The Innovative Design Process at SpaceX

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Since its founding in 2002, SpaceX has revolutionized the rocket industry by developing rapidly reusable rockets and commercializing the space industry. With countless issues on Earth, many ask, “Why explore space?” The answer is simple: Exploring space increases the quality of life on Earth. By launching Earth-observation satellites, we learn more about the climate processes that occur on Earth, and therefore we are in a better position to combat climate change. Furthermore, space exploration leads to discoveries in technologies like solar panels that can support sustainable energy on Earth. SpaceX is the research topic of this paper because developing rapidly reusable rockets has revolutionized the commercial space industry by opening space to more people than ever before, sparking innovation and inspiration worldwide. Most importantly, the development process at SpaceX is unlike any other, and it has been responsible for some of the most revolutionary technological developments of the 21st century.

SpaceX’s engineering process is well-documented, thanks to interviews CEO Elon Musk has conducted with the spaceflight community. SpaceX’s design process differs primarily from traditional processes because it centers on innovative thinking and rapid testing and iteration. This process is on full display through the development of SpaceX’s super-heavy-lift launch vehicle: Starship. From the moment Starship was proposed, the design has been evolving.

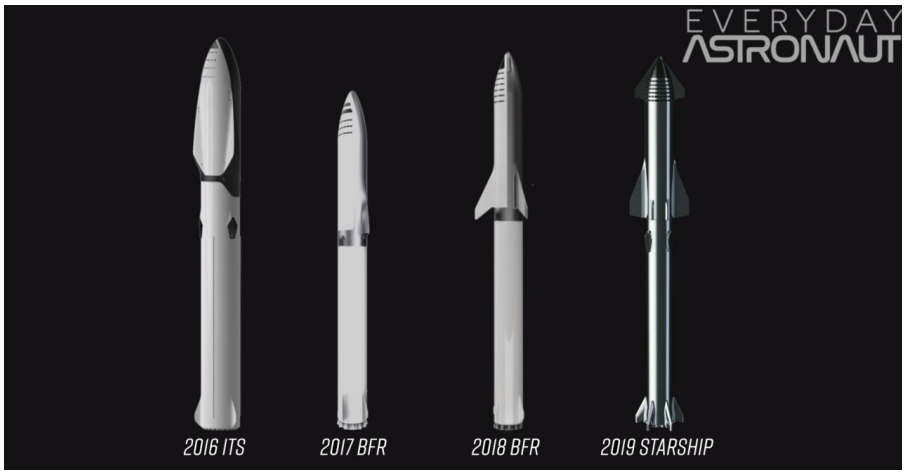
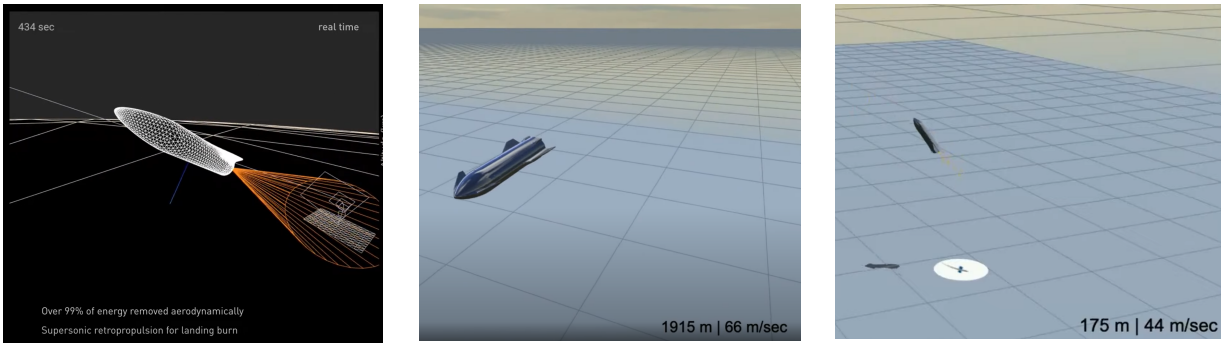


Figure 1. Evolution of Starship since 2016 Credit: Everyday Astronaut & ElonX.net

As the design changed, so did the rocket's flight profile, leading to one of rocketry's most recognizable maneuvers: The Starship bellyflop. This involves Starship plummeting towards the Earth belly-first and then igniting its engines to flip itself upright at the last minute, canceling out its horizontal and vertical velocity in time to make a soft landing.



Left: Initial landing plans Center: Bellyflop maneuver Right: Flipping upright

Figure 2
Credit: SpaceX & International Rocket Launches & ElonX.net

At SpaceX, Elon Musk uses a 5-step engineering design process. Traditionally, one of the engineering process's first steps is to define constraints and criteria. Musk adds another step: **1: "make your requirements less dumb."** Sometimes engineers will constrain designs to stay within the realm of reason, but as SpaceX has proven with the bellyflop maneuver, thinking outside-the-box is a necessity for revolutionary technology. Step 2 of the "SpaceX Design Process" is **"try very hard to delete the part or process."** The technology becomes easier to troubleshoot by simplifying the design, creating many long-term benefits. Musk says that he operates by the idea that one should delete so much that they have to add stuff back in eventually. **Step 3 is "simplify or optimize" existing parts."** This follows Step 2 because optimizing a part that should be removed from the design wastes resources and time. The previous three steps

directly apply to VEX Robotics because our team used to find ourselves working for weeks, testing and making minor changes to refine a robot subsystem, but to no avail. What ended up solving the problem was deleting the troublesome part, and after doing so, we found ourselves confused as to why we created requirements in the engineering notebook that generated that design. **Step 4 is to "accelerate cycle time,"** which basically means make things happen faster, and finally, **Step 5 is to "automate."**

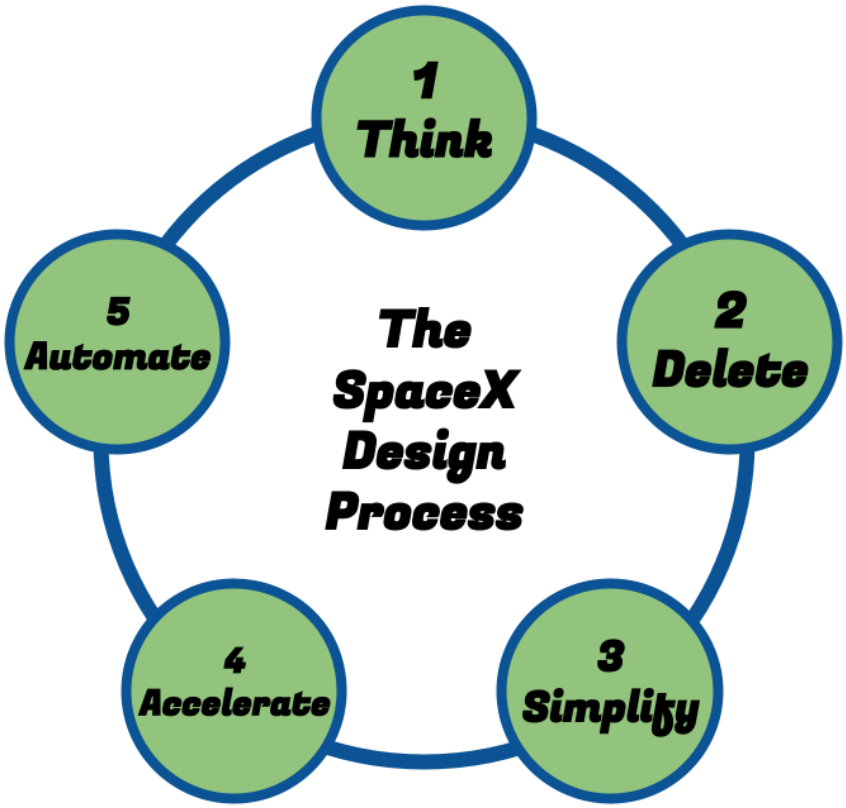
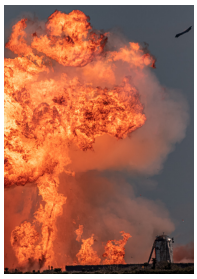


Figure 3: The SpaceX Design Process

After designing, SpaceX operates on the premise of rapid testing and iteration. For Starship, SpaceX will build and test prototypes in a matter of *weeks*. This rapid prototyping leads to frequent failures, which is excellent because SpaceX learns new attributes of Starship with each failure. According to Musk, during the Starship testing campaign, none of the failure causes were actually considered before launch.

Starship SN8



Starship SN9

Starship SN10

Starship SN11

Starship SN15 Success

Figure 4: Starship Launches

Credit: Trevor Mahlmann

Our team has embraced this rapid prototyping style to discover as many robot failures as possible. In order to make that possible, we organize our team roles so that each workday can go as efficiently as possible. For example, it is inefficient to have 10 team members physically construct a robot at once. It is much more efficient to have some teammates working on different robot systems and others working on programming and borrowing the robot periodically to test the program. This organization allows our team to work rapidly, creating an exciting challenge in logging the incredible amounts of daily work in the engineering notebook. Another way VEX

Robotics prepares our team members for a future STEM career is through the engineering notebook. The engineering notebook at Brookwood Robotics has become a significant source of success for the club, garnering 4 Design Awards and 1 Excellence Award in the past three seasons. The engineering notebook has taught our team many things, including how to take practical engineering pictures and the importance of logging test results. The engineering notebook is also a helpful resource that can be referred to later in the season and even in future seasons to look for inspiration or see what others attempted.

Finally, a critical step of SpaceX's engineering design process and any design process is pre-build simulation. Our team is working to improve this capability because it is critical in many engineering careers. We usually create robot CADs before building, which increases building efficiency by reducing time wasted on poorly executed designs. This year, we added another level to our CADs by rigging the robot with joints to simulate ranges of motion. In the future, we are looking to utilize physics simulations in CAD. The use of physics simulations has been well-documented during SpaceX's development of the Starship rocket (as shown in Figure 2). In VEX, they are beneficial for simulating the behavior of game objects like rings. This year, we performed basic contact simulations between robots and rings. However, by learning how to simulate more advanced collisions, we will be much better prepared to use CAD in an actual workplace environment.

In conclusion, Brookwood Robotics has seen a dramatic increase in success by taking inspiration from one of the most revolutionary design processes in modern engineering. Through VEX Robotics, our club has prepared many of us for future STEM careers by teaching us everything from CAD to the engineering notebook to innovative thinking, which are all critical skills for the STEM workforce of tomorrow.

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