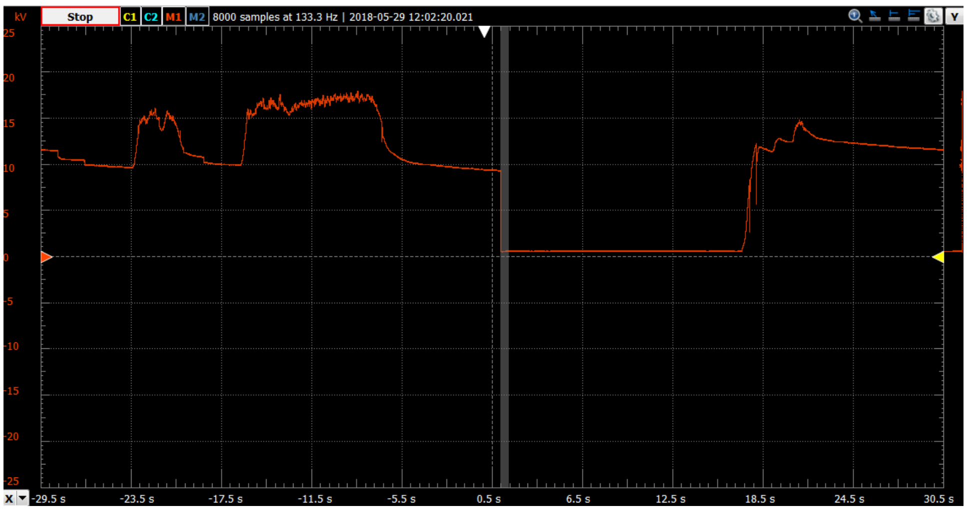


Figure 13- Destructive I2C Testing

The expansion hub was killed at around -11.5s. It produced an error with the color sensor and upon restarting the robot, the control system could no longer see the color sensor and was also unable to see it on other I2C ports. The color sensor worked correctly with a different expansion hub.

Test 16: How to Kill a Grounded Expansion Hub

I realized that with the grounding shunt, it would be possible for a fast discharge of the frame to knock out the I2C ports if there was a sensor immediately next to the frame because the capacitance of the electrical system cannot discharge instantly and thus, there is very briefly a large potential difference between the electrical system and the frame. I tested this by charging up the robot with the expansion hub grounded through the shunt, then bringing the color sensor close to the frame and discharging the frame while the color sensor was down. It took numerous tries, but I was eventually able to kill all of the expansion hub I2C ports with a 20kV shock (the phone showed the 'Warning: problem with "color"' error message. Lower voltage shocks did not seem to have any effect. Interestingly, after this shock, the LED on the expansion hub went out and the hub was unresponsive until I did a full power cycle. The sensor also seemed to be dead. It caused other expansion hubs to hang on init.

Given that it was more difficult to produce this failure mode than the equivalent non-grounded failure mode, I believe that the grounding shunt is an improvement, but that it should be paired with additional measures, such as a ferrite choke.

Test 17: Ferrite Choke on I2C

In an attempt to mitigate the problem identified in test 16, I added a clip-on ferrite choke to the color sensor wire and re-ran test 16.

The following screen shot is of one of the discharges:

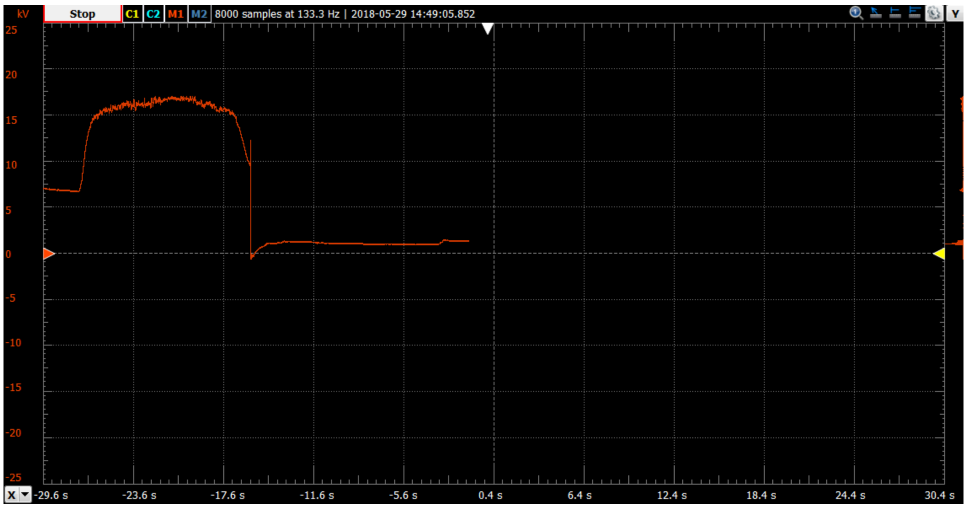


Figure 14- Discharge into I2C wire with choke

The other discharges were similar. I shocked the system four times. The first three times appeared to kill the expansion hub (LED was off and it was unresponsive), but after being power cycled it recovered. The final test seems to have killed all of the I2C ports. This is an improvement over test 16, which leads me to believe that the use of ferrite chokes is a good idea.

Test 18: More Shunt and Choke Testing

This test is a continuation of the testing of the grounding wire and ferrite chokes. This time, I used the modern robotics system and zapped a range sensor connected over I2C to produce errors. I added a second cable in series with the range sensor's cable and zapped the connector in the same way that I zapped the color sensor connector in previous tests. These tests produced three different outcomes 1) The system was unaffected 2) Something disconnected and required a restart (and sometimes a power cycle) 3) The system went into the "OpMode stuck in loop" error.

Description	Unaffected	Restart	Stuck in Loop
4.7 M Ohm grounding cable, choke on signal wires only, 7.5 kV	3	6	1
4.7 M Ohm grounding cable, choke on all four I2C wires, 7.5 kV	7	3	0
4.7M Ohm grounding cable, no choke7.5 kV	4	6	0
No grounding cable, no choke, 7.5 kV	9	10	1
120 Ohm grounding cable, no choke, 7.5 kV	9	1	0
120 Ohm grounding cable, choke on all four I2C wires, 7.5 kV	9	1	0
120 Ohm grounding cable, choke on all four I2C wires, 13 kV	10	0	0

As shown by Greg's testing, the OpMode stuck in loop error is unlikely. I saw it only twice in 80 tests. The 120 Ohm shunt had substantially better performance than the 4.7 M Ohm shunt. Using a choke on only the signal wires was similar or slightly worse than using no choke at all, but the use of a choke on all four wires of the I2C cable significantly improved the system robustness.

Because the electrical system was not grounded in the test without the grounding cable, I left the I2C wire next to the frame while charging, which allowed the electrical system to charge up via arcing, then I discharged the frame as in the other tests.

Interestingly, I did not kill a core device module in the above tests (though I did kill one at a higher voltage earlier). I suspect that the Modern robotics firmware is less robust than the firmware on the expansion hubs, which means that the Modern Robotics hardware can be disrupted at voltages that do not damage it.

I believe that the 120 Ohm shunt performs better because it brings the time constant of discharging the capacitance of the electrical system closer to that of an ESD event so a smaller fraction of the total current goes through the ESD sensitive I2C port. I suspect that the use of a choke on the signal wires alone produces a significant potential difference inside of the Core Device Module, which causes problems internally.

The 120 Ohm shunt is probably a bit smaller than it should be. I was able to produce an error in one of the ten tests I conducted by shorting the frame to ground without the sensor wire close to the frame, which indicates that there is significant current flow through the shunt or that current was arcing from the servo. A slightly larger shunt should fix this problem.

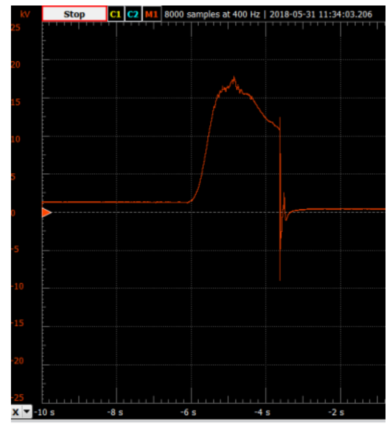


Figure 15- Discharge with shunt

Test 19: Zapping Servos

Tom noted that some teams had found success preventing issues by adding chokes to their servo wires. I tested this by adding a long metal arm to the servo, placing it on the electronics platform, and programming it to touch the frame. Running tests at 10 and 12 kV, I had few problems with or without a choke, which leads me to believe that the MR servo module is reasonably robust (at least when it is the only thing being zapped). I additionally tried zapping a set of servo wires, which also showed an insignificant difference between using a choke and not using a choke.

Test 20: Characterizing Different Sized Shunts

After my tests with the smaller shunt, I wanted to characterize the behavior of some different resistor values. The testing setup and procedure was identical to the setup from test 18, except that I added a choke to the servo wires.

The results were as follows:

Grounding Shunt Val.	Frame Voltage (kV)	Choke?	Pass	Fail
120	7.5	Y	10	0
470	7.5	Y	10	0
2k	7.5	Y	9	1
20k	7.5	Y	10	0
200k	7.5	Y	10	0
4.7M	7.5	Y	10	0
120	20	N	10	0
470	20	N	10	0
2k	20	N	9	1

20k	20	N	7	3
200k	20	N	8	2
4.7M	20	N	9	1

Interestingly, all performance in this test was better than in test 18. I suspect that this is the result of the choke on the servo wire since that was the only difference from test 18, though this contradicts the results of test 19. It's likely that having multiple points of discharge increases the probability of having a problem in the same way that using a choke on only I2C signal wires does, which makes it important to use chokes everywhere.

Test 21: Different Shunts

The other potential problem with using a grounding resistor is that the quick discharge of the ground line could disrupt communications or damage things. To characterize this with different resistor values, I completely isolated the electrical system from the frame, then added a grounding resistor, charged the frame to 20 kV, and discharged it.

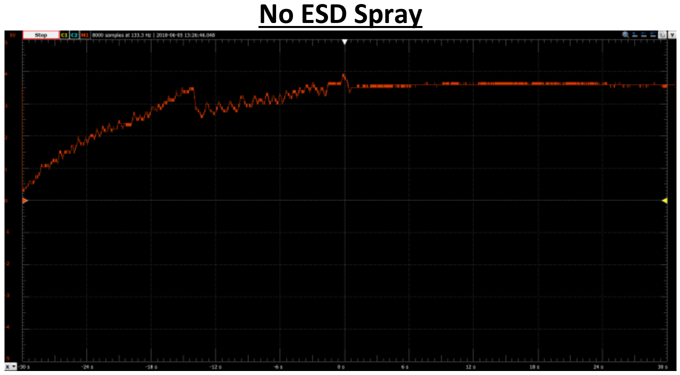
Grounding Shunt Val.	**Pass**	**Fail**
120	10	0
470	10	0
2k	9	1
20k	9	1
200k	7	3
4.7M	10	0

It seems that there is not much risk on this front although it is interesting that the 200k resistor performed somewhat worse than the others. I think that the best option for a grounding shunt is the 470 Ohm resistor. It seems to provide a nice, short time constant that takes some of the current when there is a discharge through a sensor wire but is large enough to limit current flow to 25 mA if a 12V power wire is inadvertently shorted to the frame. At .3W, this will not dissipate excessive heat in the resistor, allow teams to run power through the frame, or cause other problems. These cables could be made for <$5.

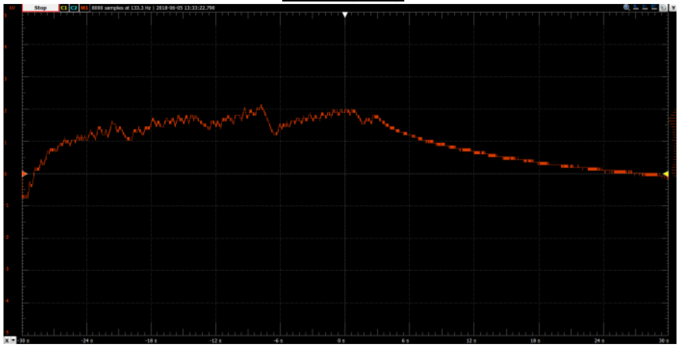
Test 22: ESD Spray and Water

For this test, I sprayed a single tile with ESD spray or water and turned the robot back and forth to build up charge. The voltage on the frame was measured with the electrostatic field meter and logged with the Digilent Analog Discovery 2. For each test, I stopped roughly halfway through the capture and allowed the robot to sit and discharge. The relative humidity for these tests was around 35%, which I achieved by using a heater.

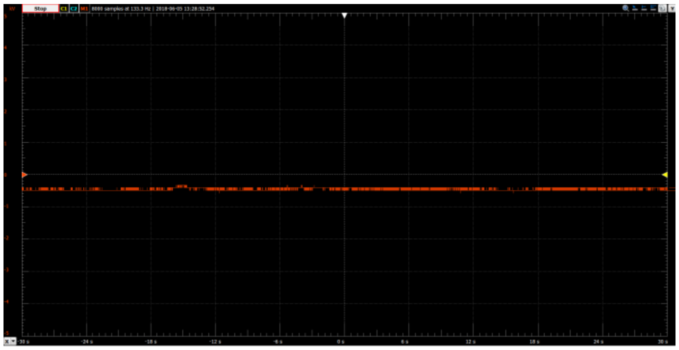
No ESD Spray



ESD Spray



Water

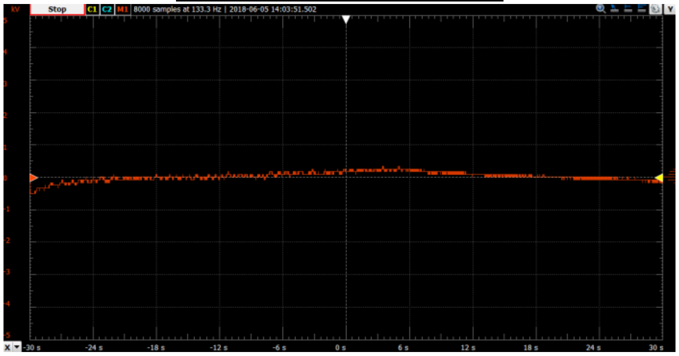


It is clear that spraying the surface with water is the most effective but this also made the surface much more slippery, which would make it difficult for teams to write reliable autonomous modes. The ESD spray cut the charge build up in half and instead of holding charge after I stopped moving the robot, it discharged back down to around 0V. The ESD spray does not seem to have any noticeable effect on the surface qualities of the tile.

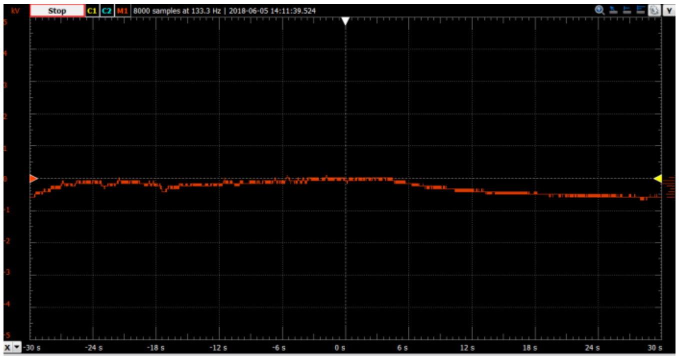
Test 23: Static String and ESD Spray

After testing the ESD spray alone, I ran the same test again with static string and a ground plane. The results are below:

Static String and ESD Spray

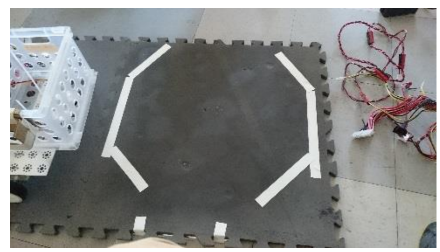


Static String, ESD Spray, and Ground Plane



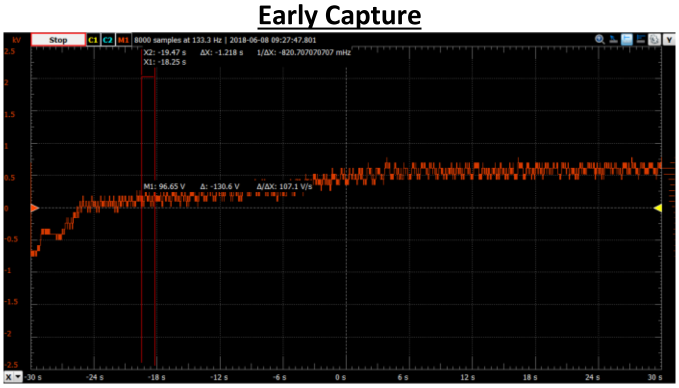
The static string is a large improvement over ESD spray alone. The addition of the ground plane also seems to be a significant improvement over only ESD spray and static string, but the charge buildup is minimal in both cases.

Test 24: ESD Spray Longevity

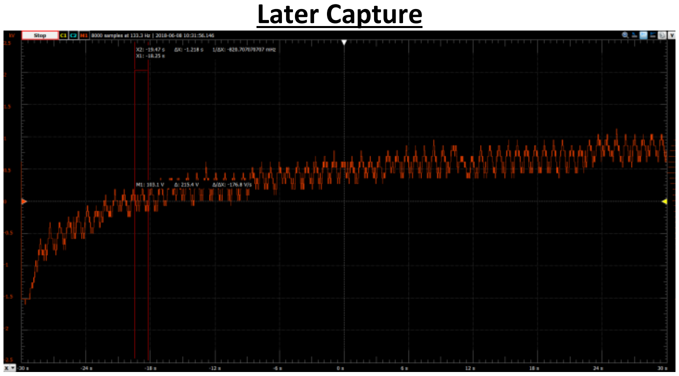


I wanted to assess how frequently the ESD spray should be applied to the tiles, so I set up the test bot to turn back and forth within a set of lines. I ran it briefly to check the charge accumulation, then allowed it to run for an additional hour and checked the charge accumulation again.

Early Capture



Later Capture



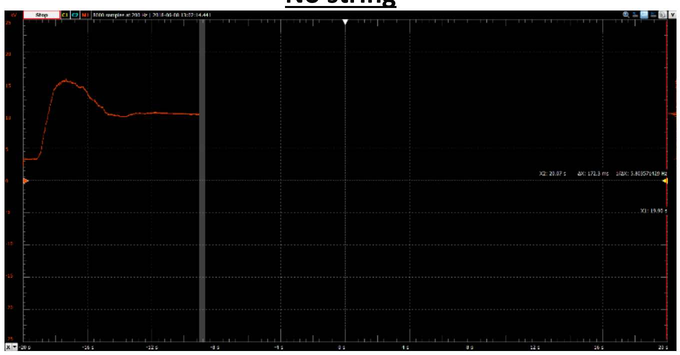
On a few occasions later in the test, I saw the frame voltage get up to a little over 1 kV.

In my rough estimation, this test simulates about as much wear as would be put on the tiles during a day of competition. There was a slight increase in accumulated charge over the course of the test, but charge was still low. This leads me to believe that it would be effective to spray once per event, except at larger events like the half championships and state championships.

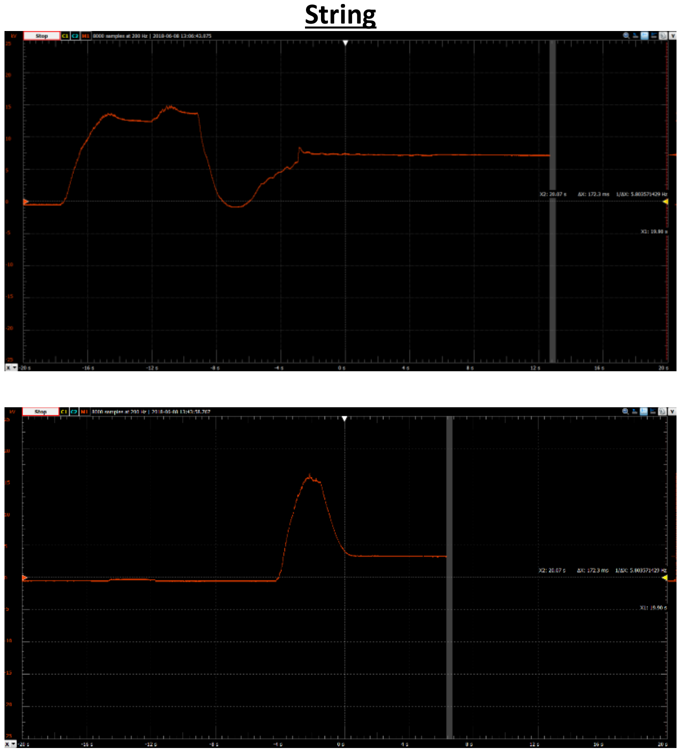
Test 25: More Discharge

These tests mostly repeated some of my early tests, but instead of recording just starting and ending frame voltages, I logged them with the scope attached to the electrostatic field meter. To do these tests, I placed the robot on one end of a strip of three tiles and charged it to around 15 kV with the Van de Graaff generator, then drove it to the other end of the strip. The electrostatic field meter was mounted to its usual place and the cable was taped to the table to prevent it from falling on the ground or touching the frame. The results of the testing were as follows:

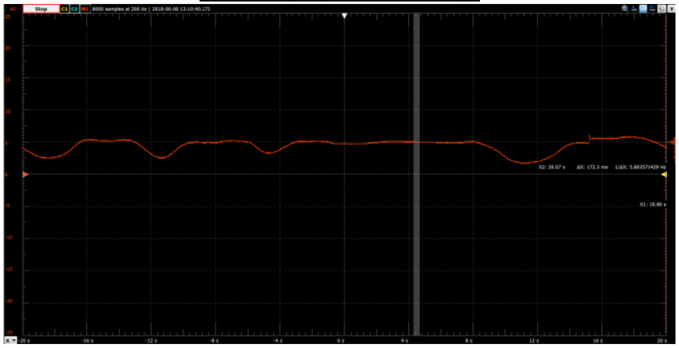
No string



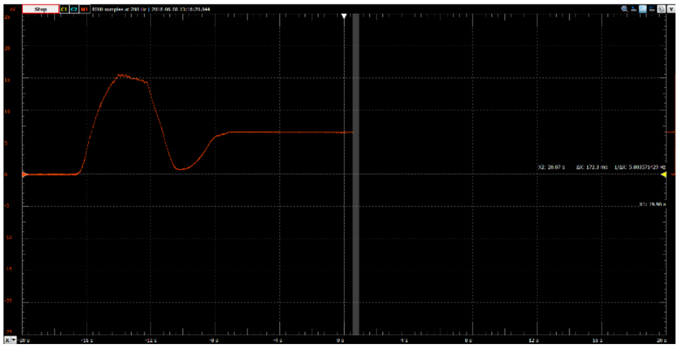
String

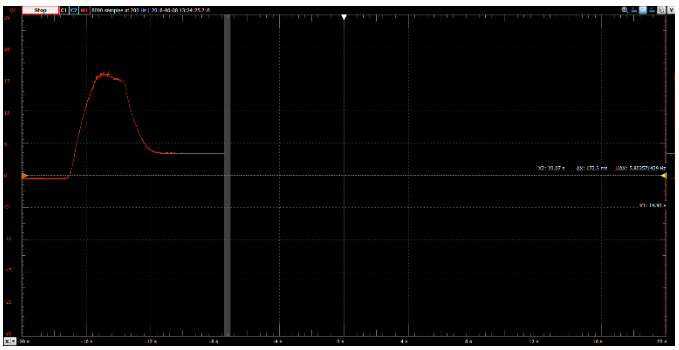


Recharging with string:

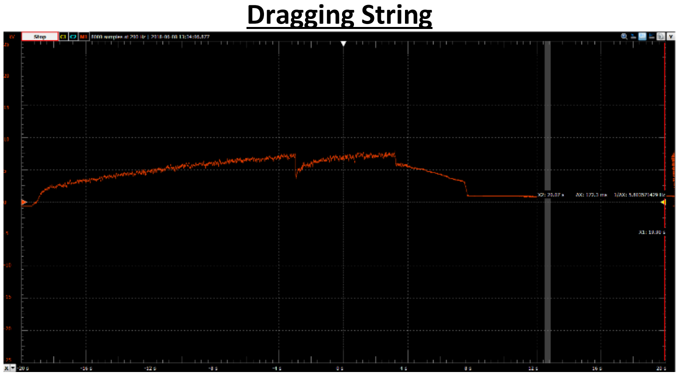


String & Ground Plane



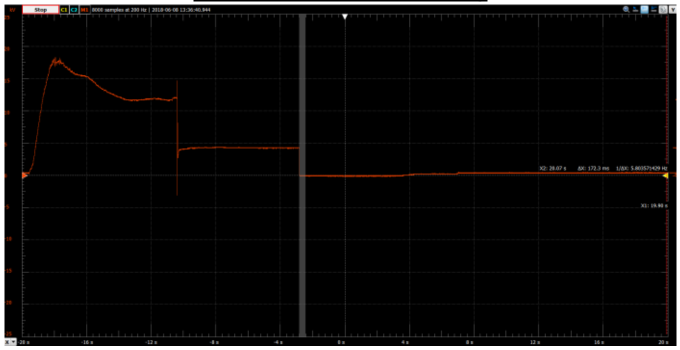


Dragging String

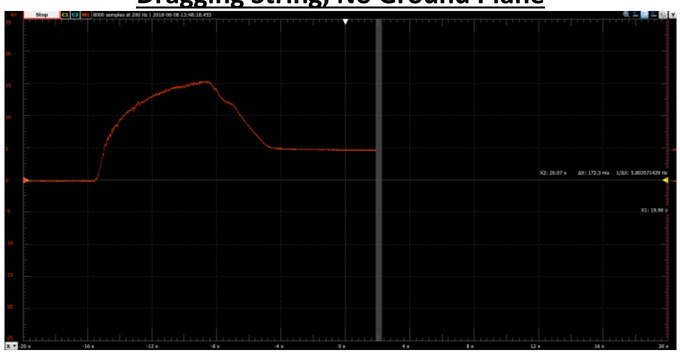


Note: I believe that the static string was arcing to the ground plane at the edge of the tile on charging

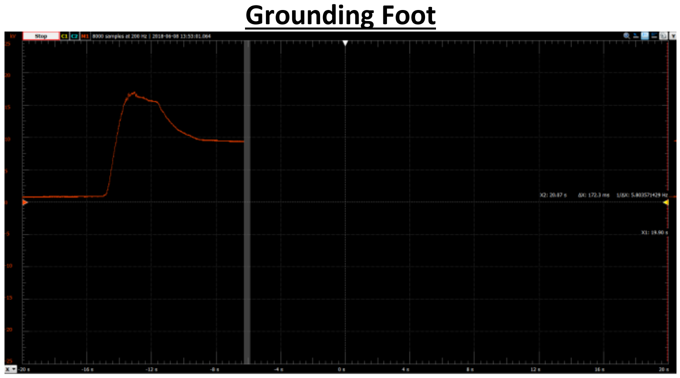
Ground Plane, No String



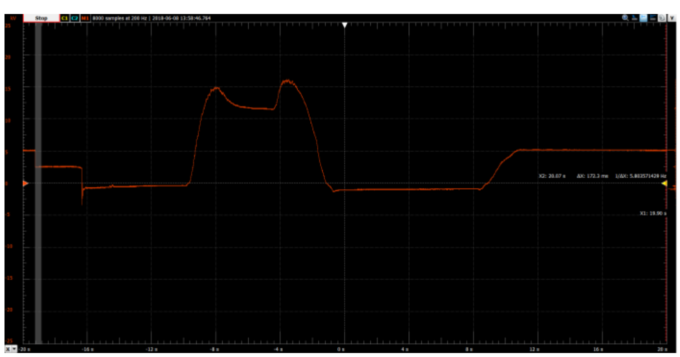
Dragging String, No Ground Plane



Grounding Foot



Dragged String, Perpendicular to Direction of Motion



This testing revealed a few noteworthy things.

In the first few tests, I drove the robot back to the starting position after driving it to the end of the tiles. While driving away, the robot dropped down to a relatively low voltage, but when it drove back, it picked up an interesting amount of charge again. This may be seen nicely in the graph labeled "Recharging with String". I think this is a good thing because it proves that charge on the tiles can have a significant effect on the charging or discharging of the robot when the static string is attached. Since the tiles would always be negatively charged and the robot positively charged, this would increase the rate of charge dissipation in a real-life scenario.

Additionally, the perpendicular dragged string seemed to do just as well as, if not better than, the perpendicular string just above the ground. Its graph is sharper than those of tests where the string was not touching the ground, which indicates that it saturates the tiles with charge more quickly. I think these two methods are probably functionally equivalent in a real-life scenario, though the stretched string is less of an entanglement hazard.

Test 26: Heavy Duty Staticide

Heavy Duty Staticide is marketed as being effective on porous surfaces while the General Purpose Staticide is not, so I wanted to test it to see if it was more durable. I used an identical testing setup to the previous Staticide tests, except that I used Control Hubs and color sensors instead of Modern Robotics electronics because I did not want to deal with the Modern Robotics system.

The Heavy Duty Staticide was extremely effective. The robot did not build up any measurable charge during the hour-long test.

The only downside I see is that the Heavy Duty Staticide has a faint chemical smell reminiscent of an industrial cleaning fluid, which some people might find unpleasant. The smell seemed to mostly go away after the spray had dried, but I may have just gotten used to it.

Conclusions

Summary

Charge Dissipation (Test 8)

Test	Start	End	% Decrease
String, Ground Plane	9.5 kV	2.5 kV	74%
	9 kV	2.3 kV	74%
String, No Ground Plane	9.5 kV	4.4 kV	54%
	10 kV	3.6 kV	64%
No String, Ground Plane	12 kV	7.2 kV	40%
	10.8 kV	6.2 kV	43%
No String, No Ground Plane	12.7 kV	7.5 kV	41%
	13 kV	6.9 kV	47%
String at 1", Ground Plane	11.8	4.4	63%
	11.8	4.3	64%
String Perpendicular to Primary	12.6	5.3	58%
Direction of Motion, Ground Plane	13.3	5.6	58%

Charge Reduction with ESD Spray (Tests 22-24)

Test	Voltage	Notes	Changes to Surface Quality
Nothing	3.5 kV	-	-
General Purpose Staticide	2 kV	Slightly less effective after durability test	Minimal
Heavy Duty Staticide	0 kV	No difference after durability test	Minimal
Water	0 kV	Dries quickly and needs to be re-applied	Slippery

Failure Rates of Different Grounding Resistor Values in Worst Case Scenario Discharge (Test 21)

Grounding Shunt Val.	Pass	Fail
120	10	0
470	10	0
2k	9	1
20k	9	1
200k	7	3
4.7M	10	0

Failure Rates of Different Choke Combinations (Test 18)

Description	Unaffected	Restart	Stuck in Loop
4.7 M Ohm grounding cable, choke on signal wires only, 7.5 kV	3	6	1
4.7 M Ohm grounding cable, choke on all four I2C wires, 7.5 kV	7	3	0
4.7M Ohm grounding cable, no choke7.5 kV	4	6	0
No grounding cable, no choke, 7.5 kV	9	10	1
120 Ohm grounding cable, no choke, 7.5 kV	9	1	0
120 Ohm grounding cable, choke on all four I2C wires, 7.5 kV	9	1	0
120 Ohm grounding cable, choke on all four I2C wires, 13 kV	10	0	0

Note that these tables give only a rough summary of the effectiveness of the various solutions and to understand their full implications, it is best to read all of the testing logs.

Recommendations

I believe that the following solutions (in order of importance) should be considered for use during the 2018-2019 FTC season.

- **Encourage teams to add ferrite chokes to signal wires-** The combination of ferrite chokes and frame grounding proved to make the control system extremely robust in testing and it is very simple to add clip on chokes to wires.
- **Ground the electrical system to the robot frame through a large resistor-** Because it is difficult to perfectly isolate the electrical system, it is important to grounding the electrical system to the frame to prevents shocks from the frame to the electrical system. Testing showed that using a relatively small resistor could mitigate shocks on discharge. This resistor size should have a mandated minimum value of around 100 Ohms to limit current if a power wire is shorted to the frame and to prevent teams from using the frame to carry current. There need not be a maximum allowed resistor value. A reasonable starting value is 470 Ohms because it proved to

work well in testing. This should be made clear to teams and an effort should be made to inform mentors who are not familiar with electrical design principles that grounding the frame does not pose a safety risk.[1]

- **Isolate electronics to prevent arcs-** Isolating the electrical system from the frame can prevent arcing to sensitive components. Electrical isolation includes making sure that there is a large air gap (greater than 3/8" or 1 cm) between any exposed metal in the electrical system and any conductive frame member.
- **Use anti-static spray on floor tiles-** Heavy Duty Staticide substantially reduces or completely eliminates charge buildup and increases the rate of charge dissipation, even without static string or a ground plane. Heavy duty Staticide is designed to work on porous surfaces, like the FTC tiles while other formulations of Staticide are not. It is more durable and more effective.

Items that are Effective but Currently Not Recommended[2]

[Editor's Addition] Although Eric's tests demonstrate that the use of commercial anti-static string, when combined with placing a conductive ground plane underneath the competition field's tiles, is effective at mitigating ESD effects, *FIRST* does not currently recommend using these techniques. Although this technique if effective at reducing the risk of ESD disruptions, it is not practical to implement and presents an entanglement hazard for a robot.

Also, "real-world" testing conducted in the summer of 2018[3] (in Arizona) suggest that the recommended techniques that are listed in the previous section of this document are very effective at mitigating ESD-related effects.

- **Run lengths of anti-static string attached to the frame just above the ground-** Although this technique was shown to be effective, it requires that the anti-static string be mounted low and close to the soft tile surface. It also requires that the string span a direction that is perpendicular to the motion of the robot. This presents a possible entanglement hazard for the robot. *FIRST* does not recommend the use of this method to reduce the risk of an ESD disruption.
- **Add a conductive ground plane underneath the playing field-** This technique is most effective when used in conjunction with commercial anti-static strings mounted on the robots. Since the anti-static strings present an entanglement hazard, and since the use of Heavy Duty Staticide spray is already highly effective, *FIRST* does not recommend the use of a conductive ground plane underneath the playing field.

Next Steps

The testing outlined above has a few glaring limitations: much of it was conducted with testing setups, not real robots, and the humidity in the testing room was much higher than the expected humidity at some competitions, which limits charge build up. While I tried to simulate worst case scenarios with my testing setup, there are almost certainly robots that have ESD issues that fall outside of my testing due to the large

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[1] Editor's Note: the FIRST Tech Challenge rules mandate that teams can only use a FIRST-approved, commercially manufactured resistive grounding strap (such as the REV Robotics cable REV-31-1269).

[2] Editor's Note: Although Eric's testing determined that these techniques were effective at reducing ESD effects, they are not currently recommended by FIRST due to potential entanglement issues.

[3] Thank you FTC Teams 2844, 8081, 10523, 10523a, and 10984, and the volunteer team from Arizona (including Robert Garduno, Susan Garduno, Richard Gomez, Matthew Rainey, Christine Sapio, Patricia Strones, and David Thompson) for assisting with the ESD mitigation testing in the dry Arizona heat!

number of FTC teams. Because the triboelectric effect is dependent on humidity, my testing robot was unable to generate as much charge as teams have reported in the past.

To more accurately characterize static issues in the real world we would need to do more extensive testing at extremely low humidity. It would be informative to do one of the following:

- Build a humidity controlled chamber using an industrial dehumidifier, a frame, and some plastic sheet for characterizing the effectiveness of different solutions low humidity. If the humidity controlled chamber is large enough, FIRST should run a scrimmage inside of it.
- Run a scrimmage in a dry climate, like Arizona, running two fields: one with ESD mitigation and one without. Each team should be given an equal number of matches on each field and certain robots should have their charge logged for the duration of the competition.[4]

Sources:

https://www.researchgate.net/publication/275859607_Effect_of_humidity_and_pressure_on_the_triboelectric_nanogenerator

https://en.wikipedia.org/wiki/Triboelectric_effect

https://en.wikipedia.org/wiki/Corona_discharge

[4]Editor's Note: "Real-world" testing was conducted with the help of volunteers and teams from Arizona in late Summer 2018, after Eric wrote his white paper.