THEY CAUGHT A ROCKET

How SpaceX engineers designed a system that catches the Super Heavy in mid-air.

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Abstract

This document focuses on the technical aspect of recovering the first stage of the SpaceX mega-rocket *Starship*, named ***Super Heavy***. We will seek to understand how such a maneuver was carried out as well as the development iterations that made it possible to succeed on the first try. Using concepts in physics-chemistry, mechanics, as well as 3D simulations, we will reveal the reasons for certain decisions regarding the design of the Super Heavy in order to better appreciate the magnitude of the task solved by SpaceX.

It is important to note that the *Starship* program is still very young, having timidly started in 2019. Since then, it has evolved at a very high speed, which is why it is extremely likely that the majority of the information in this document will become obsolete within a few years. The goal is not to understand how the company will continue on this path, but how it has already unfolded.

Finally, this document specifically studies the return of the *Super Heavy* as it occurred on **October 13, 2024** during the fifth flight of the *Starship Super Heavy* rocket.

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1 Context and introduction

The night of December 22 to 23, 2015 was very tense in Florida. Indeed, that night saw the 20th liftoff of SpaceX's flagship rocket, the *Falcon 9*. During this mission named "*Orbcomm OG2 M2*" in reference to the satellite that was on board, the first stage of the Falcon 9 once again attempted a maneuver hitherto deemed too hard: the return to earth of the "booster".[1]

To the cheers of the employees, the booster *B1019* landed perfectly on "*Landing Zone 1*" which had been prepared for the occasion. Of course, it took several attempts to get there. This success allowed the American firm to reuse a rocket stage for the first time in history in 2017.[2]

With the arrival of the famous *Starlink* launches in 2019,[3] SpaceX's launch cadence went into overdrive.[4] The company broke all records by constantly reusing its first stages. Although the launch price of a *Falcon 9* is secret, it is safe to estimate that SpaceX obtains a reduction of at least 30% on its launches. This price drop makes it possible to drastically reduce the prices per kilogram. Recently, SpaceX even offers a *Rideshare* (understand carpooling) offer for only $6000 per kilogram; it's affordable.[5]

However, the path is not all mapped out. Certainly, SpaceX brings the United States back to the forefront of the space scene, notably with the return of astronaut launches from American soil,[6] certainly they enjoy an immense lead over their competitors, certainly the company is estimated to be worth $350 billion but SpaceX remains a fallible company.[7] One day or another, they will no longer be the only ones repeatedly launching rockets and they know it.

The only solution is therefore to take a big lead even before being caught up. SpaceX has always had as its main goal since its founding; the planet Mars.[8] In 2016, barely a year after the first return of a booster, the founder *Elon Musk* unveils the first plans for the construction of a huge rocket named "*ITS*".[9] (Interplanetary Transport System) This draft is not the first iteration of such an idea but knowing that the company has just achieved a feat considered impossible, it is harder not to believe in it a little.

A few years later and after several name and design changes, *ITS* is called ***Starship Super Heavy***. Officially, "*Starship*" is the name of the upper stage while the lower stage is called "*Super Heavy*". However, the name "*Starship*" is commonly used to designate the entire rocket; the interpretation depends on the context.

The development of the program begins in 2019 in a small, virtually abandoned village in southern Texas named *Boca Chica*. It is not a question of targeting low earth orbit but rather the moon, mars and even further. Starship becomes the first rocket capable of taking a hundred people on board to be seriously developed.[10]

Starship Super Heavy is a 123-meter-high mega-rocket, the tallest ever designed. At the ignition of the 33 *Raptor* engines of the *Super Heavy*, more than 73 Meganewtons propel the rocket.[11] (More than twice the power of the *Saturn V*) At about T+2:30, (understand two minutes and thirty seconds after liftoff, hence the plus sign) the *Super Heavy* and the *Starship* (a name which this time designates the upper stage only) separate thanks to a maneuver unknown in the 21st century for modern US rockets: *hot-staging*. Simply put, the *Super Heavy* continues to propel the *Starship* at a low power while the upper stage ignites all its engines while remaining attached. The maneuver is risky but it allows keeping inertia which translates into a larger payload capacity.[12] The subject of this document resides in the landing of the *Super Heavy*, so we will not follow the *Starship* on its journey to space.

The *Super Heavy*, 70 meters long, is now alone on a trajectory targeting the Gulf of Mexico at more than $5000km.h^{-1}$ with only a small portion of its fuel remaining.

How could we recover the *Super Heavy*?

1.1 Why *catch* instead of land?

Unlike the *Falcon 9*, the *Super Heavy* does not have landing gear. Indeed, SpaceX engineers have a completely different idea. With each *Falcon 9* flight, the internal components of the rocket wear out more and more until they need to be repaired. At first glance, this is not a very serious problem, however, at SpaceX's launch cadence, these partial inspections and repairs happen very often. These components degrade precisely because they fly. They must withstand strong vibrations, extreme temperatures and load factors (called *G force* in English) that are humanly unbearable.[13]

In order to colonize Mars, SpaceX needs many launches with minimal waiting times. A solution must therefore be found. This solution consists of relocating as many components as possible to the ground. That way, it is only necessary to inspect a single component that will do the same work for several launches. That is exactly why in 2021, SpaceX announces that they are working on a giant mechanical arms project capable of catching the *Super Heavy*.[14] The idea seems crazy, but on paper, it is technically possible and economically speaking, it makes sense.

Before understanding how the *Super Heavy* will prepare to return to the launch pad, it is necessary to analyze the functioning of these mechanical arms.

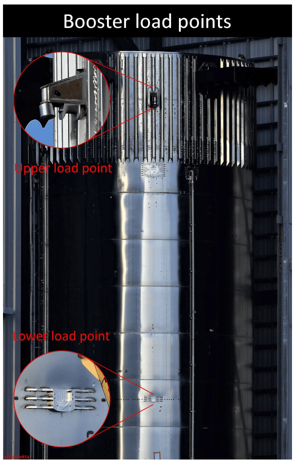
2 The Mechazilla structure

2.1 Tower *A*

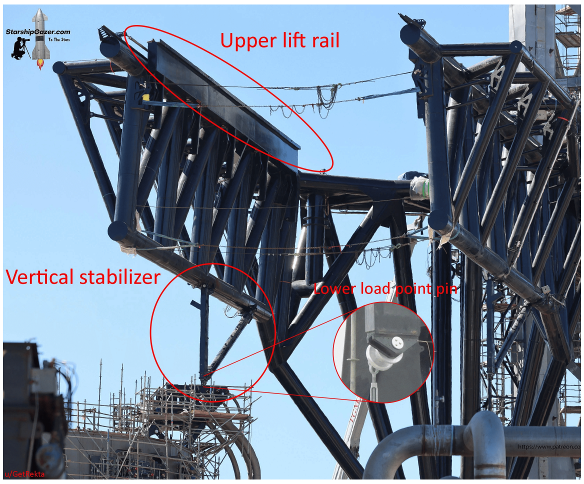
In 2021, SpaceX begins assembling its first launch tower for *Starship*. This tower is divided into eight pieces that are each assembled on top of one another.[15] The tower is 135m high, which is 15m taller than the entire rocket, because the mechanical arms must be capable of assembling the *Starship* onto the *Super Heavy*. Indeed, the ability to rapidly assemble and disassemble the rocket is essential to its main objective: *rapid* reusability. In a distant future, SpaceX wants the rocket to take off and then the booster to systematically return to the launch pad once having propelled *Starship* as high as possible.[16] The mechanical arms would only have to place the booster back on the launch pad and assemble a new *Starship* on *Super Heavy*. These arms and this tower are therefore essential to the idea of a *rapidly* reusable rocket.

Figure 1: Tower *A* nicknamed *Mechazilla* with its *"chopsticks"* arms.

2.2 How do the arms and the booster come into contact?



(a) The booster's attachment points.



(b) The arms' attachment points.

The booster has four attachment points. The two highest ones are commonly called "*pins*" or "*landing pins*" because they are the ones that make contact with the two "*rails*" that deploy from the arms.[2a] We will consider that the *Super Heavy* has "landed" when its two *pins* have made contact with the two rails. Finally, the two lower contact points are only used when it is necessary to "transport" the booster.[2b] You will note therefore that when it is resting, the

Super Heavy is not entirely held by the arms. This poses a *pitch* problem that the engineers were able to solve by designing the *pins* with a ball joint connection that allows keeping a total contact surface even when the booster lands with a non-zero horizontal velocity.[17] (in other words, it swings slightly on the arms, like a swing)

The mechanical arms use a pulley system which, with the help of small rollers that make contact with the tower, allows the structure to translate vertically. The arms are capable of opening and closing around the axis of the tower thanks to hydraulic actuators. The latter are only rarely engaged at full power because the inertia of the arms to stop at the right moment is great. It is also noted that the *Mechazilla* tower wobbles very slightly when the arms close: this is completely normal and expected. A similar phenomenon takes place when skyscrapers face the wind.[18]

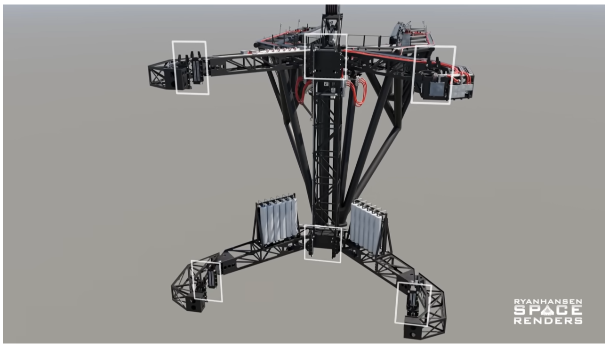
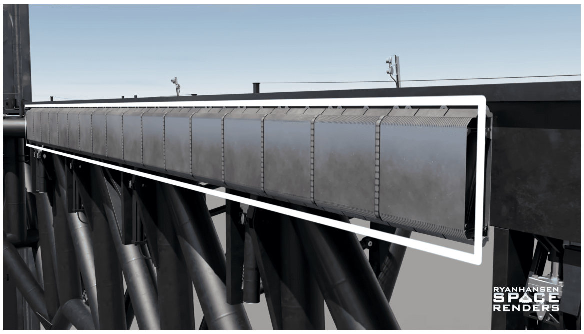


Figure 3: The structure that remains attached to the tower. The arms are invisible for better visibility.

After the fourth flight of *Starship Super Heavy* on June 6, 2024, SpaceX set itself the goal of attempting to catch the *Super Heavy* on the next flight.[19] For this, one last element is missing to add to the arms. Indeed, *catching* something means there is friction involved. Contrary to what one might imagine, a rocket's fuselage is not thick. A slightly too violent contact could therefore have disastrous consequences.[20] To remedy this, the engineers stuck plates on the side of the arms that cushion the lateral shock of the impact.[4a] Their exact material is not known but the chosen thickness guarantees contact of the *pins* with the rails as soon as the arms press on the booster.[4b]



(a) The plates absorb the lateral impact of the arms on the booster.

(b) The pins make perfect contact with the rails if the plates are pressed against the booster.

As stated previously, the *pins* make contact with the rails with a ball joint connection that allows them to keep a total contact surface even when the booster is not exactly vertical compared to the tower. Unfortunately, the angle tolerance of the *pins* is not publicly known, but it can be estimated at no more than fifteen degrees of angle, which poses no problem for a rocket, unless in a disaster scenario. There is, on the other hand, another tolerance which is much more important to take into account: the roll axis. On a rocket, roll is the axis that follows the rocket from top to bottom. On a *Falcon 9* that lands using its own landing gears, the roll is controlled but negligible. As long as the rocket lands straight, that is all that matters. The *Super Heavy* does not have the same luxury with its *pins* which must imperatively make contact on the rails. These rails only extend in one direction for a certain distance. If the booster has abnormal roll, the pins will not make contact with the rails and the booster will have to support its entire weight with its "*grid fins*". We will return later to their role during aerial maneuvers, but they are absolutely not designed to hold the *Super Heavy* and the risk of breaking in such a scenario is almost certain.

The maximum roll of the booster is not publicly known, but it has several times also been estimated at fifteen degrees of angle.[5]

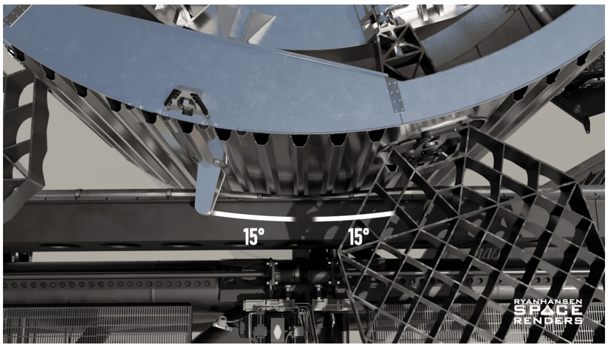


Figure 5: The rails add a constraint on the maximum roll angle of the Super Heavy.

During a catch of the *Super Heavy*, the *Mechazilla* tower and its *chopsticks* only do half the work and it is certainly the simplest. Indeed, as we will see, the first stage of the *Starship* rocket has the heavy responsibility of turning around while it is launched at more than 5000km/h.

3 Technical specifics of the Super Heavy

As a reminder; "*Starship Super Heavy*" is the official name but it is often abbreviated to "*Starship*" which also designates the upper stage. The first stage is called "*Super Heavy*", commonly called "*booster*". In this part, we will study certain technicalities of the *Super Heavy* that allow it to be caught by the *chopsticks* of the *Mechazilla* tower.

As stated previously, this fifth flight of *Starship* is the first catch attempt after a "virtual" catch performed during the fourth flight on June 6, 2024. According to the vice president of build and flight reliability, Bill Gerstenmaier, the fourth flight booster reached its target in the Gulf of Mexico with a precision of half a centimeter.[21] Knowing this, the SpaceX teams considered themselves ready for the first catch attempt during the fifth flight.

3.1 Fuel

The trend in rocket fuels is ”*methalox*”, which is the mixture of two-thirds liquid oxygen and one-third liquid methane. This fuel allows for better engine efficiency.[22]

Specific impulse

In aerospace, the efficiency of an engine is called *specific impulse* and is denoted

$$I_{sp} = \frac{v_e}{g}$$

The I_{sp} is measured in seconds in order to be able to compare the efficiency of engines regardless of the measurement system used (metric or imperial). There is therefore no physical result to be seen in it, it is a bit like a simple efficiency score, nothing more. We denote v_e the average exhaust velocity of the gases (in $m.s^{-1}$ or $ft.s^{-1}$) and g the acceleration of terrestrial gravity. (in $m.s^{-1}$ or $ft.s^{-1}$)

When liquid methane mixes with liquid oxygen, we obtain the following equation:

$$\mathrm{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

This corresponds to approximately 55% CO_2 and 45% H_2O. It is not the cleanest fuel ecologically but it is far from being the worst. Furthermore, *hydrolox* is another common fuel that only releases water. ($2H_2 + O_2 \rightarrow 2H_2O$) It is easily recognizable by an almost transparent combustion. The combustion of *methalox* has a purple and blue tint.[6]

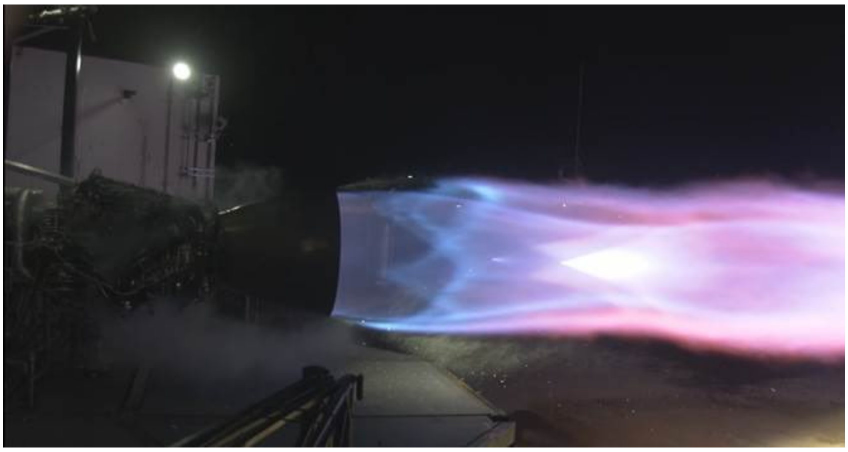


Figure 6: A Raptor Version 2 engine during a test.

In aerospace, the Tsiolkovsky rocket equation is used to calculate the ”range” that a quantity of fuel offers.

The Tsiolkovsky equation

The Tsiolkovsky equation relates the increase in velocity during propulsion to the ratio of the evolution of its mass. It is an essential equation in rocket engineering. The Tsiolkovsky equation is as follows:

$$\Delta v = v_e \ln \left(\frac{m_0}{m_f} \right)$$

Where:

- v_e is the exhaust velocity of the gases;
- m_0 is the total mass of the rocket at the beginning of the propulsion;
- m_f is the total mass of the rocket at the end of the propulsion.

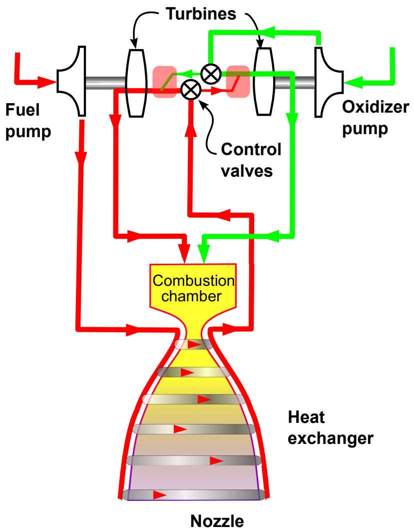
This equation can also be expressed using the I_{sp} mentioned earlier.

This fuel does not burn just anywhere. It passes through one of the most complex engines in aerospace history: the ***Raptor***.

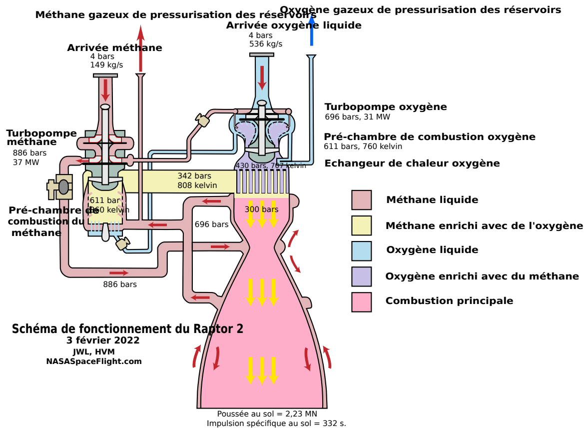
3.2 The *Raptor* engine

The idea of an efficient engine running on *methalox* is not new at SpaceX. It was in 2012 that Elon Musk announced the project for such an engine when the concept of the *ITS* (ancestor of Starship) did not even exist yet. At SpaceX, the *Raptor* is the successor to the *Merlin* engine used on the *Falcon 9*. Fortunately for the company, the *Merlin* engine is one of the most frequently used in the world thanks to the high flight cadence of the *Falcon 9*. The engineers were thus able to accumulate a lot of experience in the field. We owe part of the birth of the *Raptor* and *Merlin* engines to the engineer *Tom Mueller*.[23]

The *Raptor* also follows the new trend of "*full flow*" staged combustion cycles. Simply put, a classic rocket engine does not use 100% of the incoming fuel for combustion. A small part is dumped for mechanical reasons. On a full-flow engine, this part is reinjected into the circuit to burn all of the ingested fuel.[7a]



(a) Diagram of a full-flow cycle.



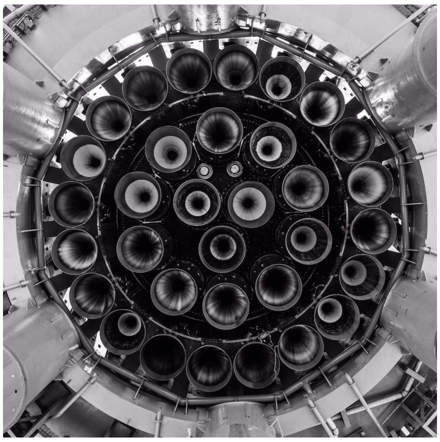
(b) Simplified diagram of a Raptor engine. (speculative information)

Rocket engines overflow with technical details that we are not going to discuss. Know however that the ignition of a single Raptor engine is extremely complex. During an ignition sequence, each engine must open or close each of its valves with very high spatial and temporal precision. If even one of these actions does not happen as planned, the flight computer that governs the engine ignition sequence in real-time will have to order the failing engine to abort its sequence in order to avoid an ”overpressure event”. (an explosion) [24]

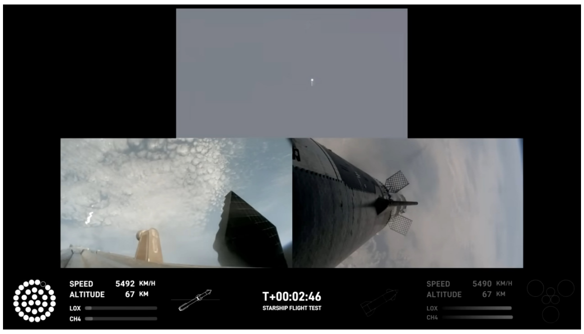
However, depending on the problem observed during ignition, an engine that failed its ignition may be entitled to a second chance if it is part of a group of engines to be relit later in the flight. This exact scenario unfolded during the seventh flight of Starship which took place on January 16, 2025.[25]

Like most liquid propellant engines, the Raptor has a *minimum* power of 40%.[26] (and a maximum of 100% of course) It measures $3.1m$ long and $1.3m$ in diameter. Note that there is a ”*vacuum*” version that has a *nozzle* (the part of the engine that looks like a bowl) optimized for the vacuum of space. No engine on the *Super Heavy* is equipped with this nozzle.[27]

The *Super Heavy* is equipped with 33 Raptor engines which are all ignited at liftoff. The engines are separated into three groups: the three center engines, the ten ”inner” engines then the twenty ”outer” engines. During a *Starship* flight, it is easy to observe the state of the engines thanks to the video stream broadcast by SpaceX.



(a) Super Heavy seen from below. We observe three ”circles” of engines.



(b) Screenshot of the video stream during the 4th flight. We can see that one Super Heavy engine did not ignite.

Let’s now talk about a crucial asset of the Raptor engines: (as well as rocket engines in general) ***thrust vectoring***.

3.2.1 Thrust vectoring

To reach orbit, a rocket must accumulate *horizontal* velocity. The rocket only climbs in order to escape the atmosphere which slows down any body due to air friction. Since the rocket takes off vertically, there must be a way to make it turn on itself to ”pitch it over”. Some rockets use aerodynamic control surfaces (like airplanes) to maneuver. However, this method is only effective in the atmosphere knowing that the lift created by these control surfaces uses precisely air friction to work.

There is also the *RCS* for *Reaction Control System*. These are unidirectional mini-engines which when actuated together in a precise order and configuration, can rotate the rocket. This method is better because it allows maneuvering in the vacuum of space with high precision but the *RCS* are not powerful enough to turn hundreds of tons in the atmosphere against air friction.[28] This is why there is a compromise: thrust vectoring.

This involves deflecting the thrust of an engine so that its thrust vector no longer passes through the center of gravity of the rocket. By doing this, a *lever arm* is created that forces the rocket to turn around its center of gravity.[9]

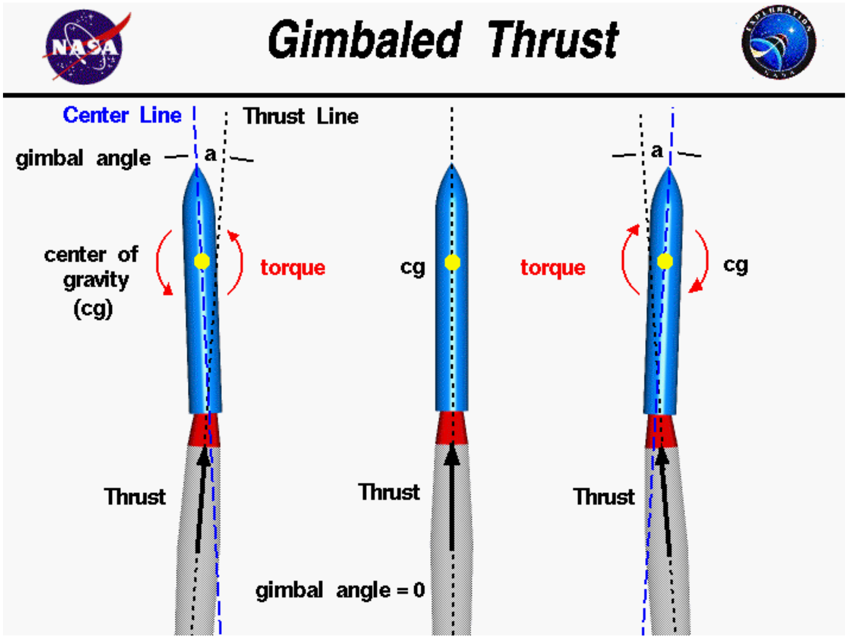


Figure 9: Explanatory diagram of thrust vectoring

This technique is commonly used for rocket launches but it becomes mandatory when you want to bring back your first stage. For example, when the first stage of the Falcon 9 is a few seconds away from landing, it uses a single engine to brake but also to adjust its trajectory thanks to thrust vectoring. High-altitude winds often blow boosters off their initial trajectory and therefore very often require a correction before landing.

Since the beginnings of Falcon 9 landings in 2015, there have been 436 attempts of which 97% succeeded. If we only count the landings since the beginning of the exponential curve of launches in 2021, this figure rises to 99%.[29] The reliability of propulsive landing which was once mocked is the only realistic solution to catch the *Super Heavy*.

Furthermore, the *Raptor* engines are capable of rotating their thrust axis by approximately 15 degrees on either side: this is unprecedented.[30] This is an extremely useful asset when, for example, an engine fails to ignite. If all the engines push vertically except one which is off, this creates a small *lever arm* that deflects the rocket from its trajectory.

Principle of the lever arm

A lever arm amplifies a force thanks to the distance from the fulcrum. The fundamental relationship is:

$$F \times d = L \times D$$

Where:

- F is the applied force;
- d is the force/pivot distance;
- L is the load to lift;
- D is the load/pivot distance.

The greater the ratio $\frac{d}{D}$, the less effort required. (This is why door handles are opposite their axis of rotation)

Thanks to thrust vectoring, one of the engines only has to slightly deflect its own thrust to counter the lever arm. It is also possible to modulate the power of several engines to create the same effect, this is called *differential* thrust. (see this link for an explanatory video)

As stated previously, thrust vectoring is not the only way to turn a rocket. That is where the *Super Heavy* and the *Falcon 9* have a common point: the *grid fins*.

3.3 Grid fins

The *grid fins* (also called cellular panels or grid fins in French) are aerodynamic control surfaces that made their first appearance on Soviet missiles.[31] As the French name indicates, a grid fin is a grid installed perpendicularly to the fuselage. When the grid fin is perfectly perpendicular to the fuselage in flight, it produces no aerodynamic effect other than a little drag. However, when it is angled relative to the airflow, (thus turning around its axis) it creates a lift vector perpendicular to the air. It is the same phenomenon as for airplane wings. Each square of the grid constitutes a mini-wing.

Lift formula

For the sake of argument, we are going to simplify the physics behind these grid fins by assuming that they form only one large wing. In this case, the lift equation is:

$$F_z = \frac{1}{2}\rho V^2 S C_z$$

where:

- F_z is in Newtons;
- ρ is the density in $kg.m^{-3}$;
- V is the velocity in $m.s^{-1}$;
- S is the surface area of the "wing" in m^2;
- C_z is the lift coefficient determined using parameters specific to the case study.

Note that in this formula, the velocity is squared while the air density only counts for half. We can draw two essential statements from this:

- the velocity of the airflow is the most important element;
- the pressure of the surrounding air is not that important.

Pressure or density?

While often confused, pressure and density are distinct. Aerodynamics relies on density (the mass of the air), but we can understand how it scales with atmospheric pressure using the *ideal gas law*. Indeed, it allows us to express the pressure P as a function of the density ρ:

$$P = \rho \cdot \frac{R}{M} \cdot T$$

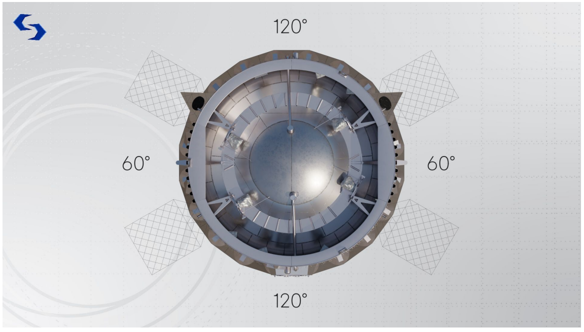
Where:

- P is the air pressure in Pascals;
- ρ is the density in $kg.m^{-3}$;
- R is the ideal gas constant;
- M is the molar mass of the air in $kg.mol^{-1}$;
- T is the temperature in Kelvin.

On the *Falcon 9*, there are four grid fins spaced 90 degrees apart. They are initially folded then deployed once the descent phase begins.[32] The *Super Heavy* also has four grid fins spaced

60 and 120 degrees apart.[10b] Unlike the *Falcon 9*, the grid fins are constantly deployed, even at liftoff. As stated previously, when the grid fins are perfectly perpendicular to the airflow, they generate very little drag and no lift. (in the ascent phase, the lift from the grid fins could be parasitic to the engines which completely handle the trajectory) This decision to lock the grid fins stems from the Starship program's development philosophy. The engineers preferred to remove these moving linkages to avoid any jamming problem, like has already happened on the *Falcon 9*.

(a) Super Heavy and its grid fins. They have rotation around their axis as their only degree of freedom.



(b) 3D modeling of the Super Heavy seen from above. The grid fins are almost invisible. This is exactly what is needed during the initial ascent phase.

As we have seen, the grid fins allow a rocket to be turned around several axes in order to maneuver with greater precision. Observing this, one might wonder if the grid fins also allow it to translate. It is more than a possibility, it is an obligation if one wishes to make a return to earth safely.

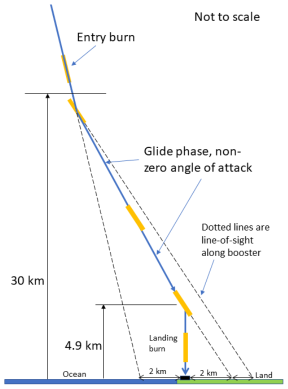
3.3.1 Transforming vertical velocity into horizontal velocity: the *glide*

Imagine the following scenario: the *Super Heavy* has finished its initial boostback burn using 13 engines to turn around toward the *Mechazilla* tower. However, during the descent phase, something goes wrong. An internal component has been destroyed, the fuel level is too low or the trajectory is not exactly the desired one. So the *catch* must be aborted, but how? In our scenario, the booster is directly sent on a trajectory that finishes its course at the tower. This is dangerous because the booster could encounter a failure preventing it from proceeding with the engine ignition. In which case, it would finish its course very close to the tower, or in the worst-case scenario, it would crash into it.

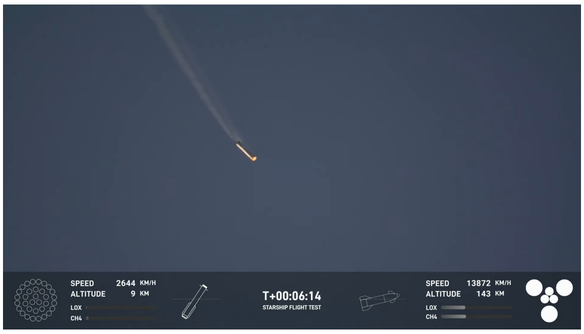
This is why the *Falcon 9* and the *Super Heavy* initially do not aim at their return site but rather an area in the water a few kilometers closer. This ensures safety for the populations neighboring the launch complex.[33] Yet, we now have a new problem; the Super Heavy is no longer aiming at its return zone. The technique that saves the booster from drowning is what is commonly called the *glide*.

This maneuver uses the grid fins to misalign the airflow and the axis of the *Super Heavy*. The flow therefore no longer hits a disk but a cylinder. All this additional drag slows down the booster but above all creates a lift vector perpendicular to the airflow. Put simply, this is basically messing with the angle of attack. (Traditionally, rockets never have a high angle of attack)

Thanks to this, the booster can wait until a certain moment before committing to the return by initiating this maneuver.[11a]



(a) Explanatory diagram of the flight profile of a Falcon 9 booster return. The same principle applies to the Super Heavy.



(b) Screenshot of the 5th flight of starship during the return of the Super Heavy. The axis of the booster is not aligned with its drag: this is the glide.

We now have all the required knowledge to move on to the timeline of the flight during which a booster was caught for the first time in history.

4 The fifth flight of Starship

This part draws its sources from the official flight timeline.[34]

4.1 Pre-launch conditions

The weather is calm at sunrise on October 13, 2024 at the Boca Chica launch site in Texas. On the launch pad sits the largest and most powerful rocket ever built: *Starship Super Heavy*. This is the fifth time SpaceX is embarking on a Starship launch. During the fourth attempt, the booster named ”B11” perfectly splashed down on its virtual target in the Gulf of Mexico. SpaceX engineers spent the last few months installing powerful actuators in the *chopsticks* of *Mechazilla* allowing it to close its arms in a few seconds. In addition, its arms are also equipped with cushions and rails to absorb the impact of the Super Heavy’s *pins*. The teams therefore considered themselves ready for a first *catch* attempt.

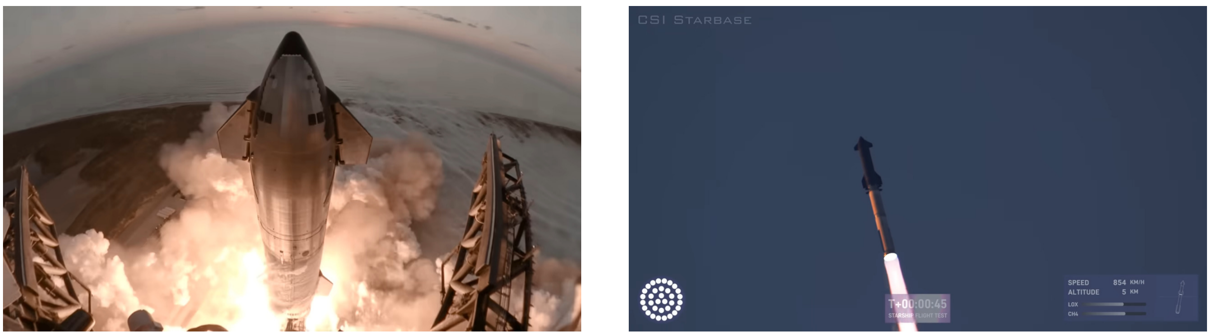
At around 7:22 a.m. Texas time, the *Starship* ”S30” and the *Super Heavy* ”B12” finished their loading of liquid oxygen and liquid methane. The 33 *Raptor* engines of the *Super Heavy* are chilling down before facing the extreme heat of combustion. While waiting for the final countdown, the 13 center engines capable of thrust vectoring make a few movements to verify that everything is in order. The ground computers indicate ”*GO*” for the weather, the exclusion zone and the onboard systems.[12]

Figure 12: S30 and B12 a few minutes from launch

4.2 Liftoff

At 30 seconds from liftoff, the *Launch Director* gives his "*GO*" to proceed with the final countdown. Twenty seconds later, the *deluge* system which sprays the launch pad with water in order to protect it from the 33 *Raptor* engines activates. Five seconds before liftoff, thirteen then twenty-eight, then thirty-three *Raptor* engines ignite. The shock wave is such that it vaporizes the surrounding mist. The chaos in the deafening noise of the engines can be heard for kilometers from the launch pad. Once the flight computer has checked all the parameters one last time, it commands full power to all engines: Starship lifts off.[13a]

Once past the tower, the thirteen center engines use thrust vectoring to slightly pitch the rocket over relative to the horizon to begin gaining horizontal velocity. At T+1:02, Starship passes *MAX-Q* which is the moment of maximum aerodynamic stress. The rocket is already at more than $4000 km.h^{-1}$ as it continues to pitch over and accelerate while the air gets thinner.[13b]



(a) View from the top of the tower of ignition

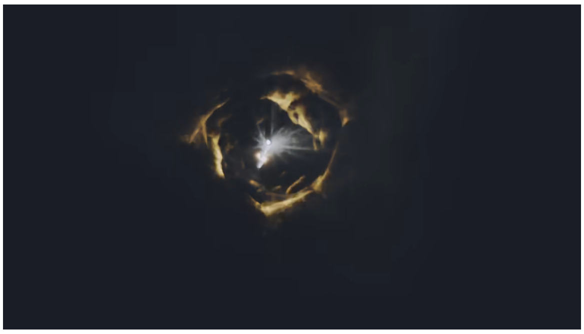
(b) Starship fights gravity with 70MN of thrust

4.3 Separation

Two minutes and thirty-five seconds after liftoff, *Starship* and *Super Heavy* separate during *hot-staging*. The *Super Heavy* shuts down all its engines except the three center ones to keep inertia. While it is still attached, the Starship ignites its six engines whose exhaust gases escape through the interstage ring. Once ignited and stable, the Super Heavy angles its grid fins and separates from the Starship.[14a]

During separation, the gases emitted by the Starship act on the grid fins like air. This allows giving the *Super Heavy* an ”impulse” to start turning around. Once the flip is completed, ten additional engines reignite and begin to brake then push the *Super Heavy* in the opposite direction. At T+3:41, the booster engines shut down: the first stage, 70m tall, is in a parabolic freefall toward the Gulf, just a few kilometers from the *Mechazilla* tower. In order to put the odds in their favor, SpaceX had planned for the *Super Heavy* to jettison the interstage ring to lose a few tons for better performance. Once the ring is jettisoned, the booster's flight computer, the ground computers and the tower's computer all indicate ”*GO FOR CATCH*”. It is the *Flight Director* who has the final say on the decision. At T+3:48, the order is given: *Super Heavy* is authorized to change trajectory to aim for the *Mechazilla* tower.

As the booster reaches its maximum velocity of 4395$km.h^{-1}$ at an altitude of only 23km, the grid fins angle to initiate the *glide*. A few seconds later, the stage enters the troposphere, which is the densest part of the atmosphere. The immense friction with the air slows the *Super Heavy* by 72% of its maximum velocity in a matter of seconds. The engines which are the first to be exposed to the airflow are red hot. A few seconds before the final burn, the booster gives the impression that it is going to crash given its speed and proximity to the ground. Some very nervous engineers on the ground start screaming.[14b]



(a) The Starship's exhaust escapes through the interstage ring while the booster remains attached

(b) The Super Heavy endures air friction at 4000km/h, notice the very visible angle of attack

4.4 The catch

The *Super Heavy* has just crossed the sound barrier back in the opposite direction while it is at 1000m altitude. At T+6:30, the thirteen center engines successfully reignite for one last time. The booster must slow down from 1200$km.h^{-1}$ to 200$km.h^{-1}$ in the space of a few seconds. SpaceX employees and the public attending the mission scream with excitement and fear. Once 200$km.h^{-1}$ is reached, ten engines shut down leaving only the three center engines.

The flight computer of the booster and of the tower check their operational status one last time. This is the final chance for the *Super Heavy* to abort the attempt. From now on, the booster **must** be caught, otherwise it risks inflicting heavy damage to the launch pad and the tower. During the previous burn, the booster intentionally aimed next to the tower in case several engines failed. This not being the case, the three center engines now aim for a precise point in the space between the two mechanical arms.[15a]

The *Super Heavy* is down to only $110 km.h^{-1}$ and a few dozen meters from the tower. The final position of the booster becomes clear and the *chopsticks* slowly begin to close. The last three engines of the *Super Heavy* gimbal to cancel the horizontal velocity and begin a vertical descent between the two arms. The *chopsticks* see the engines then the first half of the booster pass. The tower actuators close the arms as quickly as possible and the side cushions installed on the arms come into contact with the booster. The booster is slightly swung from arm to arm as it continues to descend until the two *chopsticks* exert a firm pressure on the fuselage. The *Super Heavy* can only descend toward the rails. At a predetermined altitude in the flight computer, the engines increase their power to stop the descent at the exact moment the *landing pins* of the booster touch the rails. Immediately the engines shut down and the fuel vent valves are opened.[15b]

The *Super Heavy* first stage has just been caught by a tower.

(a) ”Booster 12” approaches the tower with three engines running for the final descent

(b) The Super Heavy landing pins making contact with the arms’ rails

A few hours later, once the booster’s tanks are completely emptied, the arms lower the booster to rest it on the launch pad. About a day later, SpaceX teams come to recover the *Super Heavy* ”B12” to bring it back to the production site in order to conduct examinations. Upon its arrival, the employees applaud the booster which succeeded in the task once seen as impossible.

Figure 16: The booster empties its tanks after being caught

5 Conclusion

Since this first successful attempt, the *Super Heavy* has been caught three times. An attempt on November 19, 2024 was aborted due to technical problems on the tower's arms. The booster simply splashed down in the gulf.[35] The three catches have all seen different flight profiles, notably that of the eighth flight due to strong high-altitude winds.[36] Since then, several videos from multiple viewpoints of the different catches have emerged. Those from spectators a few kilometers away show very well the speed at which the booster arrives as well as the power of the sonic boom. (like this one for example)

On the upper stage side, (also called ”Starship”) things are more complicated. The Starship was able to splash down without a problem in the Indian Ocean during the fifth and sixth flight defying doubts regarding the reliability of the heat shield.[37] Since the seventh flight, an upgraded version of the Starship named ”Block 2” is in service. Unfortunately, neither of the two ships during the seventh and eighth attempt reached the ninth minute of flight before exploding.[38] The cause is not publicly known but it seems to have to do with the resonance frequency of the Starship. (The Block 2 is slightly taller and heavier than the original version)

In short, SpaceX's bet seems to be successful but it is only a milestone in the *Starship* program which targets the moon before 2030[39] and mars not long after. The objective of the program is to develop a fully reusable rocket but above all *rapidly* reusable in order to maximize the payload sent into space per year.

Starship will have the role of lunar lander during the *Artemis* missions of *NASA*. Although *Artemis* and its flagship rocket, the *SLS*, have fallen behind in recent years, humanity has never been so close to a return to the Moon and an adventure to Mars.

Aerospace is one of the most complicated fields, but that does not stop thousands of engineers from working day and night to have a chance to explore the stars. We all live a life here on earth, but we must never forget that we are in a vast void that is unknown to us for the most part. According to aerospace enthusiasts, the future of humanity is not here, it is supposed to be up there. We have a lot of time to explore, but not infinity. One day or another, a human will be further than the moon. One day, a human will no longer be in orbit around the earth. One day, a human will set foot on another world.

This day will arrive before you die.

Ad astra per aspera.

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