FIRST Tech Challenge®

Guide to Addressing NXT Lockups

Volunteer Thank You

Thank you for taking the time to volunteer for a *FIRST* Tech Challenge Event. *FIRST* and FTC rely heavily on Volunteers to ensure Events run smoothly and are a fun experience for Teams and their families, which could not happen without people like you. With over 4,000 Teams competing annually, your dedication and commitment are paramount to the success of each Event and the FTC program. Thank you for your time and effort in supporting the mission of *FIRST*!

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Revision History		
Revision	**Date**	**Description**
1	9/5/2014	Initial Release

Contents

Introduction

What is the FIRST Tech Challenge?

FIRST® Tech Challenge is a student-centered activity that focuses on giving students a unique and stimulating experience. Each year, Teams participate in a new Game that requires them to design, build, test, and program autonomous and driver-operated Robots that must perform a series of tasks.

Details about setting up a Playing Field can be found on the FTC website after the yearly Game challenge Kickoff.

The Playing Field for the Game consists of the FIRST Tech Challenge Game Pieces set up on a foam-Mat surface, surrounded by a metal and Lexan Field frame. Each Tournament features Alliances, which are comprised of two Teams, competing against one another on the Playing Field. Teams work to overcome obstacles and meet challenges, while learning from and interacting with their peers and adult Mentors. Students develop a greater appreciation of science and technology and how they might use that knowledge to impact the world around them in a positive manner. They also cultivate life skills such as:

- Planning, brainstorming, and creative problem-solving.
- Research and technical skills.
- Collaboration and Teamwork.
- Appreciation of differences and respect for the ideas and contributions of others.
- To learn more about FTC and other FIRST Robotics Competitions, visit www.usfirst.org.

FIRST Tech Challenge (FTC) Core Values

Volunteers are integral to the *FIRST* community. The *FIRST* Tech Challenge relies on Volunteers to run the program at many levels, from managing a region to Mentoring an individual Team. FTC Affiliate Partners coordinate the program in each region or state. These FTC Partners fundraise, run Tournaments, hold workshops and demonstrations, market FTC locally, handle public relations, and recruit Volunteers and Teams. They are a tremendous resource for Mentors and FTC would not exist without them.

FIRST asks everyone who participates in FTC to uphold the following values:

- We act with integrity.
- We are a Team.
- We do the work to get the job done with guidance from our Coaches and Mentors.
- We respect each other in the best spirit of Teamwork.
- We honor the spirit of friendly Competition.
- What we learn is more important than what we win.
- We behave with courtesy and compassion for others at all times.
- We share our experiences with others.
- We display Gracious Professionalism in everything we do.
- We have fun.
- We encourage others to adopt these values.

What is the FIRST Tech Challenge Guide to Addressing NXT Lockups?

The purpose of the *FIRST* Tech Challenge Guide to Addressing NXT Lockups is to:

- Identify conditions necessary for a lockup to occur.
- Present Robot design considerations to help reduce or eliminate the problem.
- Provide a simple method to Test designs for susceptibility to lockup.

Acknowledgements

This guide would not be possible without the contributions of time, ideas, and resources provided by the following people:

- Dale Jordan – primary author – FTA, Oregon.
- FTC Team 4318, Andrew Driesman mentor – Maryland, for ESD tutorial descriptions.
- Tom McGovern – FTA, Missouri – for his initial ESD Testing efforts.

Gracious Professionalism™

FIRST uses this term to describe the program's intent. This is one of the most important concepts that can be taught to a young person who is learning to get along in the work world. At *FIRST*, Team members help other Team members, but they also help other Teams.

Gracious Professionalism is not clearly defined for a reason. It can and should mean different things to everyone.

Some possible meanings of Gracious Professionalism include:

- Gracious attitudes and behaviors are win-win.
- Gracious folks respect others and let that respect show in their actions.
- Professionals possess special knowledge and are trusted by society to use that knowledge responsibly.
- Gracious Professionals make a valued contribution in a manner pleasing to others and to themselves.

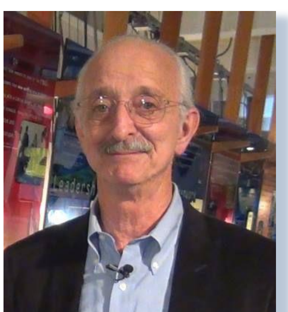
An example of Gracious Professionalism is a Team loaning a spare Motor to a competitor Team.

In the context of *FIRST*, this means that all Teams and participants should:

- Learn to be strong competitors, but also treat one another with respect and kindness in the process.
- Avoid leaving anyone feeling as if they are excluded or unappreciated.
- Knowledge, pride and empathy should be comfortably and genuinely blended.

In the end, Gracious Professionalism is part of pursuing a meaningful life. When professionals use knowledge in a gracious manner and individuals act with integrity and sensitivity, everyone wins, and society benefits.

Watch Dr. Woodie Flowers explain Gracious Professionalism in this short video.



"The FIRST spirit encourages doing high-quality, well-informed work in a manner that leaves everyone feeling valued. Gracious Professionalism seems to be a good descriptor for part of the ethos of FIRST. It is part of what makes FIRST different and wonderful."

- Dr. Woodie Flowers, National Advisor for ***FIRST***

FIRST Youth Protection Program

The purpose of the *FIRST* Youth Protection Program (*FIRST* YPP) is to provide coaches, mentors, volunteers, employees, others working in *FIRST* programs, team members, parents, and guardians of team members with information, guidelines, and procedures to create safe environments for everyone participating in *FIRST* programs.

The *FIRST* YPP sets minimum standards recommended for all *FIRST* activities. Adults working in *FIRST* programs must be knowledgeable of the standards set by the *FIRST* YPP, as well as those set by the school or organization hosting their team.

Youth Protection Expectations and Guidelines

Coaches and Mentors are expected to read and follow elements in the *FIRST* Youth Protection Program guide that are labeled as required are mandatory in the United States and Canada, and may not be waived without the approval of the *FIRST* Youth Protection Department.

FIRST recommends that the standards set forth in the *FIRST* Youth Protection Program guide be applied outside of the United States and Canada to the extent possible. At a minimum, local regulations regarding youth protection must be complied with.

Forms are available here: http://www.usfirst.org/aboutus/youth-protection-program

Information on the US Screening process is available here: http://www.usfirst.org/sites/default/files/uploadedFiles/About_Us/US-Youth-Protection-Clearance-Process.pdf

Everyone working with FIRST Teams should be familiar with the *FIRST* YPP policies.

Information on the Canadian Screening process is available here: http://www.usfirst.org/sites/default/files/uploadedFiles/About_Us/Canadian-Youth-Protection-Clearance.pdf

You can find FAQ and additional information about the *FIRST* Youth Protection Program on the FIRST website at: http://www.usfirst.org/aboutus/youth-protection-program

NXT Lockups

During an FTC Match, occasionally a Robot will make contact with another Robot or field perimeter and it will freeze. Connection to the Field Control System (FCS) is lost and attempts to reconnect it fail. The front panel buttons on the NXT are not responsive and the only way to restore control is to pull the NXT battery and reinsert it. In rare cases the NXT memory is also corrupted and requires a firmware download along with all the programs and setup information. At some Tournaments this happens rarely if at all, while at other Tournaments it is frequent.

Electro-Static Discharge

An NXT lockup is triggered by an Electro-Static Discharge (ESD) event. ESD is the sudden flow of electricity between two objects that are electrically charged to different voltage potentials. Lightning is a form of ESD, as is getting a shock from touching a door knob.

For an ESD event to occur, a charge difference between the Robot and another Robot or field perimeter must exist. The primary source of this charge difference comes from triboelectric charging. The prefix tribo- is Greek meaning “to rub”. When two dissimilar Materials come in contact and are rubbed together or just pulled apart, charge is transferred between them.

The polarity and strength of the charges produced differ according to the Materials, surface roughness, temperature, humidity and other properties. This makes it very hard to predict how much charge will build up between any set of Materials. However, a rough comparative estimate can be made by looking at the Materials involved. All Materials have a tendency to gain or lose electrons (affinity). The larger the difference in this affinity, the more charge is likely to be transferred. Appendix E: The TriboElectric Series, provided by AlphaLab, contains a detailed list of Materials sorted by their affinity.

When a charge has been built up on a Robot, it produces an electric field. Anything within this field will experience an electric force. In this case, the NXT, connecting cables, and other electronic devices will feel this force. These being electrical devices, electrons within them will reposition themselves based on the forces they feel. This is known as an induced electric field.

Finally, when an ESD event occurs, a chain of events happens very rapidly, causing normal electronic operation to be upset:

1. ESD causes charge to rapidly move through the Robot;
2. The electric field on the Robot is changing rapidly as it follows the charge;
3. This in turn causes the induced electric field in electrical component to rapidly change as well; and
4. The induced field change leads to voltage and current changes inside the NXT in unintended ways. For example, a large positive voltage can be induced on the ground wires, which momentarily reverses polarity on the electronics. In short, when this happens, the electronics become nonfunctional.

To summarize, for an NXT lockup to occur, three conditions must be met:

1. A Robot must build up a charge;
2. The Robot comes into contact with another Robot or field perimeter that has a sufficiently different charge to trigger an ESD event. Even if a Robot has not built up a charge, it is still susceptible to an ESD event if it comes in contact with a charged Robot; and
3. Sensitive electronics (NXT, cabling, etc.) experience large enough induced fields to cause the NXT to lock up.

Building Charge on the Robot

Contact Friction

The most common means of charge build-up on the Robot is contact between the wheels and the Playing Field foam Mat. This can vary widely depending on the types of wheels used. For example, many Robots use the TETRIX OMNI Wheels. The centers of these wheels are made of nylon and some point of this center is almost always in direct contact with the Mat. The Mats are made of EVA (ethylene vinyl acetate) foam. Both these Materials sit quite far apart in the Triboelectric Series, with nylon being on the positive side (+30 on the affinity scale) and EVA being on the negative side (-55 on the affinity scale). When the two Materials rub against each other the nylon easily gives up electrons and the Mat readily accepts these electrons. This leads to the Robot building up a positive charge and the Mat having a negative charge in places where the wheels have been.

Other sources of charge build-up include:

- Manipulators interacting with game elements and the Mat; and
- Moving elements on the Robot, such as a conveyor belt rubbing on slides.

Humidity

Humidity is also a major contributing factor to the level of charge that will build up. In very damp climates where the humidity is 50% or greater, almost no lockups are reported. When the humidity is between 35-45%, NXT lockups occur at a rate of a little over 1%. In very low humidity conditions, lockup rates in excess of 10% have occurred.

To discover the effects of humidity, experiments were run to observe the static build-up as humidity was varied (detailed in Appendix A: Measuring Charge Build-Up). For a basic Robot, for high humidity levels, charge buildup was less than 1kV, but as the humidity levels dropped to around 30%, the buildup went as high as 15kV (Table 1 in Appendix A).

Determining Sensitive Design Conditions for Lockup

Wiring and component placement play an important role in determining how susceptible the Robot is to locking up. Numerous experiments were conducted (Appendix B: NXT Lockup Tests) to find these placement issues. The most sensitive element is the length and placement of the USB cable between the NXT and the Samantha Module. Running a cable along the Chassis or having excess cable lengths make the NXT very susceptible to lockup. In the Tests performed, running a 6-foot USB cable around the Chassis caused the NXT to lockup with as little as 9kV of charge. This is well below the level of charge that can be built up on the Robot between the wheels and the Mat.

Design Practices to Avoid Lockup

Three conditions must occur for a lockup to happen. Avoiding any one of these should keep the NXT running.

Reducing Static Buildup

This condition can most easily be addressed at the venue by the use of a good antistatic spray. Two commercial antistatic sprays were Tested (Appendix C: Antistatic Spray Testing) and found to be very effective at reducing static. However, they do lead to increased friction which can have an impact on Robot performance. In environments where the relative humidity is less than 45%, use of this spray should strongly be considered as the positive benefit outweighs the negative impact.

Teams are encouraged to check with Tournament Hosts to see if they will be using antistatic spray at their event. Since the use of antistatic sprays increases the friction between the Robot and the Mat, if at all possible, Teams should Test their Robots using Mats that have been coated with the antistatic spray before going to a Tournament and make adjustments as necessary.

In addition, Teams should pay attention to the types of Materials they use, especially when they will rub against other Materials. If the affinities of these Materials are very similar, there should be little charge built up between them. For example, if a manipulator were to be in regular contact with the Mat, having an affinity near that of the Mat would minimize the charge build up (such as PET Materials or Gum Rubber).

Reducing Rapid Discharges

Rapid charge transfers are necessary to induce the currents needed to disrupt the electronics. Shielding the exterior of the Robot, including any screw heads with insulating Material will limit the rate of charge transfers. Many Teams have done this and have had great success in keeping their NXT functioning.

Reducing Induced Currents in the Electronics

The most sensitive point for locking up the NXT is inducing currents into the USB cable. The following solutions have been shown to be effective at minimizing the problem:

1. Keep the USB cable short and away from conducting elements on the Chassis.
2. In cases where the USB cable must pass next to conducting elements, add a USB surge protector on a short cable next to the NXT. A longer cable can then run along the Chassis to the Samantha Module.
3. A cheaper, but slightly less effective solution is to place a Ferrite Choke on the USB cable next to the NXT and only use as long a cable as needed.
4. For more information on wiring solutions to reduce current, see the FTC Robot Wiring Guide.

Pictures of these solutions are shown in Table 2 in Appendix B.

Many other methods can be used to protect the NXT. If using other methods, they should be tested before entering competitions. A simple way to do this is to set up a Test Environment similar to that in Appendix B. If you don't have access to a static voltmeter, you can apply the Van De Graaf generator for a few seconds to the Robot to build up sufficient charge for Testing. The Van De Graaf Generator used for Testing in Appendix B needed less than 5 seconds to place a 20kV charge on the Robot. **CAUTION: before doing this, be aware that ESD Events can cause irreversible damage to electronic devices.**

Even though Testing other electronics elements (NXT input cables and motor controllers) did not show large sensitivities to ESD, it is still important to follow good wiring practices and keep these components away from the conducting parts of the Chassis as much as possible. For more information on best practices for wiring, refer to the FTC Robot Wiring Guide.

Appendix A – Measuring Charge Build-up

To measure the charge build-up, a Test Environment representative of a Tournament Environment was set up.

The Test Environment consisted of a small room, air conditioner, dehumidifier, a few floor tiles, FCS system, TETRIX Robot, thermometer/hygrometer, and an electrostatic voltmeter. Figure 1 (below) shows the Test configuration.

The Robot is a square-bot incorporating two standard TETRIX wheels and two TETRIX OMNI wheels. The electronics are shock-mounted on a piece of polycarbonate so they are well isolated from the Chassis.

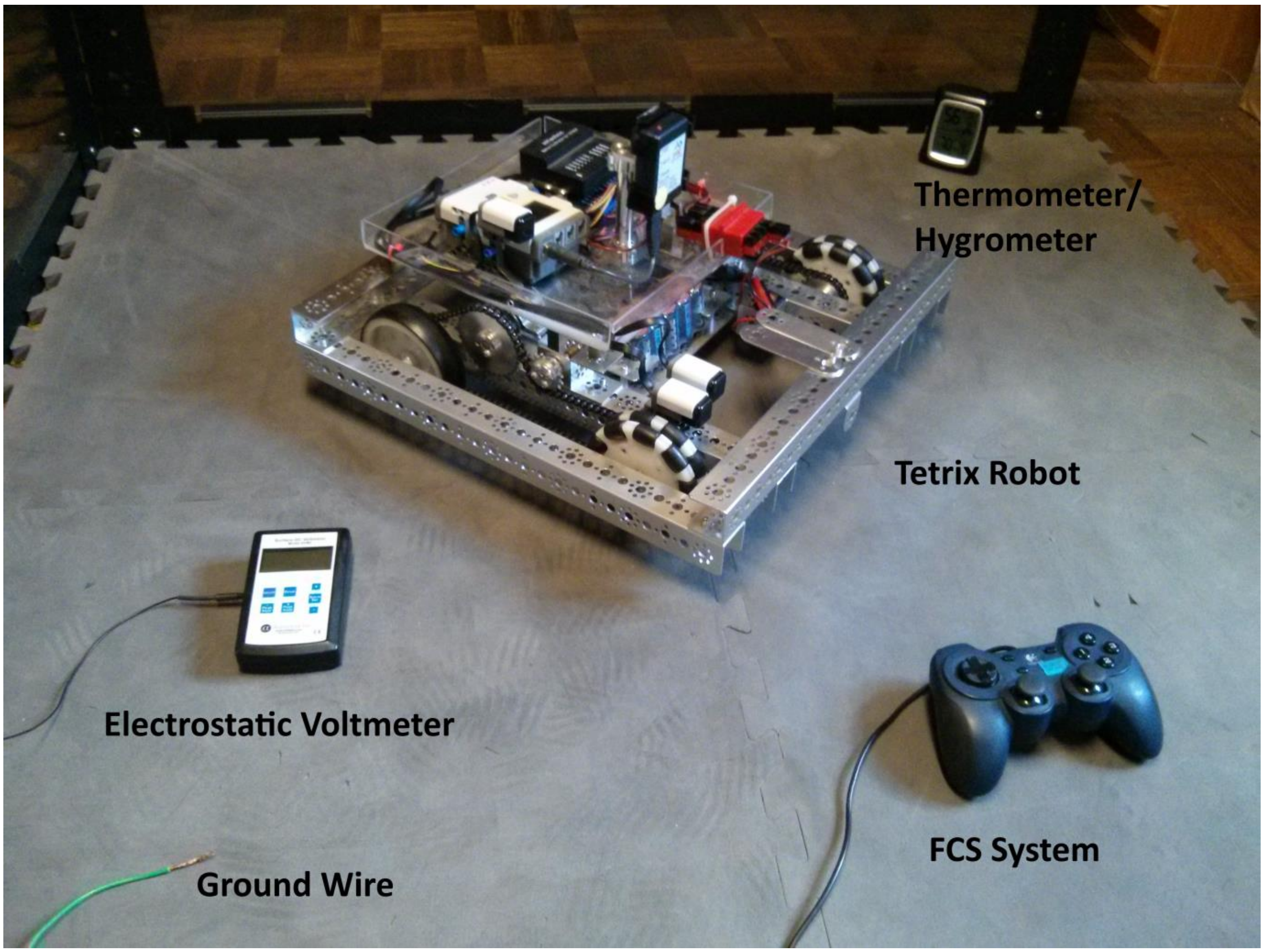


Figure 1 -- Test Setup

For measuring charge buildup, the following procedure was repeated numerous times and the maximum voltages recorded.

1. Using the air conditioner and dehumidifier, set the room to the desired temperature and humidity.
2. With the Robot in the center of the Mat, spin in-place for 10 revolutions, and then move it forward a bit so Mat voltages can easily be measured.
3. Quickly measure the voltage on the Robot. Flat plates mounted on the front provide sufficient surface area to easily do this.
4. Scan over the Mat with the static voltmeter in the area the Robot travelled and identify the peak voltages.

Table 1 (below) summarizes the results for the measured charge buildup at various humidity levels.

Humidity	Temp.	Max Robot Voltage (+)	Max Mat Voltage (-)
66%	70°F	500V	600V
47%	72°F	3kV	3.5kV
35%	75°F	9.3kV	15kV
31%	72°F	15kV	8kV

Table 1 -- Charge Buildup at Various Humidity Levels

Appendix B – NXT Lockup Tests

The purpose of this Test was to find Robot configurations that are sensitive to NXT lock up.

These Tests require putting a known static voltage on the Robot. An inexpensive way to do this is with a handheld Van De Graaf generator (Figure 2). The FunFlyStick Van De Graaf Generator is a part of a science kit and can be purchased on Amazon for around $30. This coupled with the static voltmeter make it possible to set a known voltage on the Robot.

Figure 2 -- FunFlyStick Van De Graaf Generator

Testing Procedure

The basic Robot (

Figure 3 3 (below)) has all the main electronics on a polycarbonate platform that is well isolated from the Chassis. This configuration does not exhibit any lockup issues. Modifications to this Robot were selectively made to discover which elements and placement will cause it to lock up. For each trial the following procedure was performed.

1. Configure the Robot for Testing and place it a few inches from the FTC field perimeter.
2. Start the FCS system running with the Robot connected.
3. Set the desired charge on the Robot with the Van De Graaf Generator and static voltmeter.
4. Using the FCS, drive the Robot a few inches into an FTC wall to trigger an ESD event.
5. Check to see if the NXT locked up.

Safety

When setting the charge on the Robot, the static voltmeter was used to monitor the charge as the Van De Graaf generator was run. In doing this the operator needs to be well grounded, since the generator is moving charge between the Robot and the operator's hand. Failure to do this, results in the operator having the opposite charge of the Robot and touching anything results in a nasty shock.

Observations
Many modifications to the wiring of the motor controllers and USB cable were tried. The technique that produced the most consistent failures was swapping out the short USB cable for a 6 foot cable. The excess cable was wrapped around the C-channel at the front of the Chassis (Figure 4 (below)). **Note: it is quite common to see 6-foot USB cables on Teams' Robots.** With this configuration these observations were made:

- Charge levels of 10kV or more caused the Robot to lockup almost every time it was driven into the wall; and
- At slightly less than 9kV no more lockups occurred.

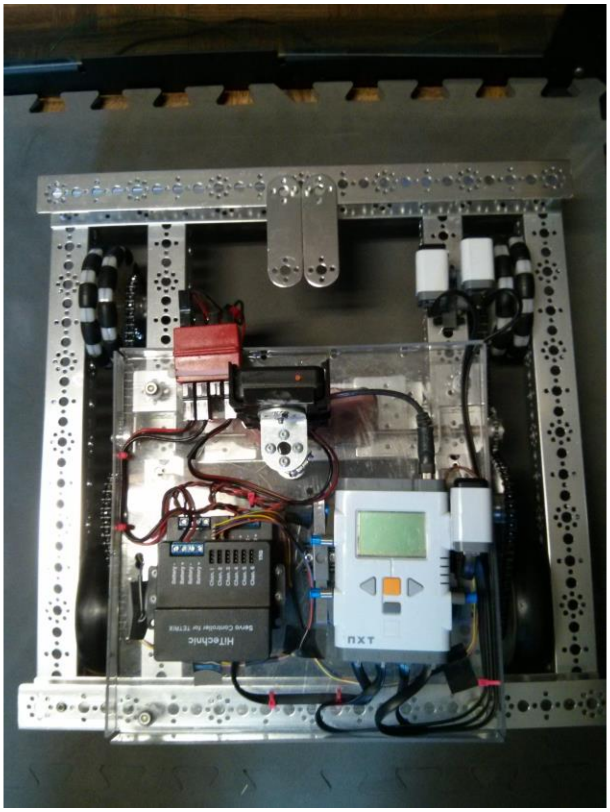


Figure 3 -- Basic Test Robot

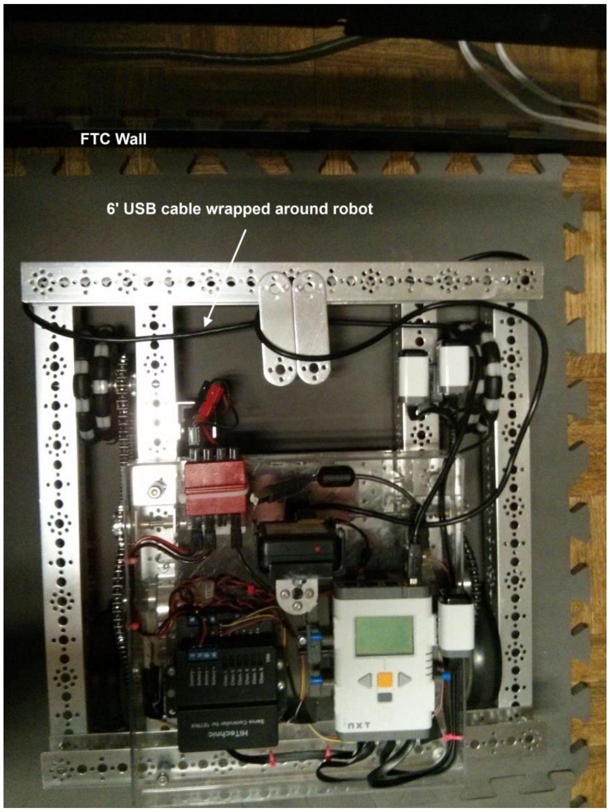
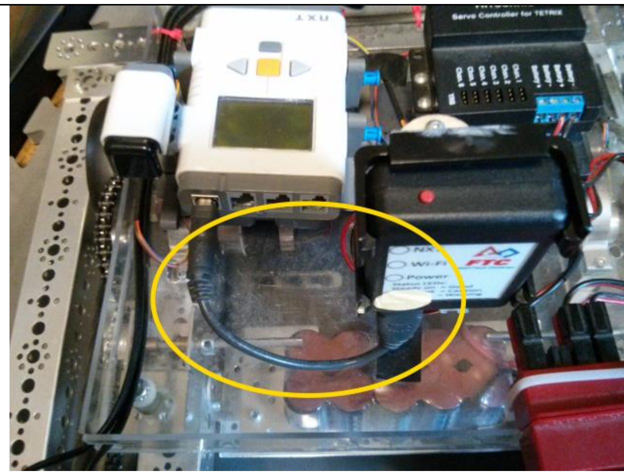
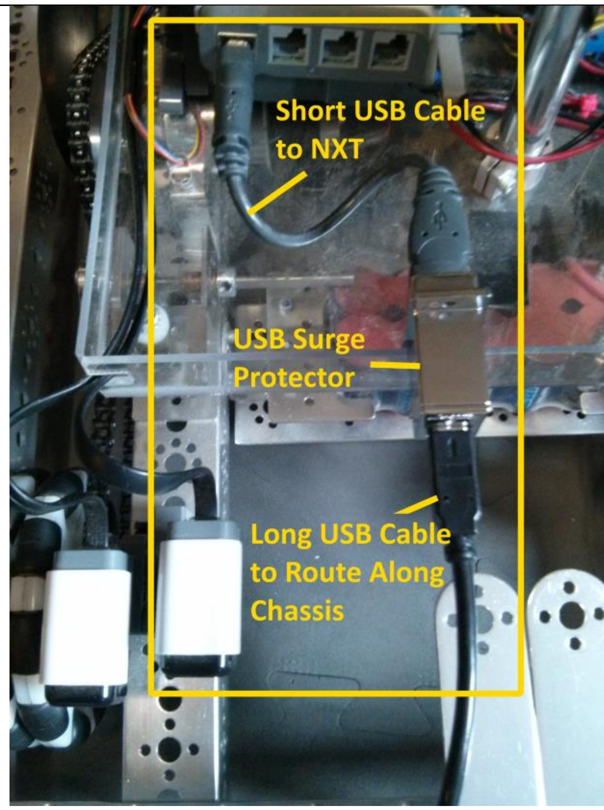


Figure 4 -- Cabling to cause Lockup

Reducing NXT Lockups

Three methods for reducing lockups were explored:

Use a very short USB cable and keep it well away from the Chassis. This was in the base Robot configuration which never experienced a lockup.	
Install a USB surge protector with a short cable to the NXT. The one Tested can be purchased from L-com.com (Item # AL-ECF504-AB) and sells for around $18. This item stopped all lockups at any voltage applied to the Chassis.	

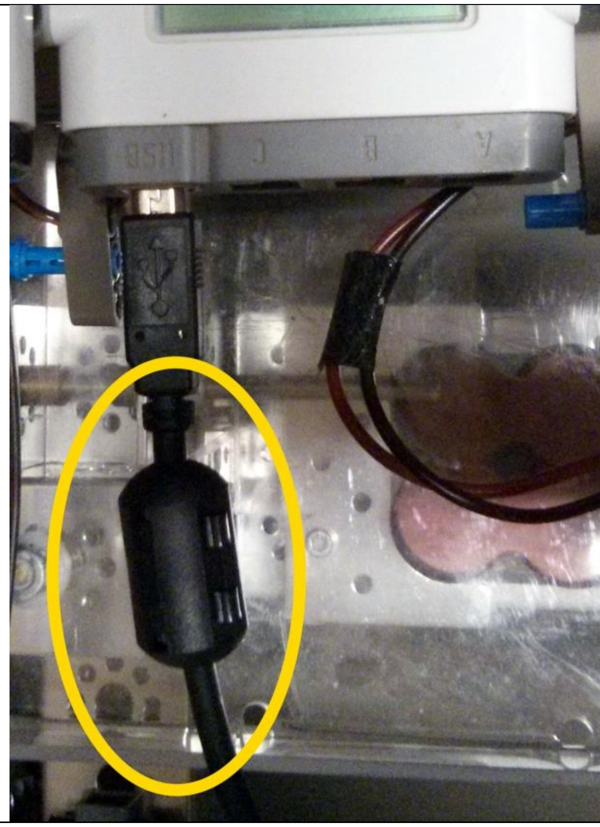
Put a Ferrite Choke on the cable next to the NXT. These Chokes are very inexpensive ($1.50) and easy to install. The Ferrite Choke prevented most lockups with 10kV of charge or less. It was far less effective as the charges grew above this to higher levels.	

Table 2 – Recommendations to Reduce Lockups from the USB Cable

For more information on best practices for wiring, refer to the FTC Robot Wiring Guide.

Appendix C – Antistatic Spray Testing

Charge build-up between the Mat and Robot is a major contributor to causing NXT Lockups. This section explores ways to reduce this build-up. In addition to examining the effectiveness of a solution, other possible negative impacts caused by these solutions were explored. These explorations addressed the following things:

- How much is static build-up reduced?
- How long does the solution last?
- How long does it take after application for Fields to be playable?
- Does it change the friction on the Playing surface?
- How well does Gaffers Tape stick to it?
- How easily can it be washed off?

Sprays Tested

One homemade and two commercial sprays were tested along with water and an untreated Mat for reference:

- Water was just misted on for a slightly damp surface.
- A homemade spray that consisted of mixing three tablespoons of liquid fabric softener with one quart of water.
- The commercial spray ZERO CHARGE® ANTI-STAT.
- The commercial spray Staticide.

Effectiveness Tests

The same procedure used in Appendix A was run for these Tests. The temperature was set to 70° and the humidity set to 31%. Table 3 shows the results of these Tests.

Longevity Tests

Longevity Tests were carried out on the commercial sprays. These were effectiveness Tests run over time. For the first day, Tests were run every two hours. In that first day a wear Test was also performed for one hour where the Robot was continuously run with only short breaks to take static voltage measurements. For subsequent days, Tests were run just a couple of times each day. Both sprays continued to be effective for over a week.

Friction Tests

Applying any coating to the Mats can alter its characteristics. Appendix D describes the friction Test procedure. Both commercial sprays showed significant increases in the friction coefficient.

Drying Time

After applying the spray the Mats are very slippery. The commercial sprays require a half an hour or more to sufficiently dry before they could be used. A good time to apply the spray is right after the field is first setup so it is dry before the first Matches are run.

Tape Test

To Test the Gaffers Tape adhesion to the Mats, a strip of tape was applied to the Mat coated with the different sprays as well as new and used untreated Mats. Used, untreated Mats require a fair amount of force to remove the tape, while a new Mat required very little. On the new Mat, the tape did stick well enough for Tournament action. For the Mat treated with Staticide, just slightly less force was needed to remove the tape than for a new untreated Mat. The ZERO CHARGE spray required very little force and could come loose during Tournament play.

If using commercial sprays, the Mats should be taped before applying the spray. If using the same Mats for multiple Tournaments several options should be considered to improve the tape adhesion:

1. Label all Mats and always assemble in the same way so that the tape can be put down in the same place each time.
2. As in the suggestion #1 above, but also pre-tape and cut along the seams of the tiles. Initially, this can take a fair amount of time, but speeds up the setup time for each Tournament.
3. If the tape is not adhering well, wash the Mats between Tournaments.
4. Consider using a Gaffers Tape with stronger adhesive qualities.

Cleanup Tests

All sprays easily washed off with a sponge and running water. However, Staticide tended to leave a little more residue. The easiest way to wash them was in a large sink or bath tub with warm running water. After that they needed to be air dried. All parts of the Mat need to be exposed to the air to effectively dry. Using a fan to blow air across them really speeds up the process.

Summary of Antistatic Spray Testing

Some of the key measured results are summarized in Table 3.

Antistatic spray Tests – humidity 31%, temperature 70°				
Spray	Max Robot Voltage (+)	Longevity	Friction Coefficient	Drying Time (minutes)
untreated	15kV	-----	0.45 – 0.75	-----
Homemade (1)	4.5kV	-----	-----	10
Zero Charge	150V	> 1 week	0.65 – 1.1	45
Staticide	210V	> 1 week	0.55 – 1.3	30
water	0	10-15 minutes	0.45 – 0.9(2)	-----

Table 3 -- Antistatic Spray Test Results

Notes:

1) Homemade spray required a heavy coat in order to last more than a few minutes.
2) Water is effective as long as visible signs of dampness are present. If the Mats are very wet, the coefficient of friction is very low, but as they dry out it increases to a level a little above the dry Mat before returning to the dry Mat condition. The variance in the numbers is strongly related to the variance in the Mats Tested. Typically the peak coefficient of friction was 0.1 above the dry Mat coefficient.

Appendix D – Friction Tests

Friction is highly dependent on the type of wheels used. For these Tests, the standard TETRIX Wheels were used. A lightweight cart was constructed from TETRIX Components. The wheels were locked in place so that they would be forced to slide. This cart, weighing only 0.95 lbs., was used as to not deform the Mat and possibly impact the measurement results. The cart was attached by a string over a pulley to a bucket (Figure 5). Gravel was added to the bucket until the cart started to slide. The weight of the bucket was then compared to the weight of the cart to determine the coefficient of friction via the formula:

$$\mu = \frac{w_{bucket}}{w_{cart}}$$

In doing these Tests there was typically no measureable difference static and dynamic friction and usually the cart would slide at a constant speed when just enough weight was added to the bucket.

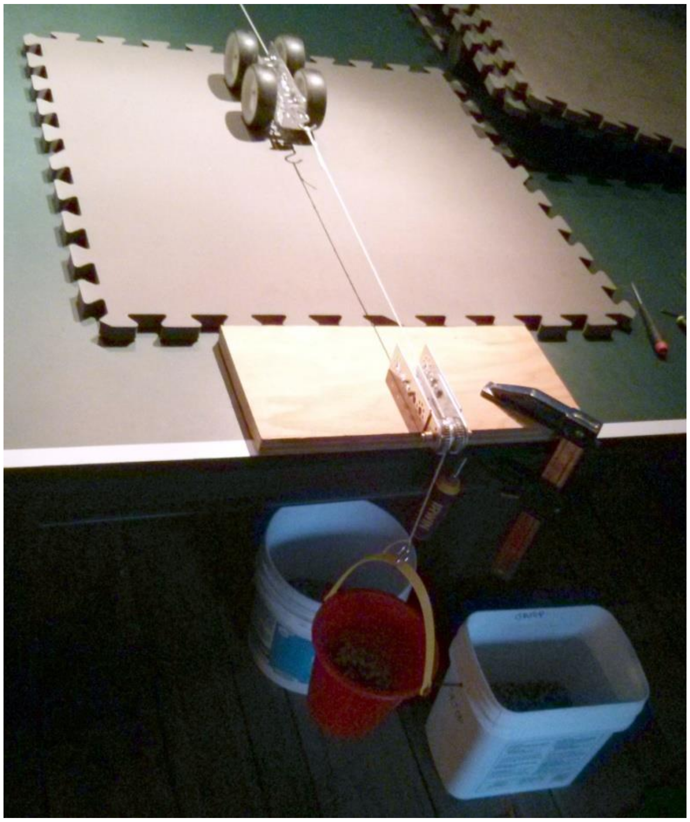


Figure 5 -- Friction Test Setup

Testing the friction for the Mats proved to be difficult. Individual Mats have a wide variance (different manufacturing lots, new vs. old, and how scuffed up they were). The TETRIX wheels tended to wear easily which slightly impacted repeated Tests. Also the spray on the Mats tended to get embedded in the wheels and they had to be carefully cleaned between Tests. In addition, it was very difficult to thoroughly clean the spray from the Mats and residue left behind impacted the Tests as well.

Appendix E – The TriboElectric Series (From AlphaLab Inc.)

When two different Materials are pressed or rubbed together, the surface of one Material will generally steal some electrons from the surface of the other Material. The Material that steals electrons has the stronger affinity for negative charge of the two Materials, and that surface will be negatively charged after the Materials are separated. (Of course the other Material will have an equal amount of positive charge.) If various insulating Materials are pressed or rubbed together and then the amount and polarity of the charge on each surface is separately measured, a very reproducible pattern emerges. For insulators, the table below can be used to predict which will become positive vs. negative and how strong the effect will be.

This table can be used to select Materials that will minimize static charging. For example, if uncoated paper (with a positive charge affinity value of +10 nC/J) is squeezed by a pinch roller made of butyl rubber (@-135 nC/J), there will be about 145 pico coulombs of charge transfer per joule of energy (associated with pinch and friction). This is about 20 times more than 7 nC/J, which is the static charge per joule that results from squeezing paper with a roller made of nitrile rubber (@+3 nC/J). In general, Materials with an affinity near zero (e.g. cotton, nitrile rubber, polycarbonate, ABS) will not charge much when rubbed against metals or against each other. The table can also be used (with other formulas) to predict the static forces that will arise between surfaces, and to help select Materials that will create an intentional charge on a surface. See further information on interpretation below the table.

TriboElectric Table

Column 1 (this col.): Insulator name. Col.2: Charge affinity in nC/J (nano ampsec/wattsec of friction). Col.3: Charge acquired if rubbed with metal (W=weak, N=normal, or consistent with the affinity). Col.4: Notes.	Affinity nC/J	Metal effect	**TriboElectric Table** Tests were performed by Bill Lee (Ph.D., physics). ©2009 by AlphaLab, Inc. (TriField.com), which also manufactured the Test equipment used. This table may be reproduced only if reproduced in whole.
Polyurethane foam	+60	+N	All Materials are good insulators (>1000 T ohm cm) unless noted.
Sorbothane	+58	-W	Slightly conductive. (120 G ohm cm).
Box sealing tape (BOPP)	+55	+W	Non-sticky side. Becomes more negative if sanded down to the BOPP film.
Hair, oily skin	+45	+N	Skin is conductive. Cannot be charged by metal rubbing.
Solid polyurethane, filled	+40	+N	Slightly conductive. (8 T ohm cm).
Magnesium fluoride (MgF2)	+35	+N	Anti-reflective optical coating.
Nylon, dry skin	+30	+N	Skin is conductive. Cannot be charged by metal rubbing.
Machine oil	+29	+N	

Nylatron (nylon filled with MoS_2)	+28	+N	
Glass (soda)	+25	+N	Slightly conductive. (Depends on humidity).
Paper (uncoated copy)	+10	-W	Most papers & cardboard have similar affinity. Slightly conductive.
Wood (pine)	+7	-W	
GE brand Silicone II (hardens in air)	+6	+N	More positive than the other silicone chemistry (see below).
Cotton	+5	+N	Slightly conductive. (Depends on humidity).
Nitrile rubber	+3	-W	
Wool	0	-W	
Polycarbonate	-5	-W	
ABS	-5	-N	
Acrylic (polymethyl methacrylate) and adhesive side of clear carton-sealing and office tape	-10	-N	Several clear tape adhesives have an affinity almost identical to acrylic, even though various compositions are listed.
Epoxy (circuit board)	-32	-N	
Styrene-butadiene rubber (SBR, Buna S)	-35	-N	Sometimes inaccurately called "neoprene" (see below).
Solvent-based spray paints	-38	-N	May vary.
PET (mylar) cloth	-40	-W	
PET (mylar) solid	-40	+W	
EVA rubber for gaskets, filled	-55	-N	Slightly conductive. (10 T ohm cm). Filled rubber will usually conduct.
Gum rubber	-60	-N	Barely conductive. (500 T ohm cm).
Hot melt glue	-62	-N	
Polystyrene	-70	-N	
Polyimide	-70	-N	
Silicones (air harden & thermoset, but *not* GE)	-72	-N	
Vinyl: flexible (clear tubing)	-75	-N	
Carton-sealing tape (BOPP), sanded down	-85	-N	Raw surface is very + (see above), but close to PP when sanded.
Olefins (alkenes): LDPE, HDPE, PP	-90	-N	UHMWPE is below. Against metals, PP is more neg than PE.
Cellulose nitrate	-93	-N	
Office tape backing (vinyl copolymer ?)	-95	-N	

UHMWPE	-95	-N	
Neoprene (polychloroprene, *not* SBR)	-98	-N	Slightly conductive if filled (1.5 T ohm cm).
PVC (rigid vinyl)	-100	-N	
Latex (natural) rubber	-105	-N	
Viton, filled	-117	-N	Slightly conductive. (40 T ohm cm).
Epichlorohydrin rubber, filled	-118	-N	Slightly conductive. (250 G ohm cm).
Santoprene rubber	-120	-N	
Hypalon rubber, filled	-130	-N	Slightly conductive. (30 T ohm cm).
Butyl rubber, filled	-135	-N	Conductive. (900 M ohm cm). Test was done fast.
EDPM rubber, filled	-140	-N	Slightly conductive. (40 T ohm cm).
Teflon	-190	-N	Surface is fluorine atoms-- very electronegative.

Symbols in the table-- Polyurethane (top) tends to charge positive; Teflon (bottom) charges negative. The charge affinity listings show relative charging. Two Materials with almost equal charge affinity tend not to charge each other much even if rubbed together. Column 3 shows how each Material behaves when rubbed against metal, which is much less predictable and repeatable than insulator-to-insulator rubbing. The charging by metal is strongly dependent on the amount of pressure used, and sometimes will even reverse polarity. At very low pressure (used in this table), it is fairly consistent. A letter "N" (normal) in this column means the charge affinity against metal is roughly consistent with the column 2 value. The letter "W" means weaker than expected (i.e., closer to zero than expected or even reversed.) The "+" or "-" indicates the polarity. In all cases where the polarity in col.3 disagrees with col.2, it is a weak (W) effect.

Limitations of these measurements-- Testing was done at low surface-to-surface force (under 1/10 atmosphere) using 1" strips of each of the insulators that are available as smooth solids. (Cotton, for example, could not be made into a solid strip.) The charge affinity ranking of non-smooth solids was interpolated by their effect on smooth solids which had measured affinity values. At this low surface force (typical of industrial conditions), the absolute ranking of charge affinity of various insulating Materials was self-consistent. Above about 1 atmosphere, surface distortions caused some rearrangements in the relative ranking, which are not recorded here. Conductor-to-insulator Tests were done also, and contrary to prevailing literature, all conductors have about the same charge affinity. However, the metal-insulator charge transfer was strongly dependent on the metal surface texture in a way not seen with insulator-insulator. Metal-insulator transfer was also more pressure-dependent in an unpredictable way, so charge transfer has not been quantified for metal-insulator. The "zero" level in this table is arbitrarily chosen as the average conductor charge affinity. "Slow conductors", like paper, glass, or some types of carbon-doped rubber, had approximately the same affinity as conductors if rubbing was done very slowly. All Tests were done fast enough to avoid this effect. Testing was at approximately 72 F, 35% RH, using an AlphaLab Surface DC Voltmeter SVM2 and an Exair 7006 AC ion source to neutralize samples between Tests. Resistivities were measured with an AlphaLab HR2 meter. Applied frictional energy per area was 1 mJ/cm^2. Total charge transferred was kept in the linear range, well below spark potential, and was proportional to applied frictional energy per area. All samples needed to be sanded or scraped clean before Testing; any thin layer of grease of oil (organic or synthetic) was generally highly positive and would thus distort the values.

Explanation of units "nJ/C" used in the table (most readers can ignore this paragraph)-- The units shown here are nC (nano coulombs or nano amp sec) of transferred charge per J (joule or watt sec) of friction energy applied between the surfaces. The friction energy was applied by rubbing two surfaces together; however, “adhesion energy" might be substituted for friction energy when using the table. For example, when adhesive tape is removed from a roll, a certain amount of energy per cm^2 (of tape removed) must be expended in order to separate the adhesive from the backing Material. Although not yet fully verified, newly-dispensed tape becomes charged approximately as is predicted by the table if the adhesion energy is substituted for friction energy. After verifying that charge transferred was approximately proportional to the frictional force (for a given pull length), the contact force was adjusted for each pair so that the friction force was 25 grams on 2.5 cm wide samples. This is 1 millijoule (mJ) per cm^2. When a Teflon sample (-190 nC/J) was rubbed in this way against nylon (+30 nC/J), the nylon acquired a positive charge and the Teflon negative. The amount of transferred charge can be found by first subtracting the two table entries: 30 nC/J - [-190 nC/J] = 220 nC/J. In this case, using 1 mJ (0.001 J) of friction energy per cm^2, the charge transferred per cm^2 was 220 nC/J x 0.001 J = 0.22 nC.

"Saturation", or maximum charge that can be transferred: Beyond a certain amount of charge transferred, additional friction energy (rubbing) does not produce any additional charging. Apparently, two effects limit the amount of charge per area that can be transferred. If the spark E-field (10 KV/cm) is exceeded, the two surfaces will spark to each other (after being separated from each other by at least about 1 mm), reducing the charge transferred below 10 KV/cm. This maximum charge per area is about Q/A = 1 nC/cm^2, from this formula. A second, lower charging limit seems to apply to surfaces with an affinity difference of < (about) 50 nC/J. Two Materials that are this close to each other in the triboelectric series never seem to reach a charge difference as high as 2 nC/cm^2, no Matter how much they are rubbed together. Although not yet fully verified, it is proposed that the maximum Q/A (in nC/cm^2) is roughly 0.02 x the difference in affinities (in nJ/C) if the two Materials are within 50 nC/J of each other. Surfaces that cannot reach spark potential obviously cannot spontaneously dump charge into the air. This is therefore a good reason to select contacting Materials such that their affinity difference is small.

Inaccurate information about air being "positive", etc.-- A triboelectric series table has been circulating on the internet, and it contains various inaccuracies. Though attribution is rarely given, it appears to be mostly from a 1987 book. It lists air as the most positive of all Materials, polyurethane as highly negative, and various metals being positive or negative, apparently based on their known chemical electron affinities, rather than on electrostatic experiments. (From actual Tests, there is little or no measurable difference in charge affinity between different types of metal, possibly because the fast motion of conduction electrons cancels such differences.) In gaseous form, air is generally unable to impart any charge to or from solids, even at very high pressure or speed. If chilled to a solid or liquid, air is expected to be slightly negative, not positive. There are three cases where air can charge Matter (in the absence of external high voltage). 1. If contaminated by dust, high-speed air can charge surfaces, but this charge comes from contact with the dust, not the air. The charge polarity depends on the type of dust. 2. If air is blown across a wet surface, negative ions are formed due to the evaporation of water. In this case, the wet surface charges positive, so the air becomes negative. 3. If air is hot (above about 1000°C), it begins emitting ions (both + and -.) This is thermal in nature, not triboelectric.