**Designing FTC Robots for an ESD (Electro-Static Discharge) Environment**
**Developed by FTC4318 – Green Machine**
**July 2014**
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**Introduction:**
The goal of this document is to recommend a set of best practices that will aid FTC teams in reducing problems associated with static build up and discharge. The document is broken up into three sections:

1) An overview of ESD and static buildup and their symptoms.
2) Best practices. With the assistance from other teams and mentors, these practices were developed by FTC4318 over a couple of years as our robots struggled with static-induced NXT lock-ups. Included are notes on robot design/fabrication as well as controlling the environment to minimize ESD. For each item, the best practice is listed in normal font. An explanation as to why something is effective or done is provided in italics. The words describing the best practice are chosen deliberately. Understanding that building a robot is fraught with trades and compromise, the word "always" or "never" is used to indicate a practice that is very effective with minimal to no perceived cost, risk or compromise. The word(s) "should" or "when possible" is used to indicate a practice that may be more difficult to implement, may require significant compromise and/or may be limited in effectiveness.
3) A note how current loops are closed during ESD events. It is a basic rule of electricity that current will not flow unless a circuit is "closed". Currents flowing during ESD events obey this rule, but in a non-intuitive way.

In general, an attempt has been made to write this document at a level that would be useful to high school aged students who may or may not have had physics.

Finally, even if a robot does not build up a charge it is still susceptible to ESD from contact with another charged robot or a person touching the robot. When a charged robot contacts an uncharged robot, an ESD event is possible on both robots. The following best practices should be considered when developing <u>any</u> FTC robot.

**ESD and Static Build:**
ESD is the sudden flow of electricity between two objects that have been electrically charged to different voltages. It is caused by contact between the two objects. Lightening is a form of ESD as is getting "a shock from a door knob". It takes approximately 10,000 volts (10 KV) to span one inch of air gap. [1]

The primary source of voltage build up in FTC robots is triboelectric charging. This is caused by rubbing dissimilar materials together. This can happen when the robot interacts with the external environment (e.g.: an NXT wheel on a field mat, plastic materials used to gather blocks, balls, batons, etc. that rub on the field mat) or within the robot itself (e.g.: a conveyor belt that drags along a chute internal to the robot, etc.). This effect is exacerbated by low humidity environments. The polarity and strength of the charges produced differ according to the materials, surface roughness, temperature, strain, and other properties/conditions. This makes it very hard to predict how much voltage will build up between any set of materials and under what circumstances. A rough comparative estimate can be made by looking

[1] Paraphrased from Wikipedia (http://en.wikipedia.org/wiki/Electrostatic_discharge) and (http://en.wikipedia.org/wiki/Triboelectric_effect)

up the affinity of the two materials in question (see table in back). The larger the difference in affinity, the more likely the materials will exchange charge. The voltage difference between a robot and earth ground can exceed 10 KV.

It is important to note that charging of a robot is not usually the cause of electrical disruptions, rather it is the sudden discharge. Discharges can occur when the robot makes contact with another conductor such as another robot or the field perimeter.

When a discharge occurs (a tiny version of lightening), the voltage of the robot suddenly drops (or increases if the robot was negatively charged). This causes current and voltage spikes to flow throughout the robot. The voltages can be large enough (thousands of volts) to inductively (requires no physical contact between electrical conductors or insulators) or physically couple into robot electronics. For example, a large positive voltage can be induced on the ground wires in the robot, effectively (momentarily) reversing polarity on the electronics. In short, nasty things happen. Likewise, electronics that are in the electrical path of the discharge can carry/experience large current and/or voltages.

Note that the only way to effectively eliminate externally induced static build up is to change the environment (e.g.: flooring selection). Static build up internal to the robot cannot be eliminated, only mitigated through the techniques indicated in the next section.

**Symptoms of ESD (from observation) in FTC Robots:**

- The NXT and (I believe) Samantha are classified as “toys” and have no requirements for (electrical) protection of internal circuits. In the presence of an electro-static discharge, the NXT can lock-up requiring a “battery-pull” to reset it. During a match this will result in a dead robot or a robot unresponsive to commands.
- The Samantha can upset, momentarily losing communications with the network (disconnects with the field).
- Again, I believe, classified as a “toy”, Servo inputs have little to no ESD protection. They will often “twitch” in the presence of even a small static discharge.

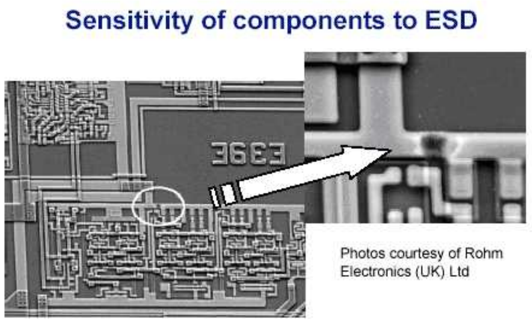
**Best Practices:** (Like all best practices, these are to be implemented when and if possible. There may be cases where these practices cannot be implemented for good design reasons. In these cases, the robot builder has made a trade or compromise. The robot builder should fully understand the risk associated with this compromise; as opposed to doing it blindly. This is common in engineering practice)**:**

- Always use a ferrite choke on the power wires to the Samantha module. Clamp on chokes are readily available from multiple sources. *Ferrite chokes work by presenting significant impedance to current and voltage spikes traveling along a wire. The ferrite chokes effect the propagating magnetic field associated with the spike.*
    - Be very careful not to mistakenly crimp power wires when clamping on a ferrite choke.
- Always use a USB cable that has two ferrite chokes, one at each end; a built-in choke is preferred. These are readily available from multiple sources in various lengths.
- Use of ferrite chokes on the power lines to motor and servo controllers is also desirable.
- Note that the FTC Game Design Committee limited allowable chokes during the Block Party season. This link below goes to the post from the Block Party Forum and may or may not apply in the future:

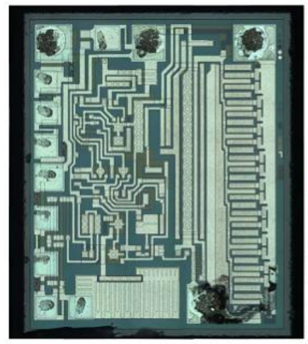
http://ftcforum.usfirst.org/showthread.php?1921-Robot-Electronics-and-Power-Answer-Thread&p=10040&viewfull=1#post10040

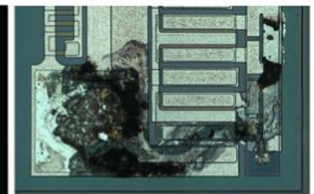
- Keep the USB cable and wires in general as short as possible while still maintaining good wire/cable management techniques.
- Always twist wires (positive and negative) that are carrying power; many are delivered from Tetrix this way. This includes wires that connect motor controllers to motors, wires that connect servo controllers to servos, power bus wires and wires that connect the battery to the Samantha module. *The reason for twisting wires is to keep the positive and negative wires in close physical proximity to one another, thus voltage induced on them is the same. The twist itself is significant as well, allowing the magnetic field of one wire to counteract the field of the other wire. Using twisted wires also limits induced currents caused by changing magnetic fields. Current will be induced in wires in proportion to the area of the loop created by those wires. Having a twisted pair minimizes the size of that loop.*
    - Long lengths of twisted pair can be made by taking a length of red and a length of black wire placing them in a hand drill mandrel, fixing the opposite end of the pair and slowly turning on the drill. Care should be taken not to over-twist the wires (they will fatigue). 3 to 5 twists per inch is fine. Look at a new motor cable to get a feel for twists/inch.
    - In cases where twisting is difficult (e.g: short wire runs) even a few twists will help.
- Do not untwist wires that are provided to you as twisted. E.g.: motor wires are delivered from the factory as twisted.
- If possible, when using a proto-board that has I/O, avoid single ended implementations. *Like twisted pairs; differential implementations are robust to common mode noise created by ESD events. Ironically, the $I^2C$ bus on the NXT is a single-ended implementation, so implementing this practice may be very limited.*
- When designing your robot, consider the grounding scheme. Good solid grounding between all components on a robot is a good-practice that yields a system that is both more reliable and more resistant to ESD. *Having good ground connections between all electrical components decreases the probability that the ground input on one electrical component will differ from the ground input on another component (when an ESD occurs). The concept of ground not being equal to zero volts during an ESD event is counter-intuitive, but very important in understanding why ESD events propagate in a robot and are so difficult to manage.*
- Consider placement of the robot's electrical components when designing and laying out your robot. Ensure that no part of the electrical system is able to be contacted by any other external object during game. *When an ESD occurs on a robot (when it contacts the field, or another robot), the entire frame and everything on it takes a giant jump in voltage. Keeping electronics out of this path allows the frame to charge and discharge independently of the electronics. Ideally, all currents will remain in the frame and not in the sensitive electronics.*
- Latent damage:
    - ESD is notorious for weakening electronics such that a later discharge or normal use will cause a failure. While it is often too expensive and time consuming to switch electronics every time a discharge occurs, particular attention should be paid to servos. Servos and/or servo controllers. After discharge events, servos can become "twitchy" when the robot is touched (by a person, another robot, etc). In this case the servo should be replaced. If this doesn't fix the problem, replace the controller.
    - *Physical damage from an ESD event can be seen in the photos below. The photo on the left shows a micrograph of an integrated circuit. The circuit has been "punctured" by an ESD causing an immediate catastrophic failure. In some cases this sort of event only damages the circuit. The micrograph on the right shows a circuit that was only damaged and ended up failing one hour after the ESD event.* ***Please note that out-right failure of***

***FTC robot electronics is not common.*** *The most common failure is a latch-up of the NXT which can be reset by pulling and re-installing the NXT battery.*




Example of an ESD damage to an IC





*Images Courtesy of Bunny Studios LCC*
This is an example of latent ESD, also known as "Walking Wounded". This three terminal regulator IC worked about an hour after the initial ESD damage.

**Wheel treads, mechanisms and things that rub:**

- Static build up is generated by moving one object over another. This is impossible to avoid in competition. Where possible, to minimize the buildup of static on your robot select materials that have a triboelectric affinity as close to the playing surface as possible. The competition playing surface is made out of EVA (Ethylene Vinyl Acetate). FTC4318 preferred material is Gum (natural) rubber, which has an affinity very close to EVA. There was a notable reduction in static build up in 4318's Block Party robot when we switched back and forth between Tetrix standard wheels and gum rubber wheels. Note that choice of wheel treads requires many other design considerations.
- Consider material selection for mechanisms inside your robot. Static build can build up internal to the robot.

**Environment:**

- When possible, fields should be sprayed down with anti-static spray. There are many products on the market that are designed for soft surfaces and can be very effective in eliminating the build of static from the external environment. Tech-Spray Anti Stat 1726QT is used industrially and in other robot competitions; available from Mouser.com. It is recommended that you start with a small sample of your field prior to spraying the whole field. Be careful of applying the spray too often. Fields can experience a buildup causing tackiness. *Antistatic sprays work by leaving a residual film on a surface that is slightly conductive. Even slight increases in surface conductivity greatly reduce static build-up. This film is transparent and does not affect the robot's interaction with the field surface.*
- If you are consistently getting a discharge when touching your robot. Touch a resistive wand to the robot before touching it with your hand. This wand will bleed charge from the robot to your body in a controlled manner.
    - Attaching a 1MΩ to 10MΩ resistor attached to any piece of metal will do. 4318 screws a 1MΩ to a 288 mm flat bar.
- Humidity is your friend. Increasing humidity levels to >40% is best.

**Special Note on "Closing the Circuit" for Static Build-up:**

One if the barriers to understanding how static build-up affects electronics is associated with the basic concept of closing electrical circuits.  To get current to flow in a circuit, the circuit must be "closed loop".  Electrons need to the ability to return to ground, whether it is earth ground or battery ground. This is true of all electrical circuits; however, the way a circuit closes in the case of static build up is not apparent.  In the case of static, the circuit does in fact close, but over a much longer period of time than is found in common circuits.  An example:

At the start of an FTC match:

1. The field mats, Robot A, Robot B and the field perimeter are all at the same voltage (potential). The field is placed on a concrete floor.
2. As the match progresses Robot A triboelectrically picks up electrons from the field mat. The field mat's intimate contact with Earth ground via the concrete, allow relatively easy sourcing or sinking of electrons. The voltage on Robot A starts charging negatively as electrons are removed from the mat and accumulated on the robot. The mat, in turn may charge slightly positively or not at all due to its intimate contact with ground.  The robot stores these electrons much like a capacitor stores electrons.
3. At some time during the match, Robot A contacts the field perimeter.  Since Robot A is at a significantly different voltage potential, an ESD occurs.  This discharge transfers electrons from Robot A to the field perimeter.
4. These electrons from the field perimeter bleed back to the mat and/or the concrete (earth ground).
5. The circuit closes.  Electrons flow from Earth to concrete, to matt, to robot (triboelectrically), to field perimeter, back to concrete, back to Earth.  The robot stored the electrons for a while until the discharge occurred and the electrons were released.

**Acknowledgement**

FTC4318 would like to thank engineers at the Johns Hopkins University Applied Physics Laboratory, the Garret Engineering and Robotics Society, Battel Engineering as well as others in the FTC community for their advice, support and mentorship with regards to managing static and ESD.

## TriboElectric Table (From Alpha Lab Inc.)

| 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 are 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 AlphLab 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.