Design Review

Push-push latch mechanism for iPod battery door- housing interface

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Hook-based vs One-way Ratchet based mechanisms

Factors considered:

i. Space constraint
ii. Reliability
iii. Mfg. and part quality
iv. Ease of Assembly
v. Aesthetics
vi. Ease of usage

i. Part design & complexity
ii. Working of mechanism
iii. Functional cross-sections
iv. Free-body diagrams
v. Critical tolerance stacks
vi. Part Analysis (calcs, FEA)
vii. Factor of safety on critical features
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Problem Statement

Apple Product Design | Design Test

Revised Feb 2013

Objective:
People have complained that the iPod doesn't have replaceable batteries. For your design project, we would like you to create a battery door mechanism, which will include a door, release button and door latching features to house and cover 2 AA batteries. The button should reside **within** the mechanical outline of the battery door.

Mechanism Requirement:
As depicted on the next page, the door should unlock when a user presses a button, which causes the door to pop open in the opposite direction. Please come up with 2 different mechanisms for this door.
Note carefully the mechanism requirement: a downward force on the button, normal to the door, should activate the button.

Deliverables:
1) Please create a 12-14 page Powerpoint (or keynote) presentation showing the evolution of the design. The presentation should tell the story.
   a. Concept sketches
      - Provide inspiration list. Remember, there is no shame in 'benchmark' researching and borrowing/improving upon existing designs.

   b. Decision tree
      - Let us know which of the two is your preference and why. Make clear any assumptions you may have made (e.g. "the battery is part of the door")

   c. Initial technical calculations

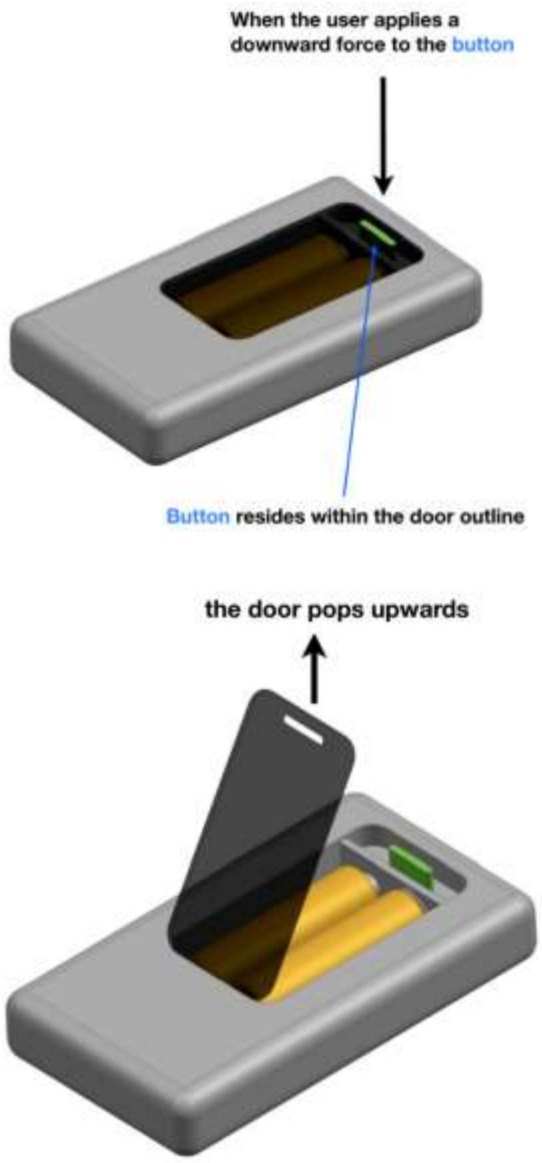
   d. Few slides showing the 3D CAD (screen-shots) with highlights of the mechanism and relevant details.
      - Suggest adding a few cross sections of the important mechanism structure, showing the critical surfaces/features.

   e. FEA (if any)

   f. Create a Bill of Materials for each mechanism: list of parts, materials, and rough cost estimate

2) Please make a 3D model your favorite mechanism and send this to us as a Parasolid (.x_t) or a Step (.stp) file. 3D CAD is strongly recommended.

Please let me know if you have any questions during the week. We look forward to seeing what you come up with. **Impress us!**



Mechanism's User and Functional Requirements

User Requirements:

1. Simple to operate
2. Overall design should be subtle, aesthetically pleasing and unobtrusive.
3. Button should be accessible to user fingers and thumb
4. Least frequently used mechanism on iPod in terms of daily use. Thereby, it should not be prone to accidental actuation
5. Mechanism should support easy removal of batteries

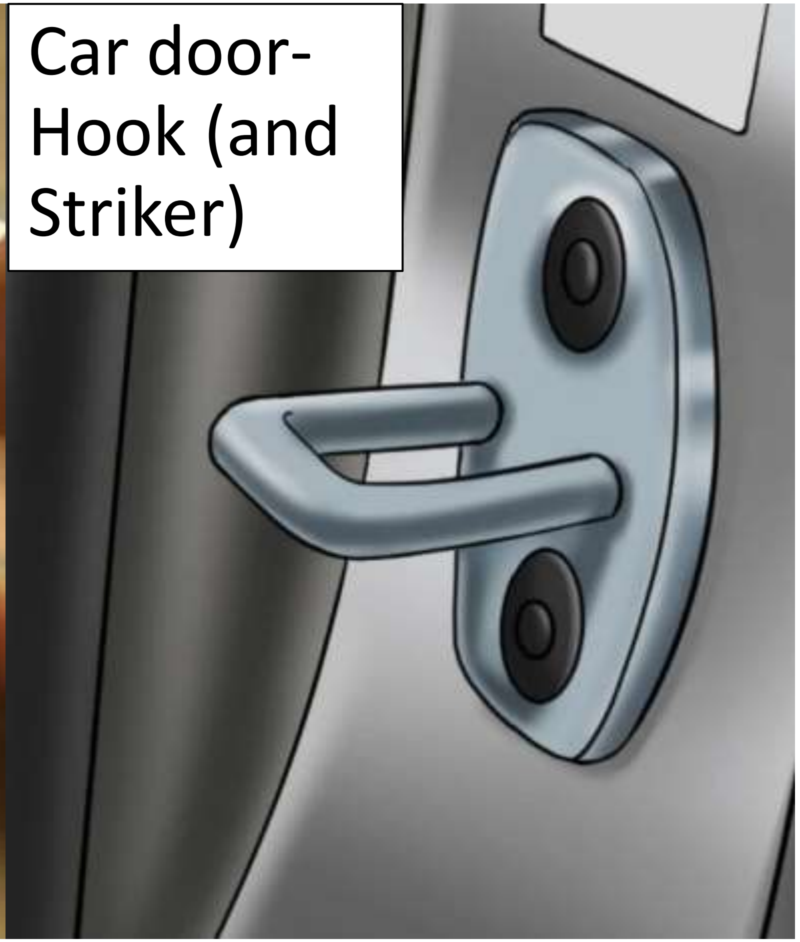
Functional Requirements (assumed):

1. Force to press button should be greater than 0.75lb and less than 3lbs.[1] Value at higher end isn't necessary bad as it is better as don't want inadvertent pressing of button. (Requirement met)
2. Button displacement to actuate the mechanism should be between 0.080"-0.120"[2] (3mm OR .120" travel)
3. High fidelity design. Should work for 1000 open/close cycles (160k music hours worth battery usage)[3] (To be tested)
4. Should not snap open when dropped from 2ft. If it opens at >2ft drop, parts shouldn't disassemble (or rattle internally) or break (To be tested)
5. Mechanism should not add any further thickness beyond what's available with use of AA batteries. Assumed thickness of iPod is 1.0in[4] (Requirement met)
6. Mechanism should not add more than 50g (approx. the weight of 2-AA cells)[5] (mostly plastic components. Added weight <50g)

Inspirations (1 of 2)

(examples of various push-push mechanisms)

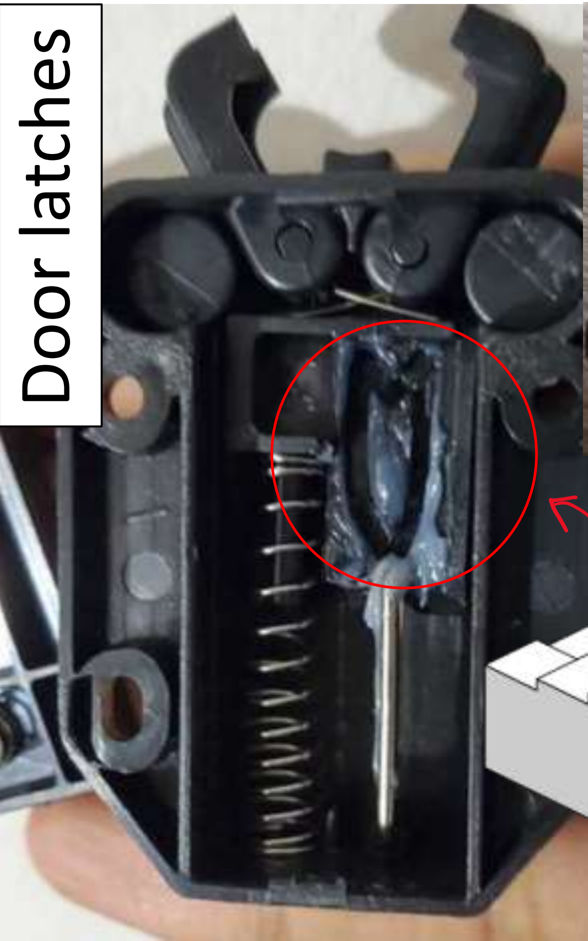
Hook-striker based design. This body of concepts consist of a spring-loaded striker that loops around a hook. Here, the main engineering task is to make the hook non-back drivable in case unintended forces are applied while the striker is engaged with the hook.

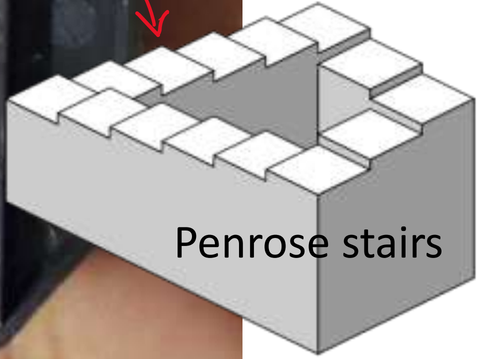


Inspirations (2 of 2)

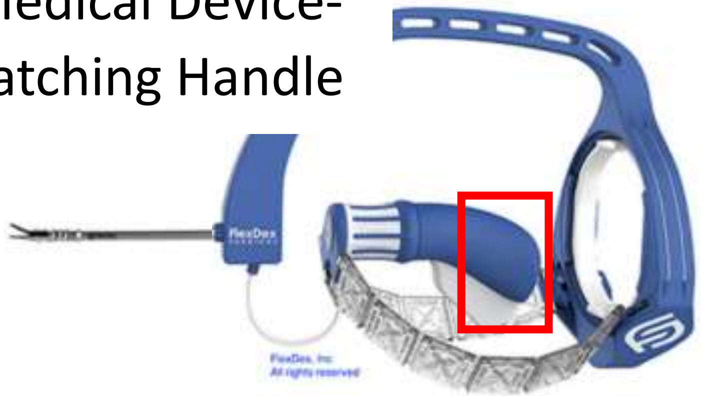
(examples of various push-push mechanisms)

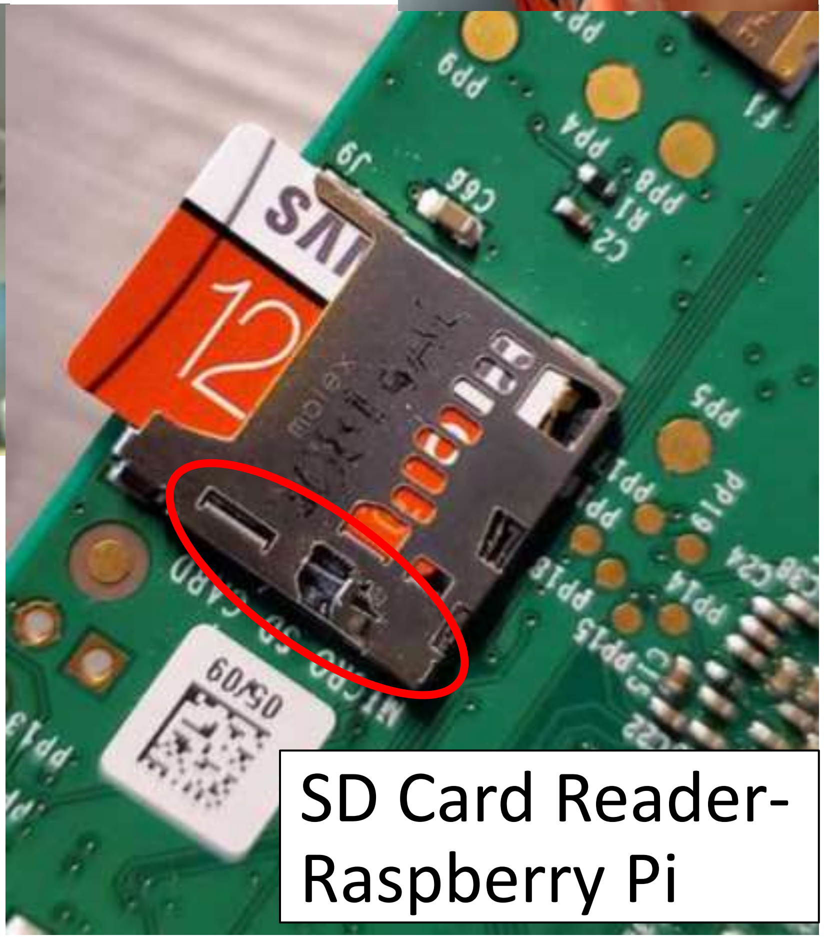
One-way ratchet-based design. This body of push-push mechanisms are used in devices across various applications as well as size/volume. **One-way ratchet refers** to stepped sections that are travelled by a moving feature. There is locked position and an unlocked destination. Upon closer review (teardown), it was found that the door latch mechanism has functionally identical components. They are just miniaturized in case of SD-card reader. Highlighted in red balloon is the one-way ratchet mechanism.





Medical Device-
Latching Handle

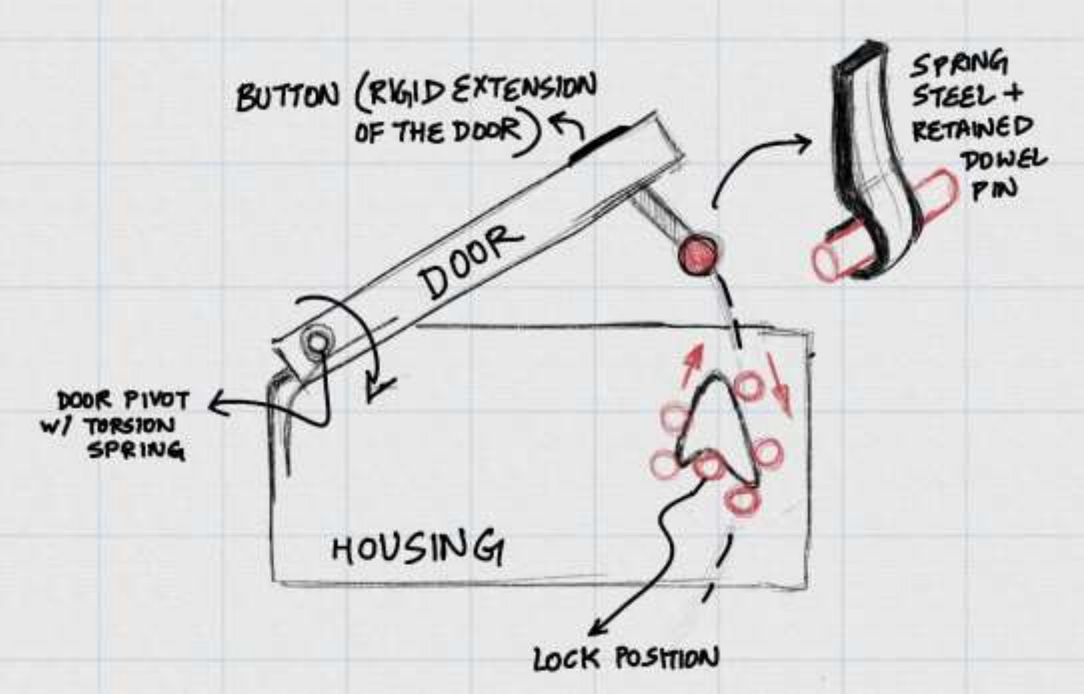




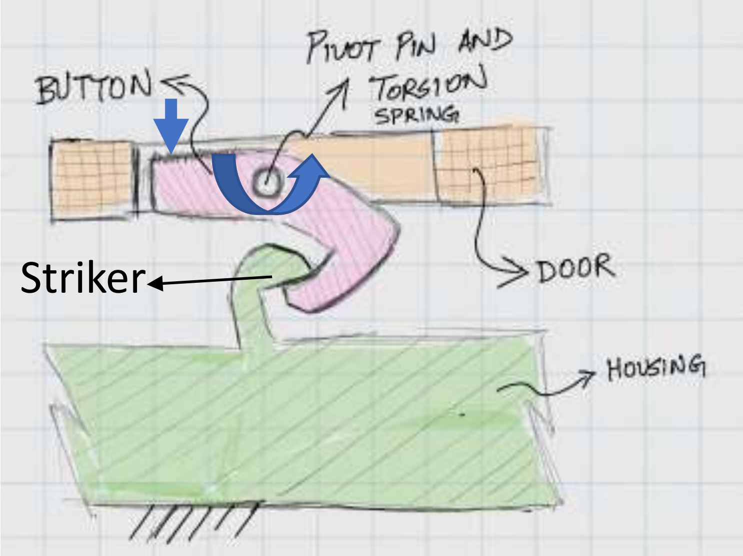
Concept Sketches and Notes (1 of 2)

Assumptions:
i.) Door pops open due to stored energy in torsion/ leaf spring located at pivot pin/ hinge at the door and housing interface
ii.) Both AA batteries are located within the housing and not rigidly attached to the door (assembly)

Concept 1: Leaf Spring-based latching mechanism
Pro: Standard go-to, highly reliable latching mechanism used across various industries.
Con: May require considerable thickness to achieve required button travel.



Concept 2: Hook-striker design
Pro: The hook-striker design can be engineered such that positional and dimensional tolerance variation of button and housing hook features do not impact latching performance
Con: Button travel can be limited depending of distance of finger land (on button) from button pivot

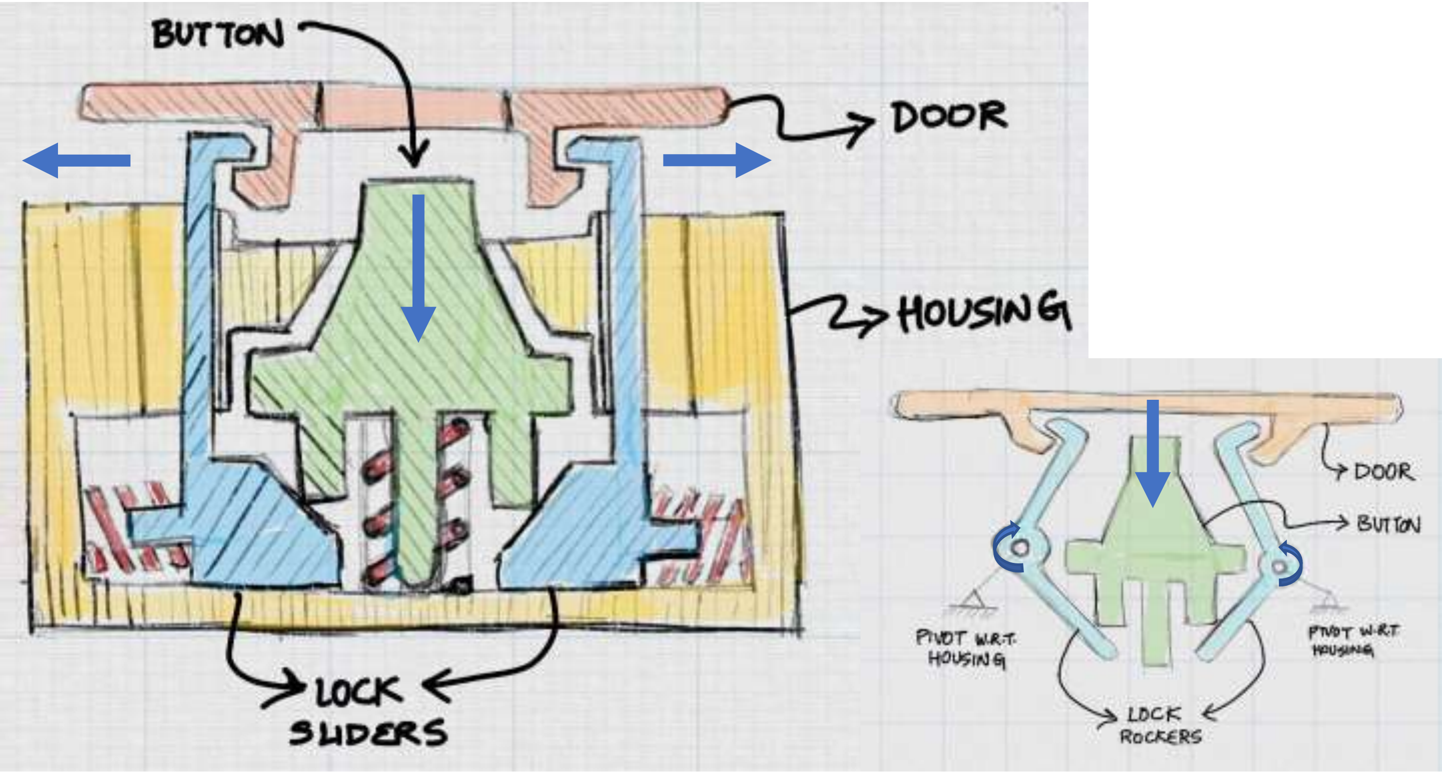


Concept Sketches and Notes (2 of 2)

Concept 3: Locking sliders/ rockers mechanism

Pro: Due to transverse travel of sliders/rockers, the mechanism can be made compact while maintaining required button travel.

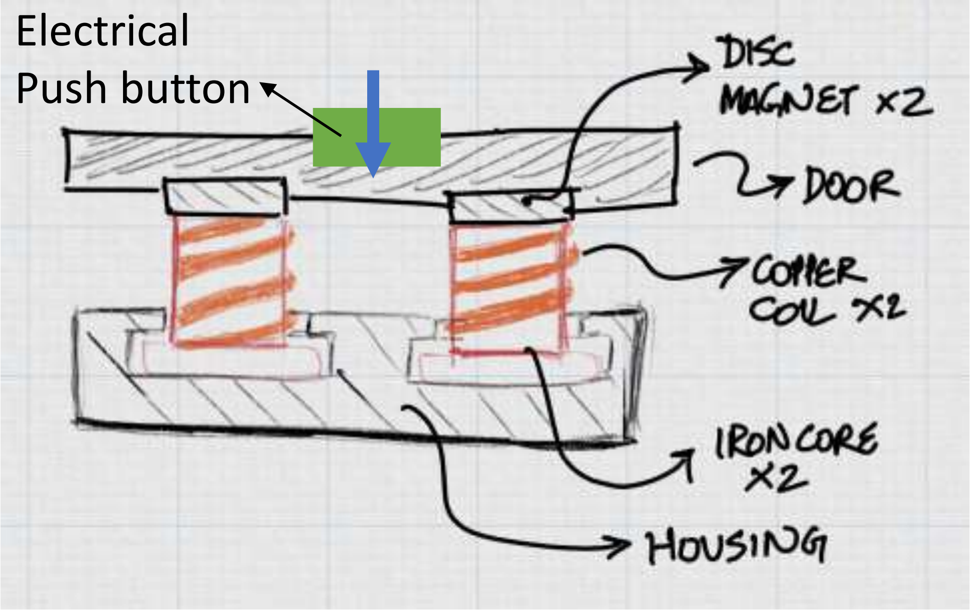
Con: High # of components, higher design complexity as features providing degree of constraints are required to prevent unwanted reaction forces/friction. Also, user needs to put finger through the door to actuate button



Concept 4: Electromagnet-based mechanism

Pro: Less # of parts, highly consistent retention force.

Con: Requires software-based aid where a small fraction of battery is saved for use of push button which actuates electromagnets

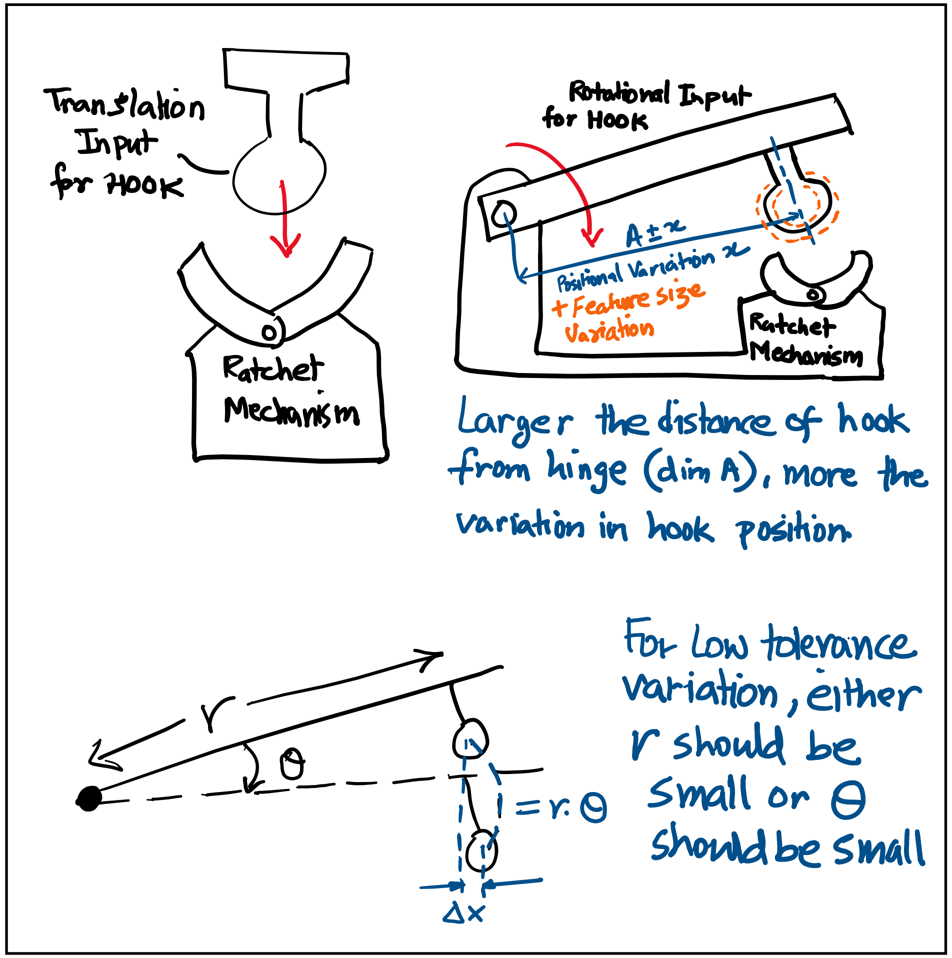


Choosing between mechanisms (1 of 3)

Two bodies of mechanisms shown here are- hook-striker based and ratchet based.

Concept 1 and Inspiration 2of2 mechanisms show a **one-way ratchet mechanism** which is highly reliable (reason why it's used in millions of cars, Raspberry Pis, laptops, medical devices, etc.). The amount of vertical travel required (high), and size of parts (large) used in this mechanism were my concerns seeing the door latch until I found the SD card reader. **The problem with SD card reader mechanism is that it is back drivable** i.e. I could pull the SD card out post-locking it as parts within the mechanism assembly are small and compliant.

Unlike the door latch design, where the input is pure translation, a rotating input (in case of door) adds further tolerance variation to the position of input hook relative to the overall mechanism. **Rotating door mechanism will require some compliant mechanism to compensation of positional variation (e.g. use of spring for the hook as shown in concept 1).** Also, in case of iPod, it makes sense to keep the door simply a rotating interface with the chassis instead of a door coming down vertically.



Choosing b/w mechanisms (2 of 3)

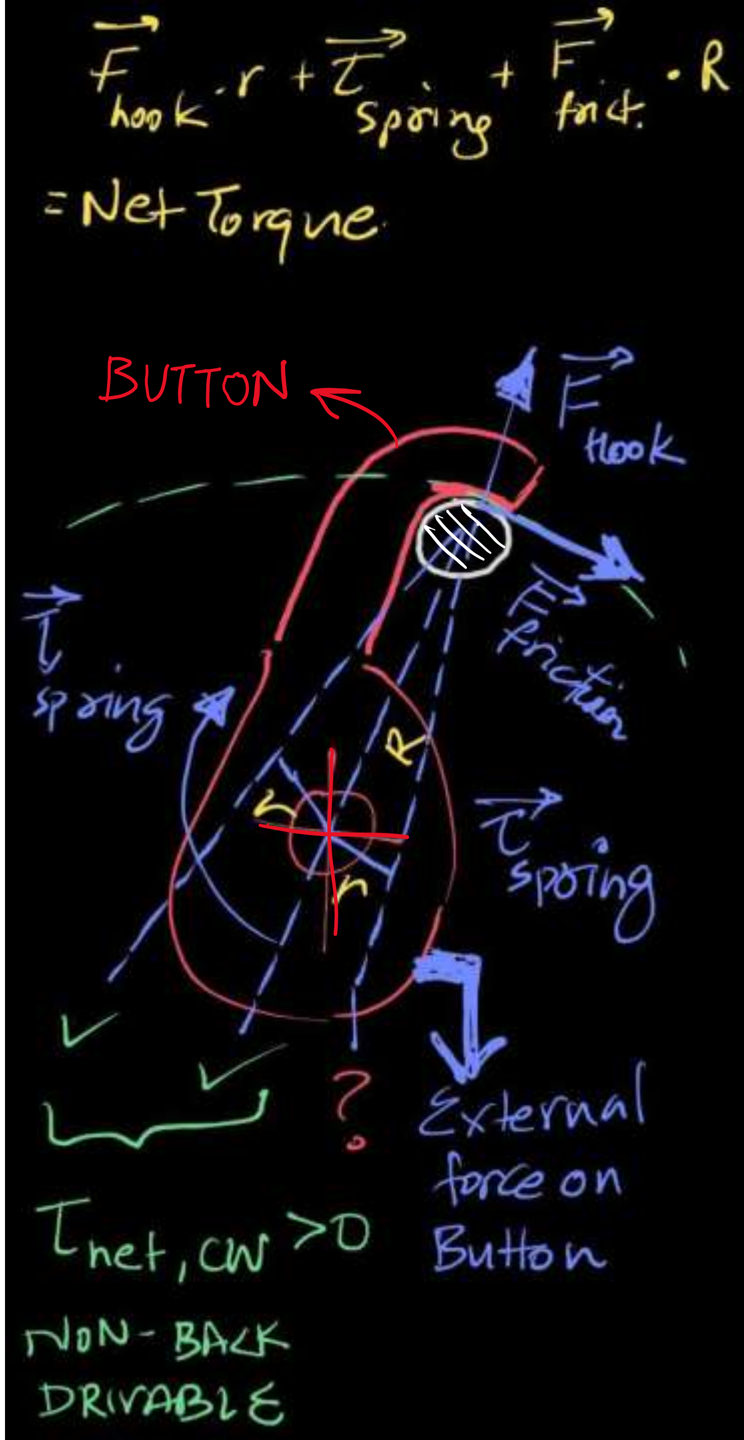
Concept 3 uses wedging action to translate vertical displacement to horizontal motion. This can be effective tool when considering reduction in amount of rotation of the door (θ) when used in conjunction with **concept 1**. **One disadvantage of a push-button (shown in concept 3)** is that **the user is pressing the button while going through the door that is going to spring back in opposite direction.** Therefore, it isn't convenient unless a flexible rubber overmold is applied on the door that squishes down to press and produce required button travel.

Concept 2 refers to rotating button that latches onto a stationary tab. This mechanism, in itself, is not a push-push mechanism as the button requires rotational input motion provided by the user. It can be used in combination with other push-push mechanism to effectively retain a tab (as shown in figure).

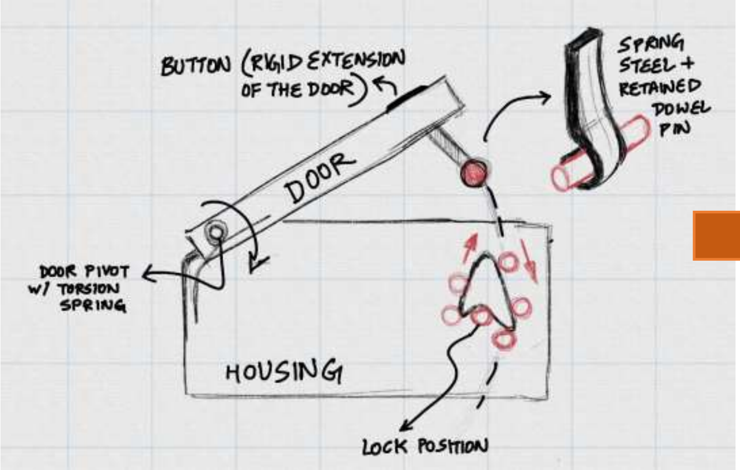
In many applications, key design aspect of a button-tab locking mechanism is whether the button can be back-driven by applying an external force.

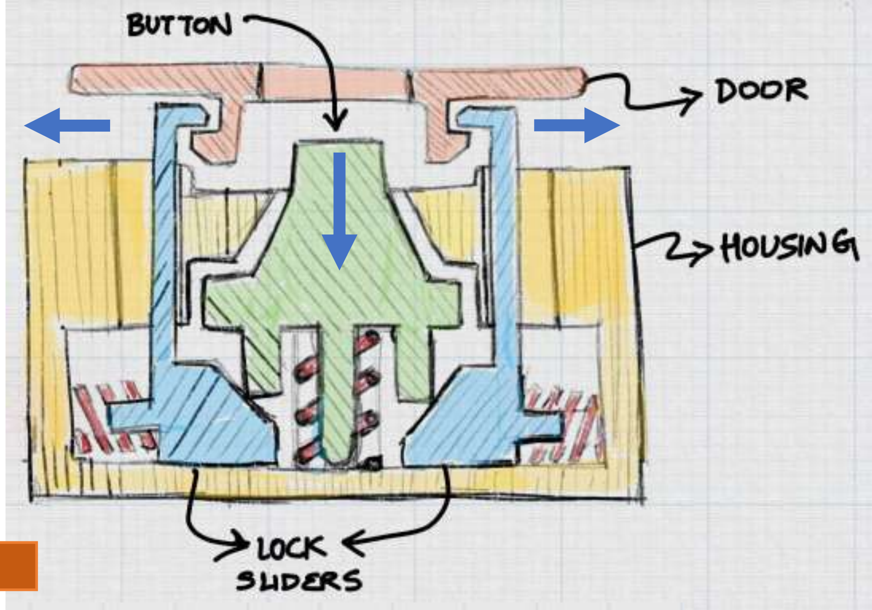
Based on all the aforementioned inputs, **ONE one-way ratchet mechanism (similar to concept 1) with a wedging action to reduce door rotation (concept 3) are used as basis for mechanism design. Therefore, this mechanism will combine the strengths of each concepts.** These along with a spring-loaded button lock (concept 2) maybe used wherever necessary.

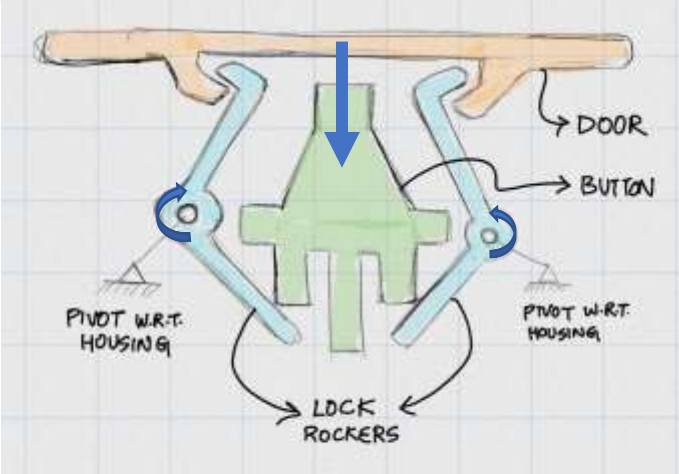
Note: *Concept 4 is not considered to keep mechanisms dominantly mechanical.*



Choosing b/w mechanisms (3 of 3)





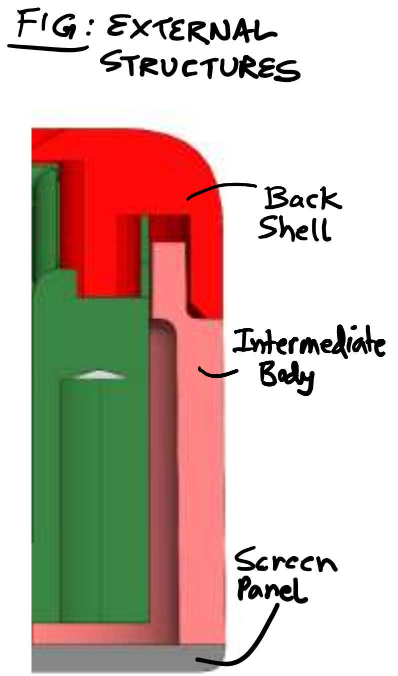


Mechanism Design overview and details

Design details are broken down into:

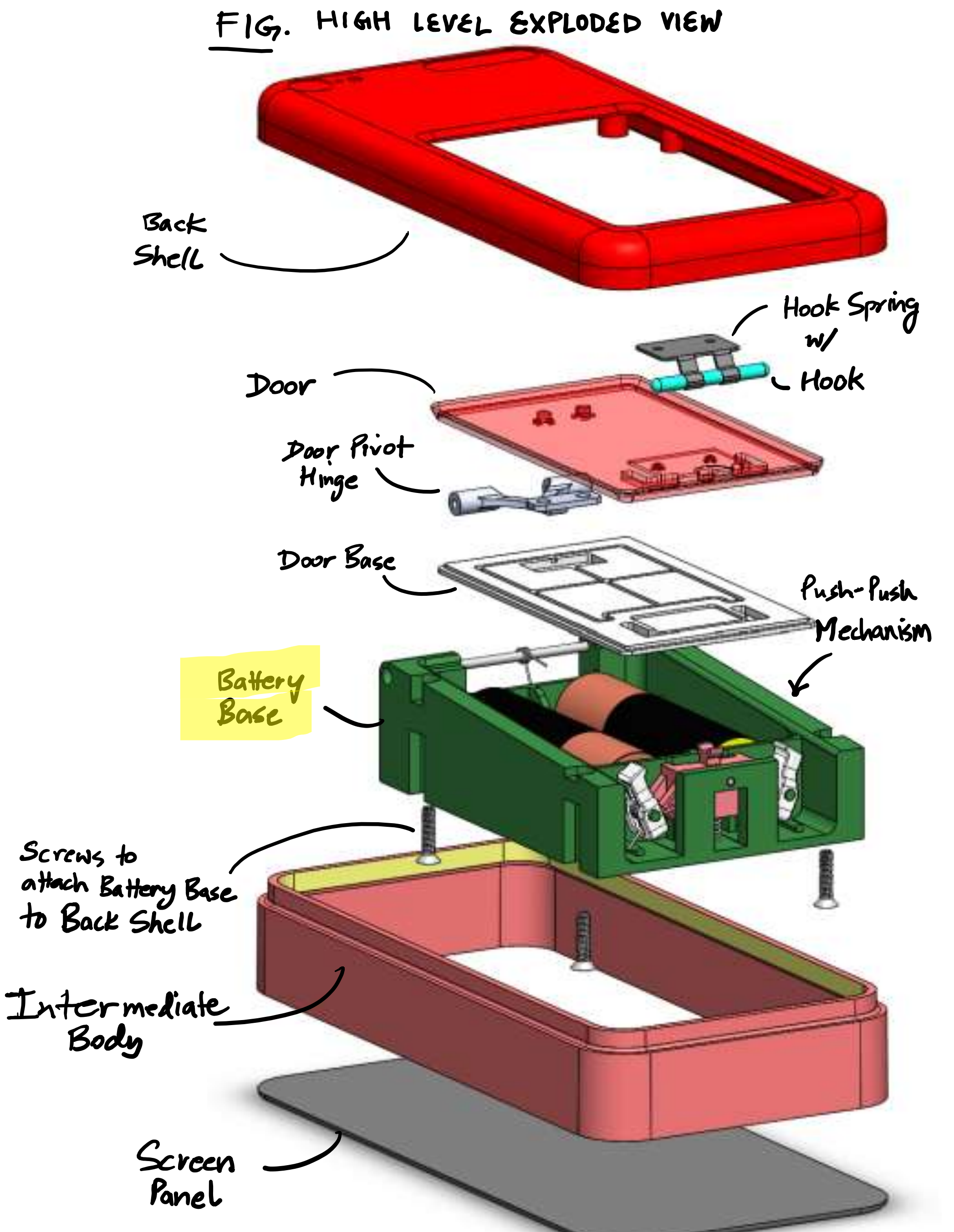
1. Walk-through of overall structural design and key components
2. How mechanism works
3. Key design choices to develop a viable design
4. Tools used to make design decisions-
   i. Free-body diagram,
   ii. force calculations,
   iii. tolerance stack analysis,
   iv. FEA,
   v. mechanical intuition/judgement
5. Material selection and rationale
6. DFM description for few important components
7. Important x-sections
8. Force vs displacement plot. Force efficiency description
9. BOM

Design walk-through (1 of 2)

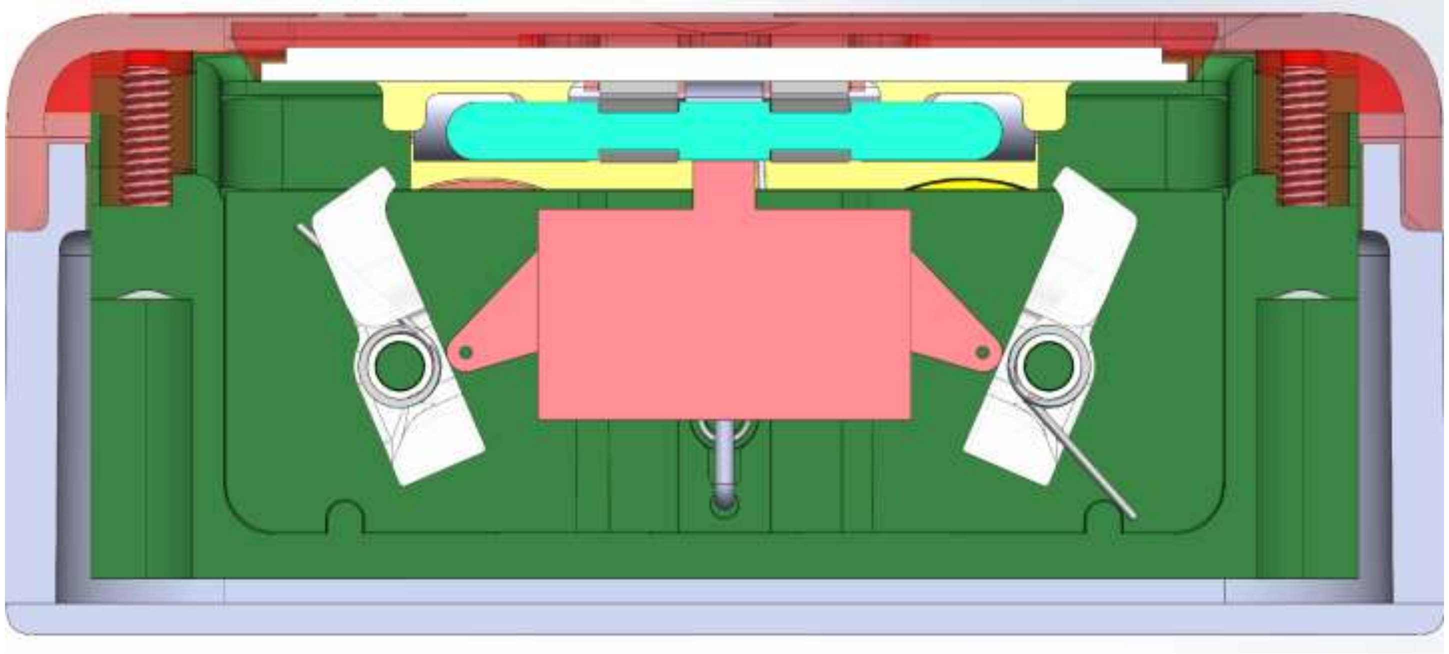


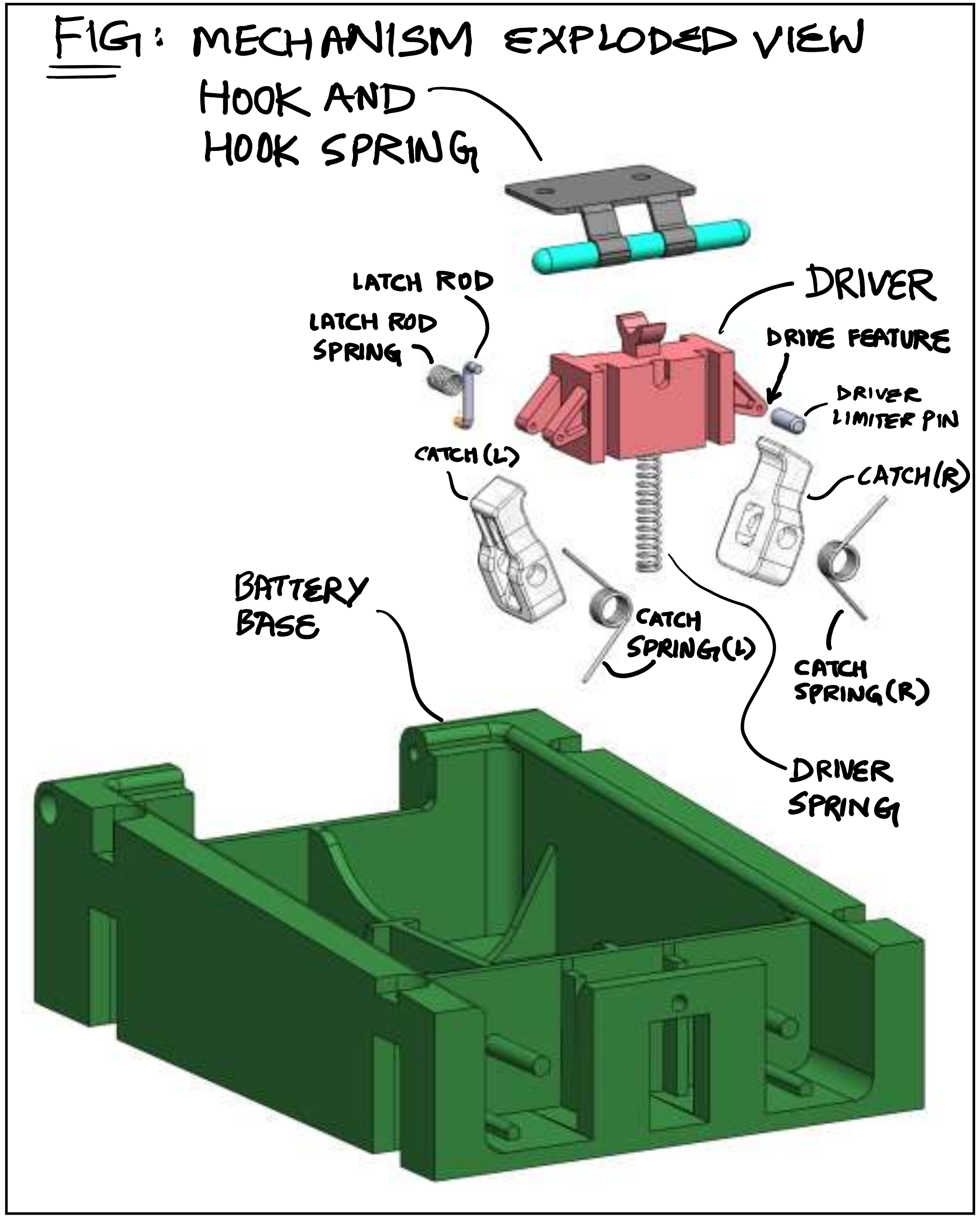
First step is to understand the key structural components that will be used and how will they be mounted and retained. Fig. on left shows the layered construction of iPod with AA batteries. It doesn't make sense to machine aluminum/magnesium/SS back shell to produce the entire external rigid structure (~1"). Therefore, **an intermediate body is added that can be made of aluminum, carbon/glass-filled filled polymer** (negative being aesthetics) and can be attached using mechanical lap joints/adhesives/ultra-sonic welding (if both bodies are plastic), etc.

Battery base **(or case)** is the "housing" for the push-push mechanism. It is attached to the Back shell from the proximal (screen end) to keep screw access from the same side as other peripheral attachments within an iPod for the assembler. An assembler would take a battery base, push-push mechanism and door assembly housing 2 AA cells and assemble it to the back shell from the screen end.

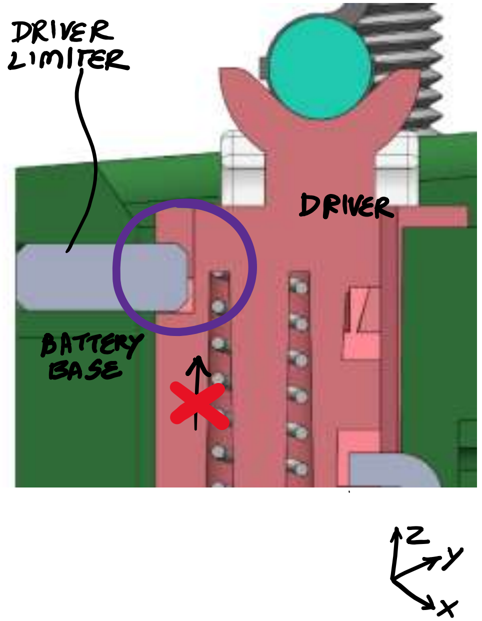


Design walk-through (2 of 2)

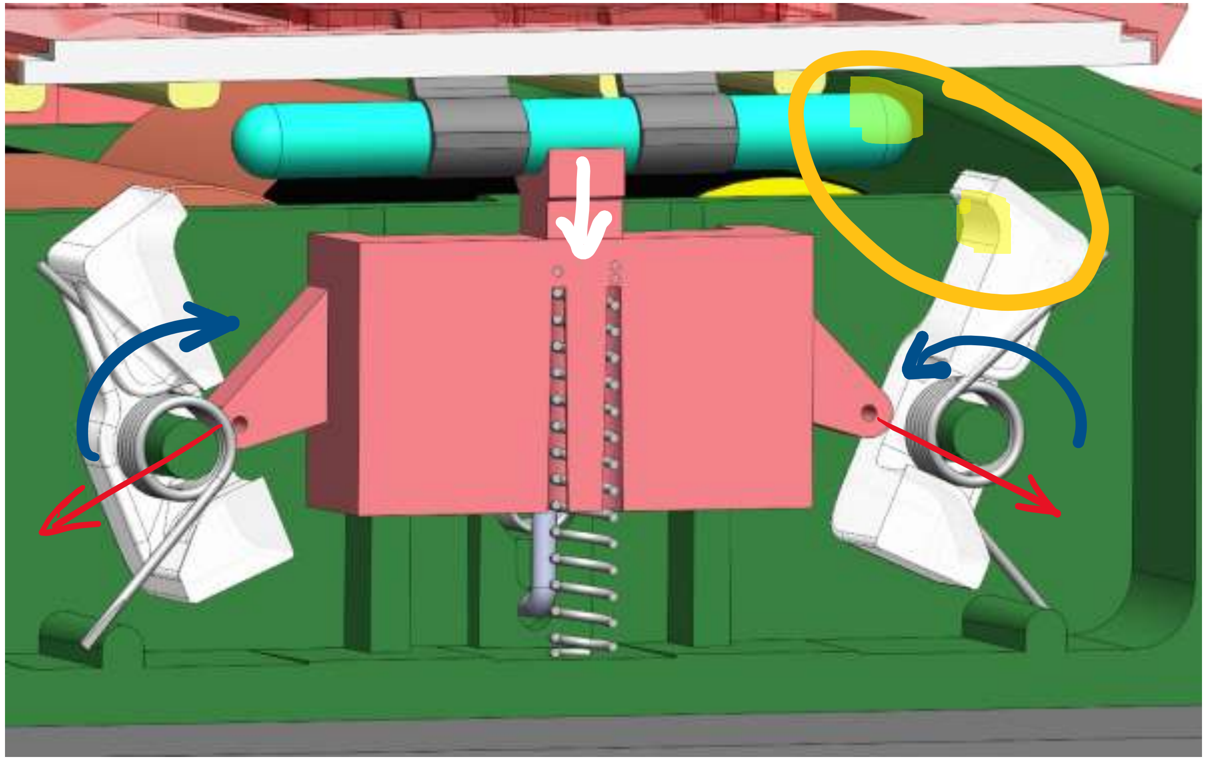


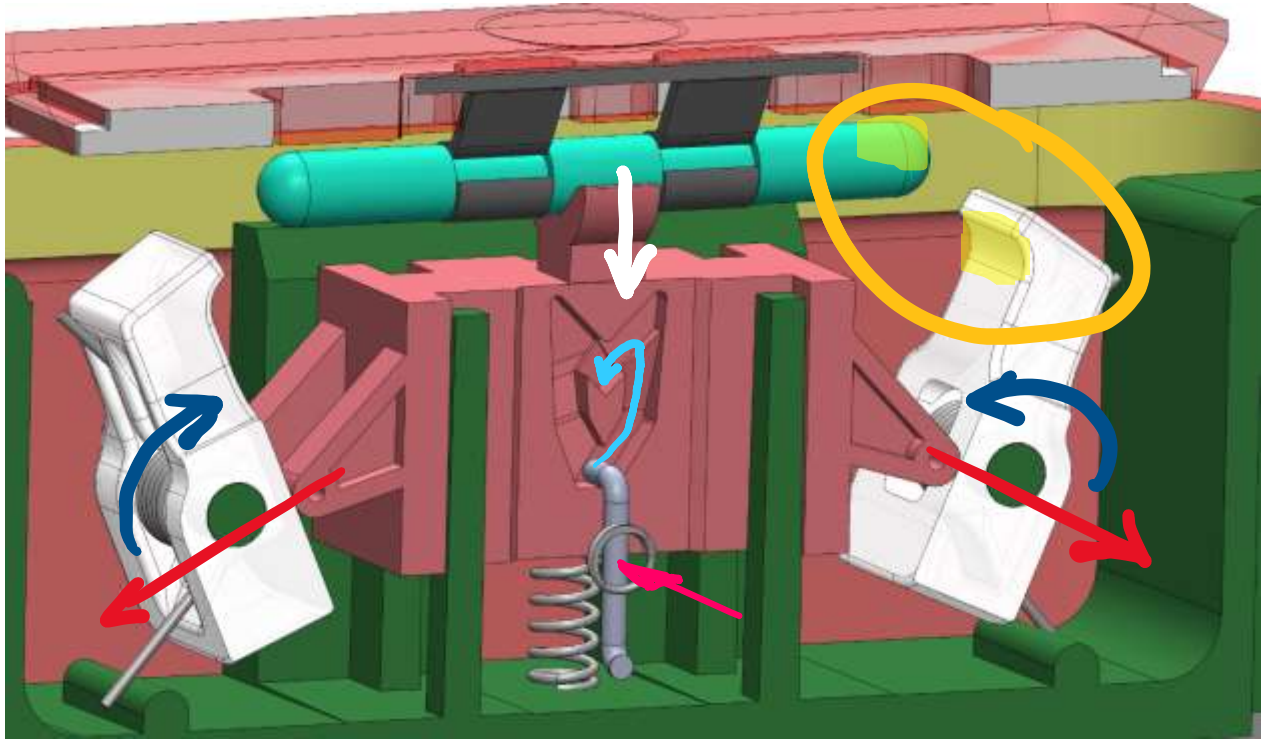


How mechanism works (1 of 3)

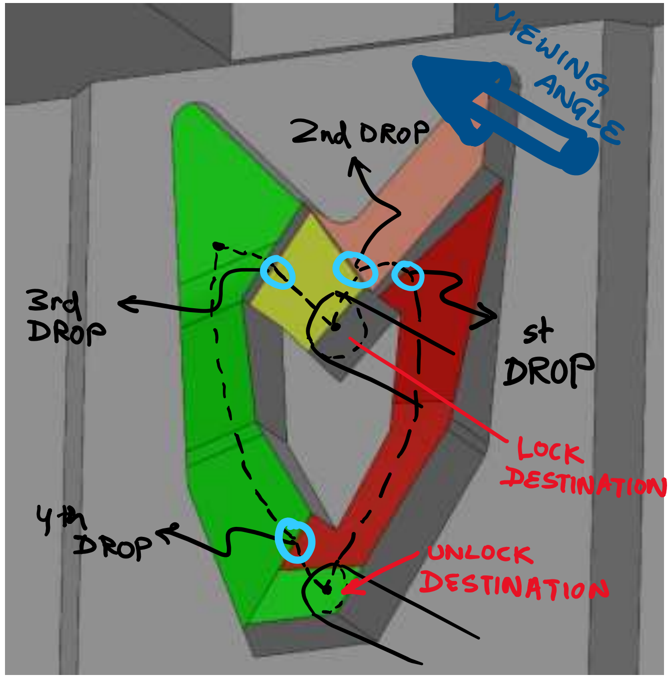


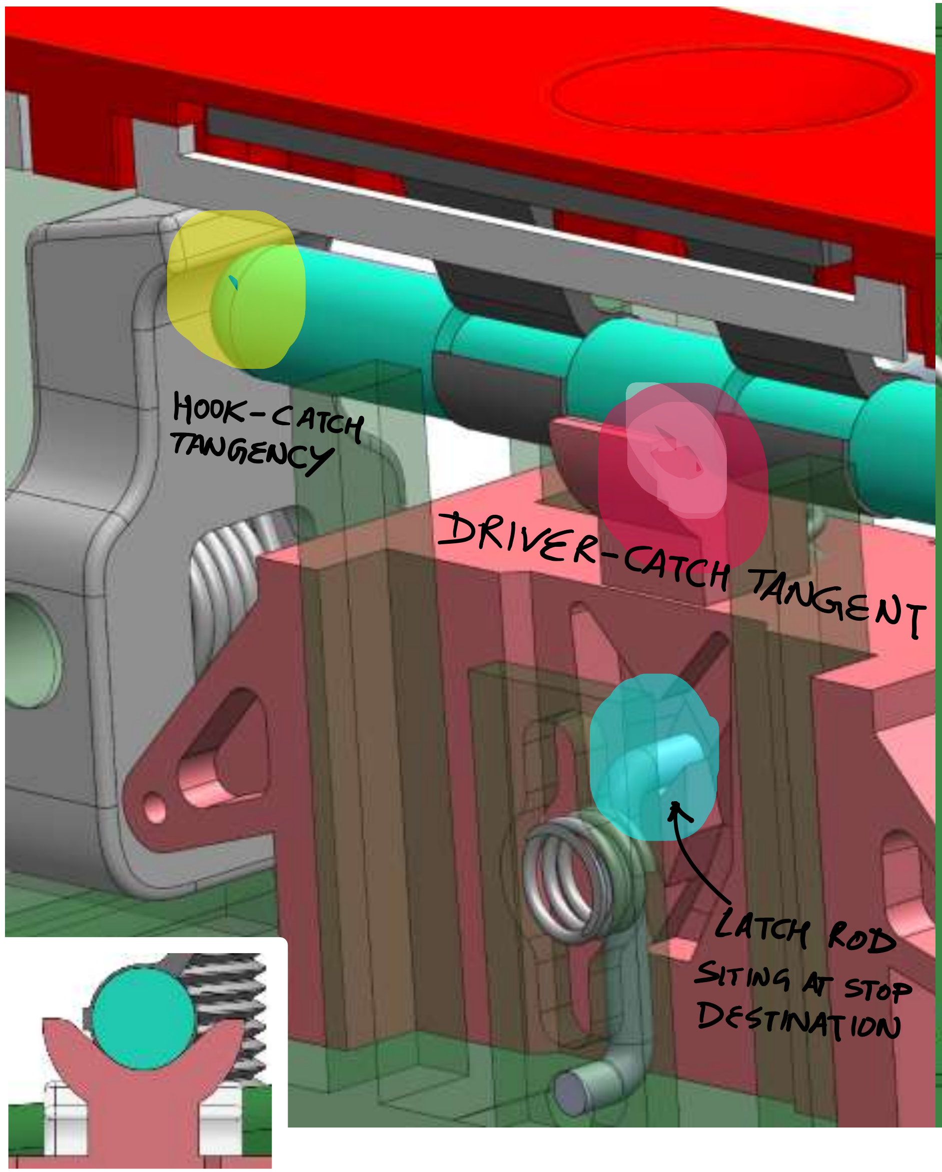
As the door is rotated, the hook pushes the down onto the driver (concept 1). Also shown by **WHITE arrow** below. This, in turn, applies force onto catch L & R rotating them towards the driver (concept 3), see **RED arrows and DARK blue arcs**. Catch L & R are pre-loaded by torsional springs. At the same time, latch rod travels along the provided path on driver ultimately reaching the lock destination (concept 1), see **LIGHT BLUE path**. At the point when latch rod locks the driver, the catch captures the hook (concept 2), see **YELLOW highlight**. Thereby, the hook which is part of the door assembly, is locked with respect to the driver. The driver is further constrained from moving in +Z direction by driver limiter pin, see **PURPLE highlight**.

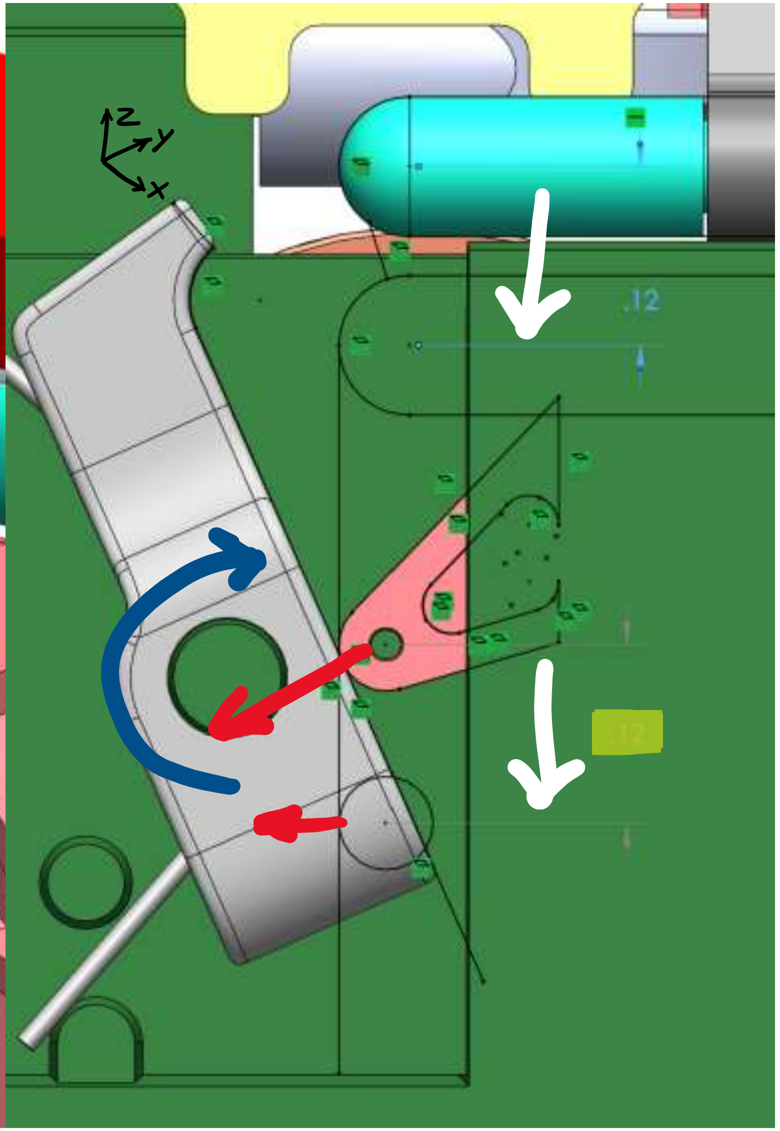




How mechanism works (2 of 3)





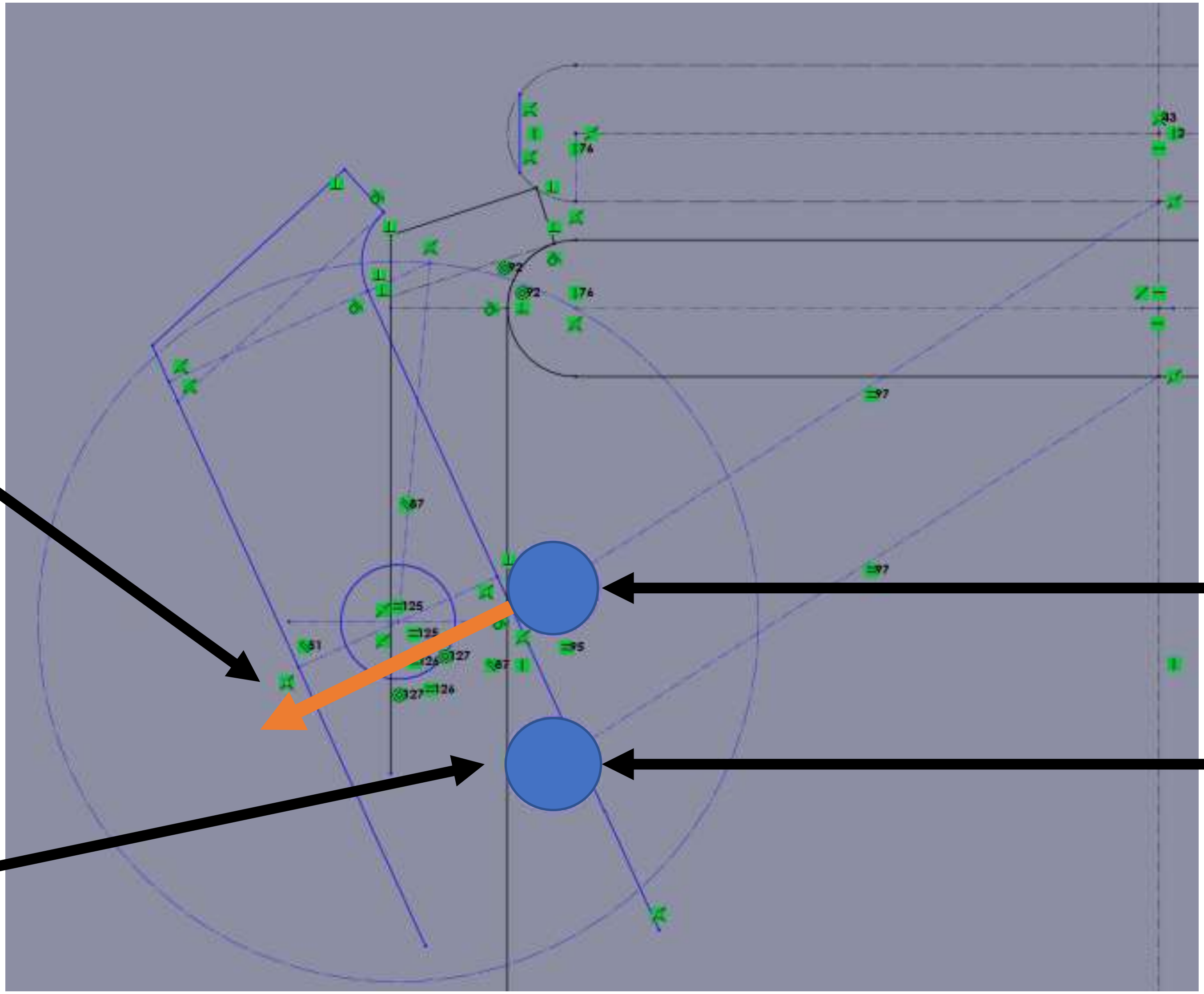


After **0.12 in of travel, equivalent to 2.7^o degrees of door rotation**, the hook is locked by the catch (see fig. on the right). The latch rod reached and sits in the groove at its stop destination. Lock and unlock destination are shown in detail above.

Note: The hook moves away by 0.005” along –Y direction upon door rotation. This will be compensated by the hook spring and the lead-in features (see on the right) present on the driver

How mechanism works (3 of 3)

Force applied by driver on catch



No normal force further applied by driver on catch

Starting position of driver.

Stop position for driver. 0.12” vertical travel.

FBD of Driver

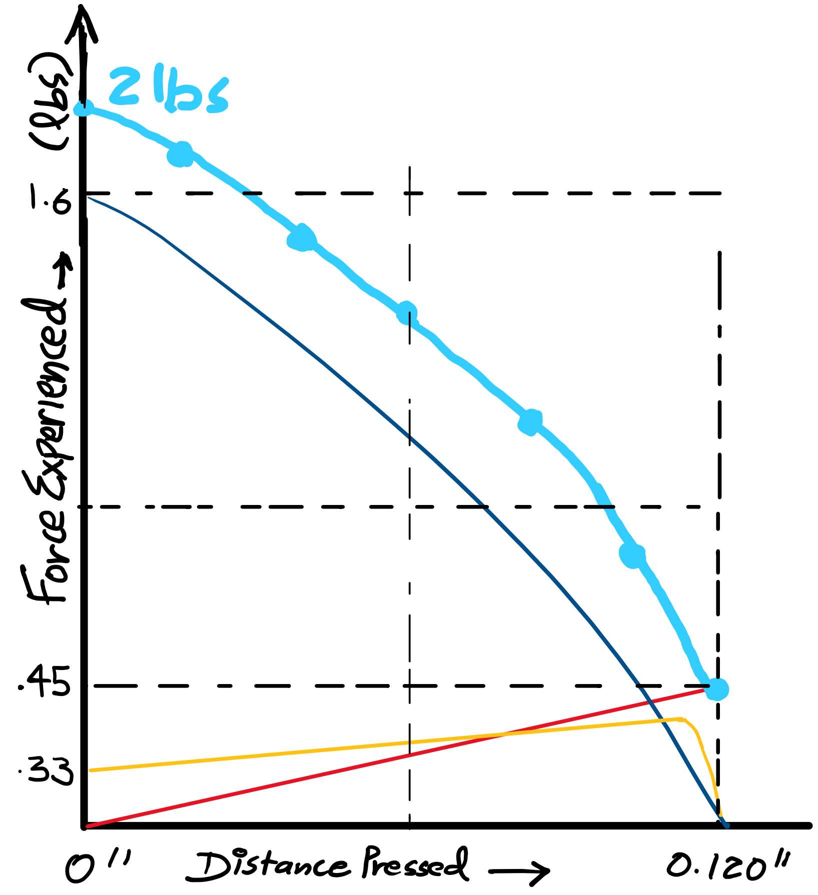
$F_{NET} =$

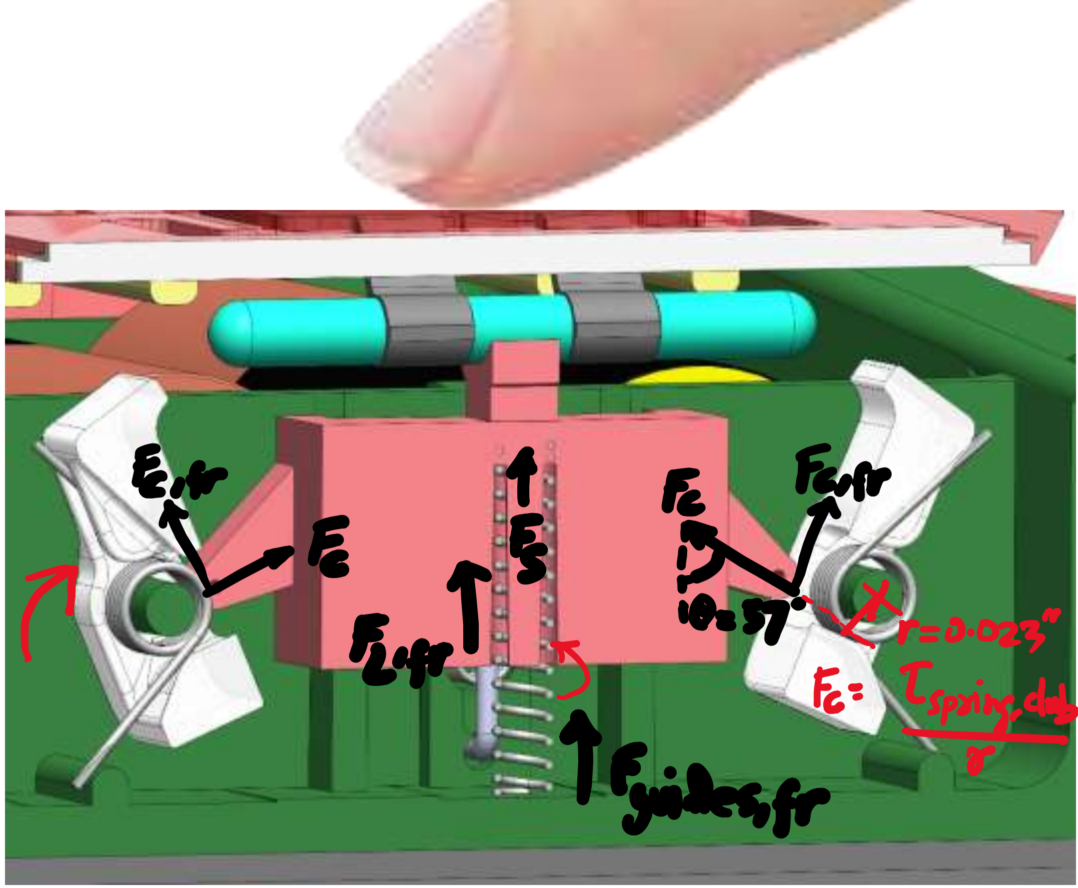
$2 \cdot F_{catch} \cdot \cos\theta' + 2 \cdot F_{c,fr} \cdot \sin\theta' + F_{spring} + F_{latchrod,fr} + F_{guides,fr}$

$(\mu_{catch} = 1.2)$

At start of stroke	End of stroke
$\theta = 57°$	$\theta = 90°$
$F_{spring} = 0$	$F_{spring} = 0.45lb.$
$F_{net} \approx 2.2lb$	$F_{net} \approx 0.5lb$

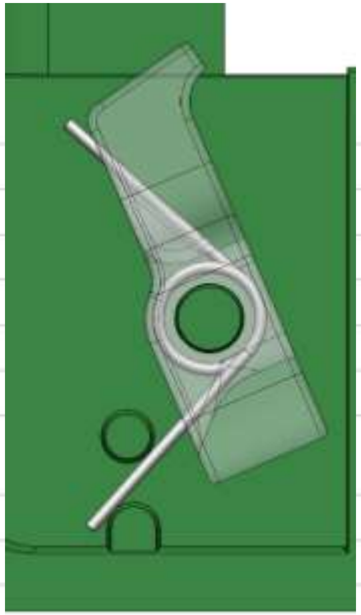
As the catch rotates, force due to catch on driver keeps on reducing. At the same time, compression spring force keeps on increasing.



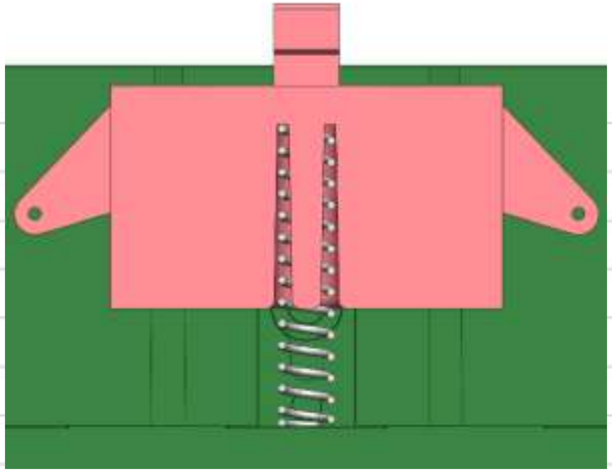


Max. force experienced by user is approx. 2lbs. Other than catch, other friction values are considered within 10% of force values. The drop in force from 2lbs to 0.45lbs must provide user a tactic feel that door is about to be locked or unlocked

Spring Forces



Spring Type	Compression
System of Measurement	Inch
Length	0.5"
OD	0.088"
ID	0.064"
Wire Diameter	0.012"
Compressed Length @ Maximum Load	0.2"
Maximum Load	1.16 lbs.
Rate	4.16 lbs./in.
Material	316 Stainless Steel
End Type	Closed
Rate Tolerance	-0.42 to 0.42 lbs./in.
OD Tolerance	-0.003" to 0.003"
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
RoHS	RoHS 3 (2015/863/EU) Compliant



Spring Type	Torsion
Deflection Angle	180°
Wind Direction	Left-Hand
OD	0.133"
For Shaft Diameter	0.078"
Wire Diameter	0.014"
Leg Length	0.5"
Number of Coils	5
Spring Length @ Maximum Torque	0.105"
Maximum Torque	0.07 in.-lbs.
Material	302 Stainless Steel
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
RoHS	RoHS 3 (2015/863/EU) Compliant

Hook Spring Design (1 of 3)

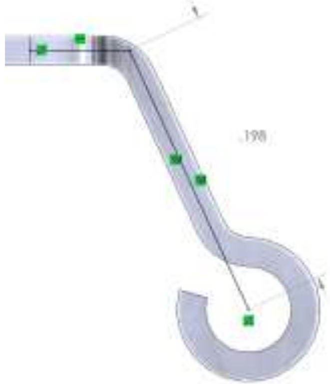
Property	Value	Units
Elastic Modulus	28000000	psi
Poisson's Ratio	0.3	N/A
Shear Modulus		psi
Mass Density	0.29	lb/in^3
Tensile Strength	185000	psi
Compressive Strength		psi
Yield Strength	140000	psi

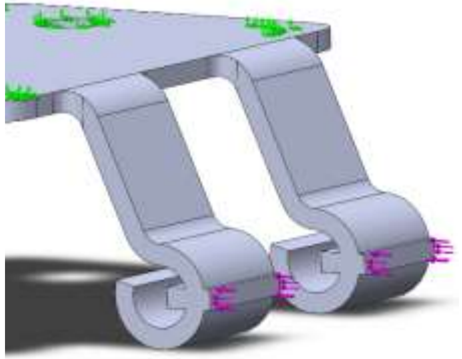
Hook spring is designed to be 0.020” thick and to be made from 301 SS FH. This grade to steel provides high tensile strength (185ksi) and is commonly used for leaf springs.

FEA: In order to assess impact of misalignment between hook (hook spring) and driver, both FEA and hand calcs are performed. Results from FEA show the following:

Force = 3.4lbs, Displacement = 0.0079”, FOS = 3.3

Force = 8lbs, Displacement = 0.0179”, FOS = 1.39





Hook spring Design (2 of 3)

Property	Value	Units
Elastic Modulus	28000000	psi
Poisson's Ratio	0.3	N/A
Shear Modulus		psi
Mass Density	0.29	lb/in^3
Tensile Strength	185000	psi
Compressive Strength		psi
Yield Strength	140000	psi

SLENDER OBJECT, THEREFORE EULER BEAM THEORY CAN BE APPLIED

$$\delta = \frac{F.\ell^3}{3.E.I} \text{ (cantilever beam)} = \text{NET DEFLECTION}$$

$$\sigma = \frac{M.y}{I} = \text{TENSILE STRESS UNDER MOMENT } M.$$

$\because$ Here, $M = F.\ell$

For 301 Hardened SS [Choosen for its high tensile strength & past success]:

$$I = \frac{bh^3}{12} = \frac{(0.125 \times 2) \times (0.02)^3}{12} = 0.17 \times 10^{-6}\ in^4$$

$$\sigma = \frac{3.\delta.E.I}{\ell^2} . \frac{(0.010)}{I}$$

In worst case, tol. stack to:

1. Door pivot to hook spring ground = ±0.003" (on door)
2. Hook spring angle (on spring) = ±1° (equivalent to 0.0035")
3. Hook spring length (on spring) = ±0.005" (equivalent to 0.0022")
4. Position of mating feature on driver = ±0.003"

0.0117"

Adding 0.0055" of displacement due to 2.72° of door rotation, net potential displacement = 0.0172"

σ for $\delta = 0.0172"$ is:

$F = 10.5$ lbs for $\delta = 0.0172"$

$$\sigma = \frac{My}{I} = \frac{10.5 \times 0.198 \times 0.01}{0.17 \times 10^{-6}} = 122{,}294\ psi$$

Yield Strength = 140 ksi.

$\therefore$ FOS @ worst case displacement = 1.15

FOS @ nominal 0.0055" displacement:

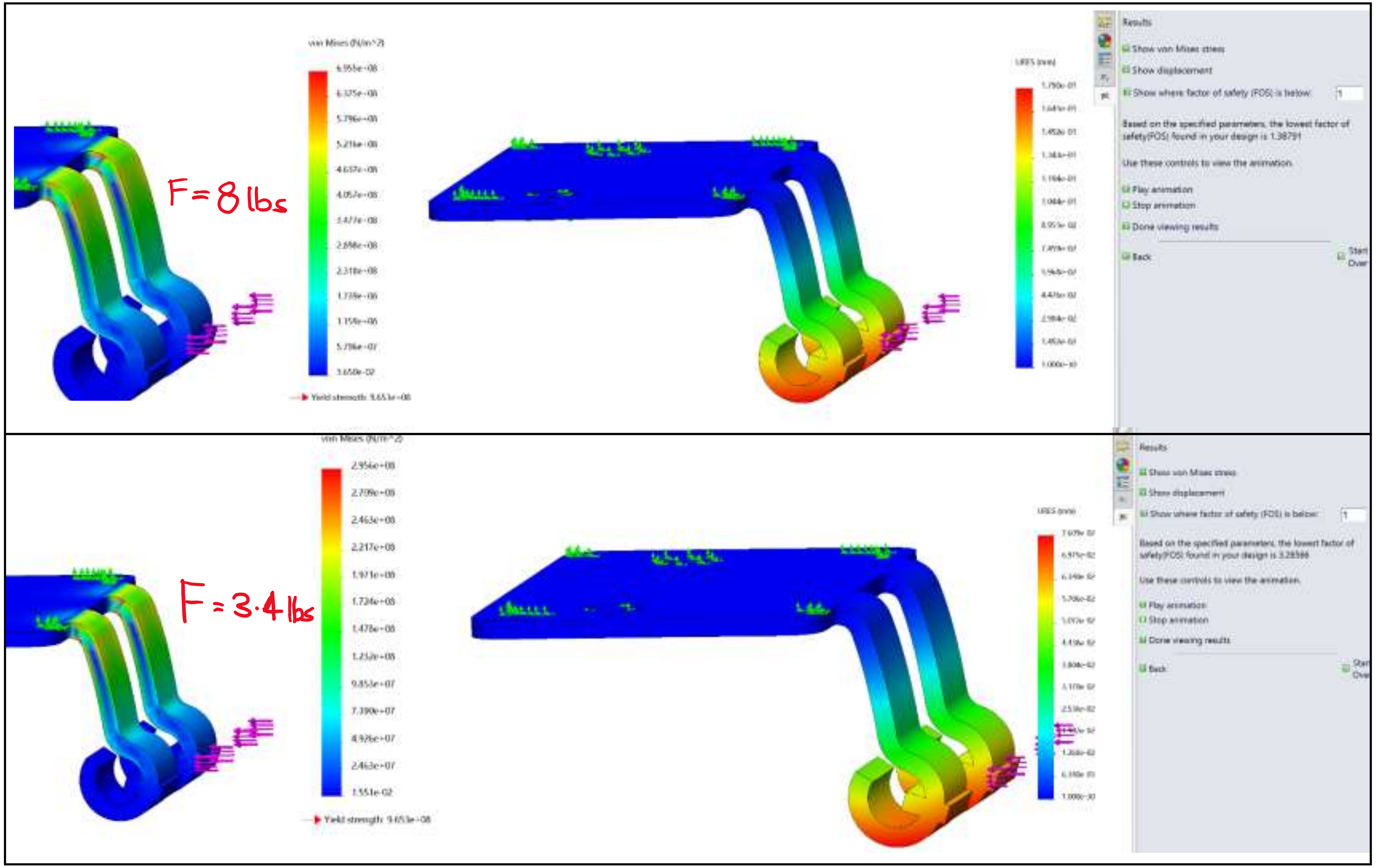
$$\frac{\sigma_Y}{\sigma} = \frac{140k}{\left(\frac{3.4\,lbs \times 0.198\,in \times 0.01\,in}{0.17 \times 10^{-6}\,in^4}\right)} \Rightarrow 5.5$$

Hook Spring Design (3 of 3)

Property	Value	Units
Elastic Modulus	28000000	psi
Poisson's Ratio	0.3	N/A
Shear Modulus		psi
Mass Density	0.29	lb/in^3
Tensile Strength	185000	psi
Compressive Strength		psi
Yield Strength	140000	psi

Based on tolerance stack analysis, worst case displacement is 0.017”. FOS for 0.018” displacement is 1.39 (FEA) and 1.15 (hand calcs).

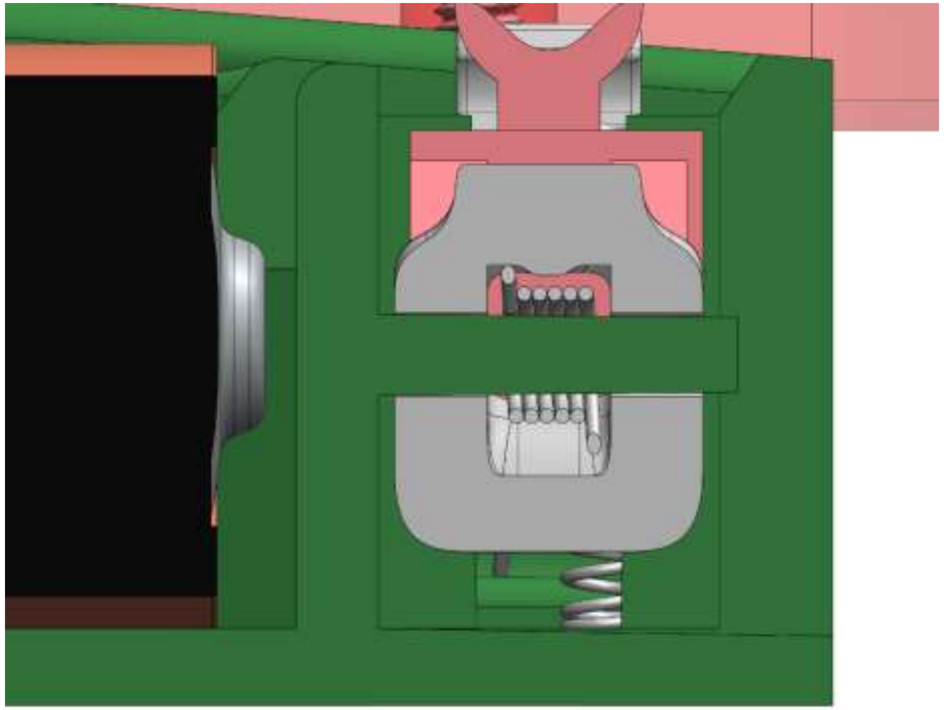
These numbers give enough confidence in the design for a wide range of displacement. **Hence, the design is acceptable.**



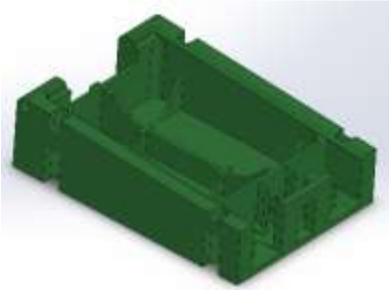
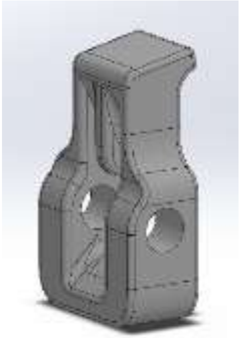
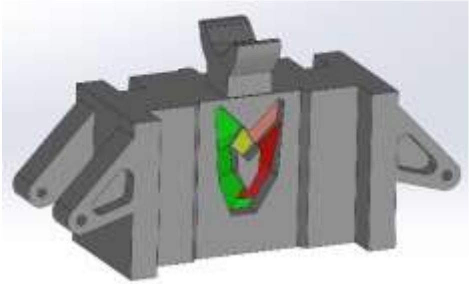
Integrated pins- Battery base

Integrated pins save assembly hassle if they can reliably perform their respective functions. In case of battery case, the most important integrated pin is the pivot pin for the “catch”.

This is a simple supported cantilever beam problem. For a 0.080” diameter pin, using a PC/ABS (polycarbonate) with 20% GF blend (e.g. RTP 2505), it takes 12lbs for force applied at the center plane to break the pin. The load requirements here are 3-4 lbs.. In case of drop, there is some unknown risk to the design that should be tested and mitigated.

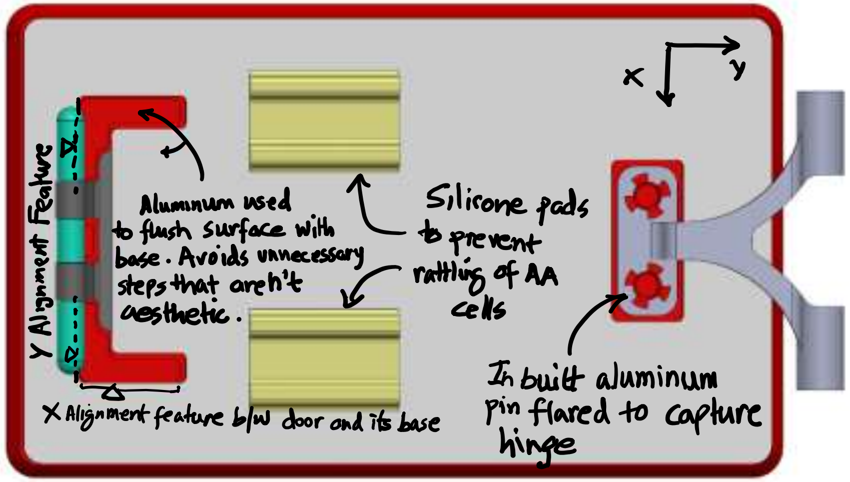


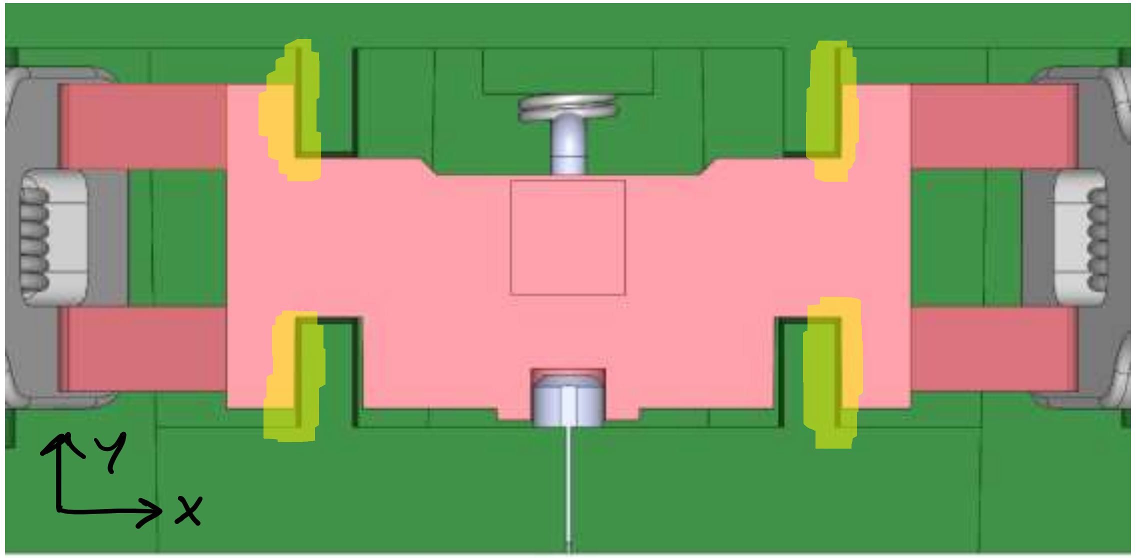
Material selection

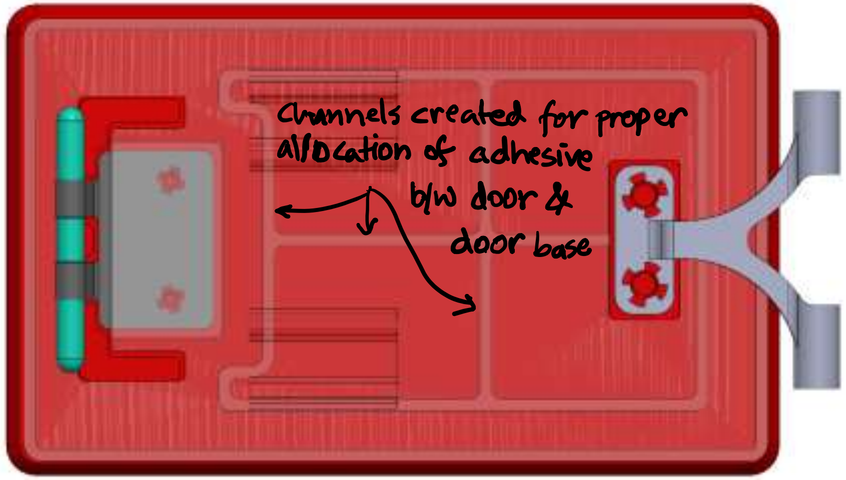




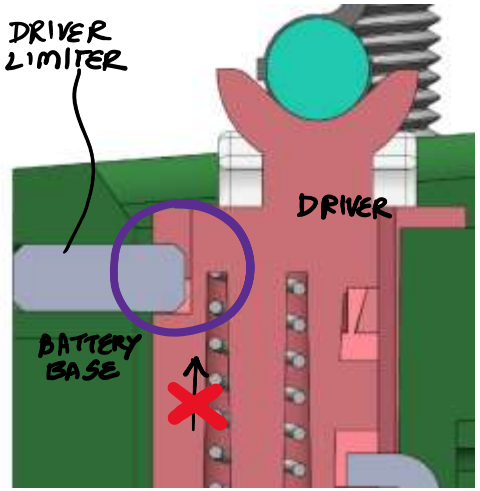
1. **Battery Case:** Glass or carbon reinforced polymer e.g. Nylon 6/6 with 20% glass fiber; PC/ABS blend with 20-30% GF (RTP 250 used in past); PPS (similar to Vectra) with GF/CF (e.g. RTP 1383, 1387, 1300). Reinforced plastic with modulus ≥ 10 GPa and tensile strength ≥ 100 MPa should suffice. As this component is the backbone of entire battery, door and mechanism sub-system as well as incorporates few integrated pins, a higher strength plastic is required.
2. **Catch:** Catch is a relatively small component that should not deflect enough to release the hook. Also, load is shared with the driver (as seen in FBD) and therefore, ABS or PC or a variant of POM (acetal) should suffice.
3. **Driver:** Driver requires low friction interface with battery case to avoid high friction build up at the alignment guides. Therefore, either Acetal (natural), Acetal with 10% GF or PC with 20% acetal blend should suffice. In terms of load bearing ability, the load is ultimately transferred to battery case via “latch rod” and “driver limiter” pin.

Other key aspects of design (incl. x-sections)

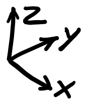




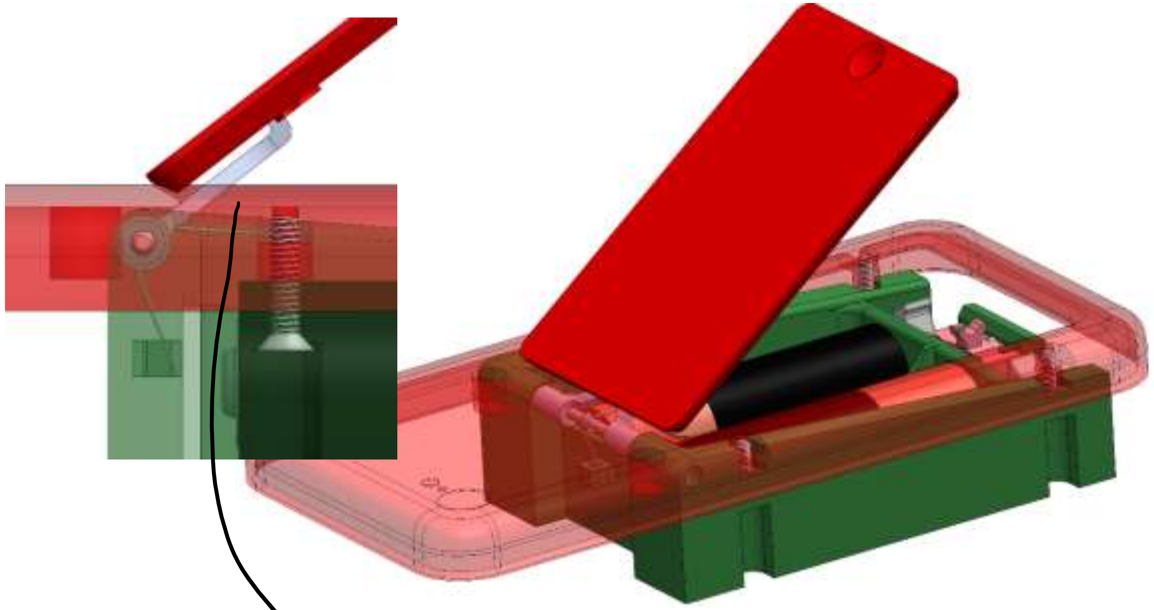




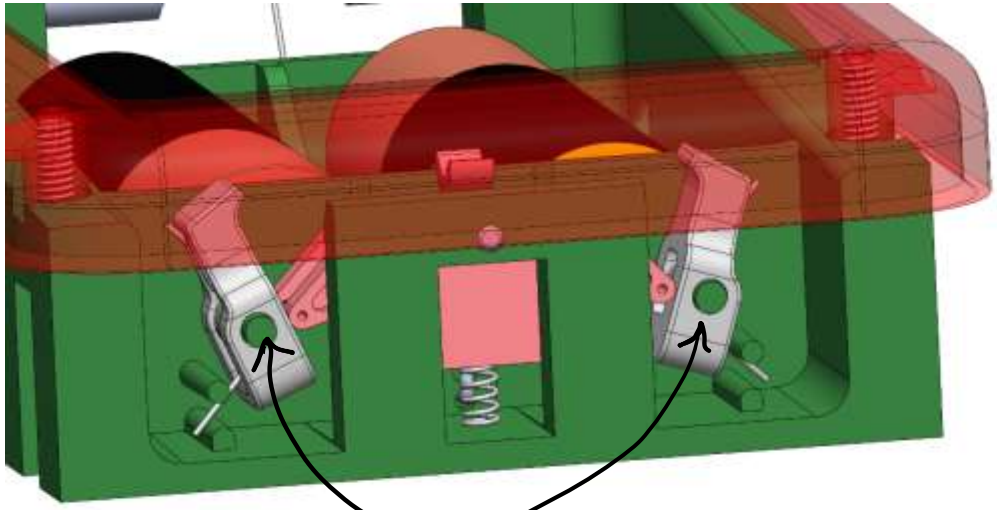
5 degree of freedoms (DoFs) constrained by yellow highlighted features and +Z constrained by "Driver Limiter" Pin



Other key aspects of design (incl. x-sections)

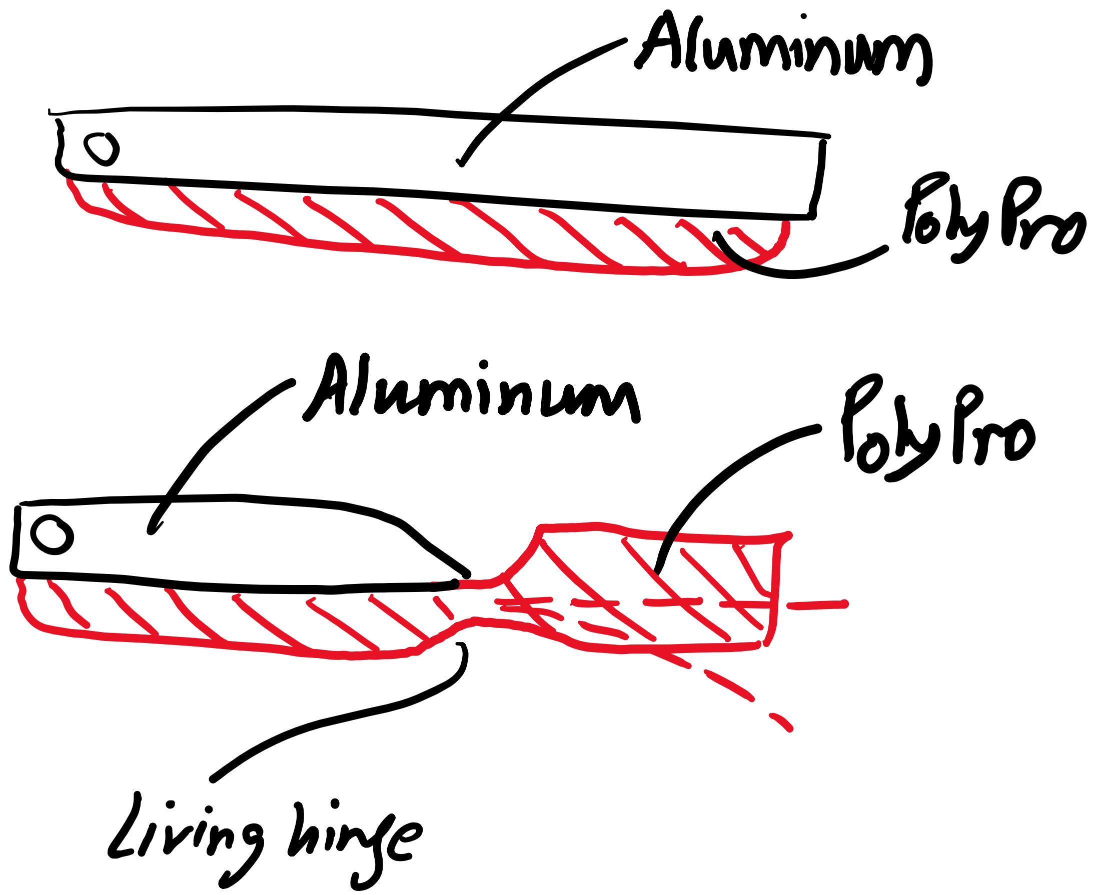


Door hinge designed to provide more than 45 degrees of opening for the door.



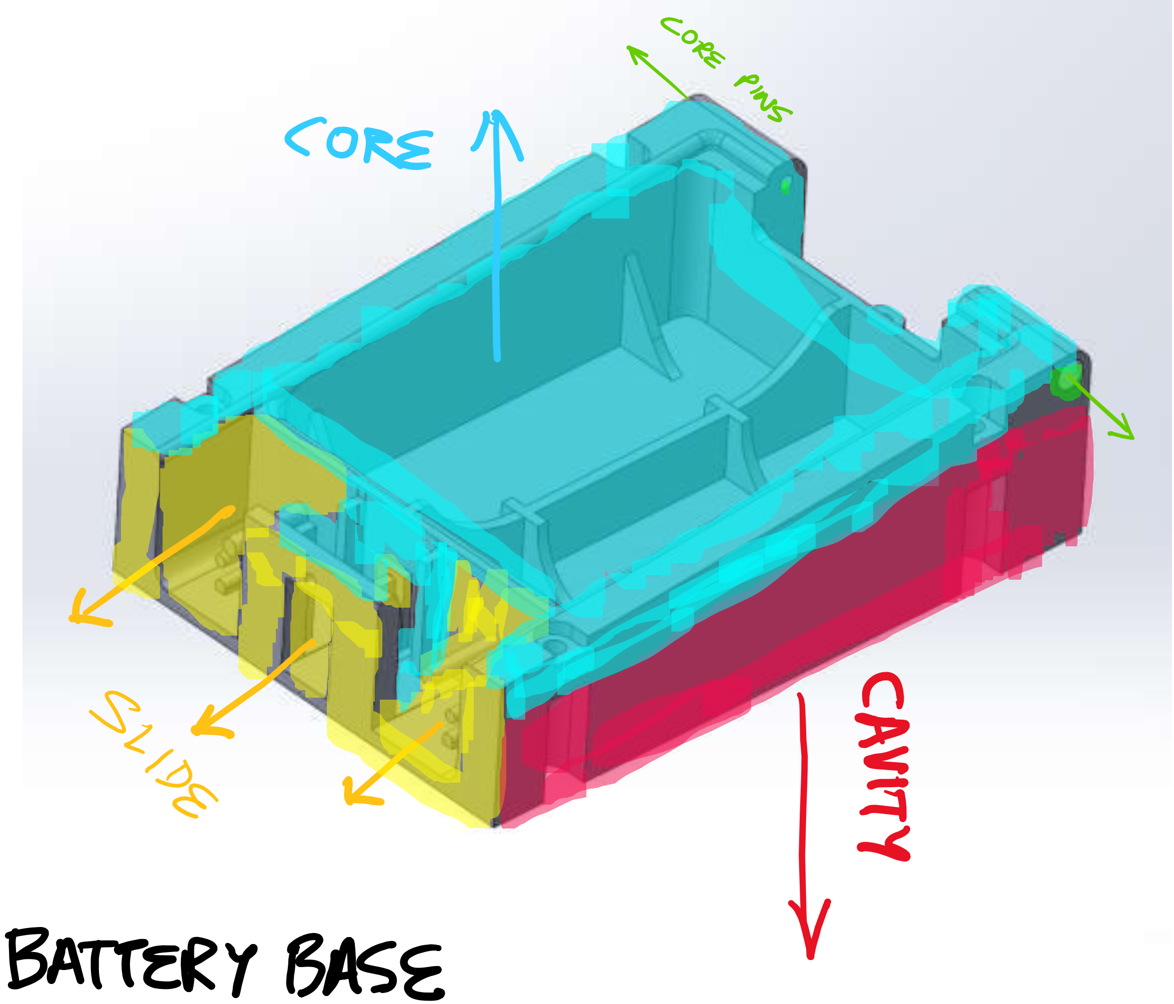
Need to heat stake or terminate the ends of these pins isn't required as they are always under transverse (to pin axis) load via "driver".

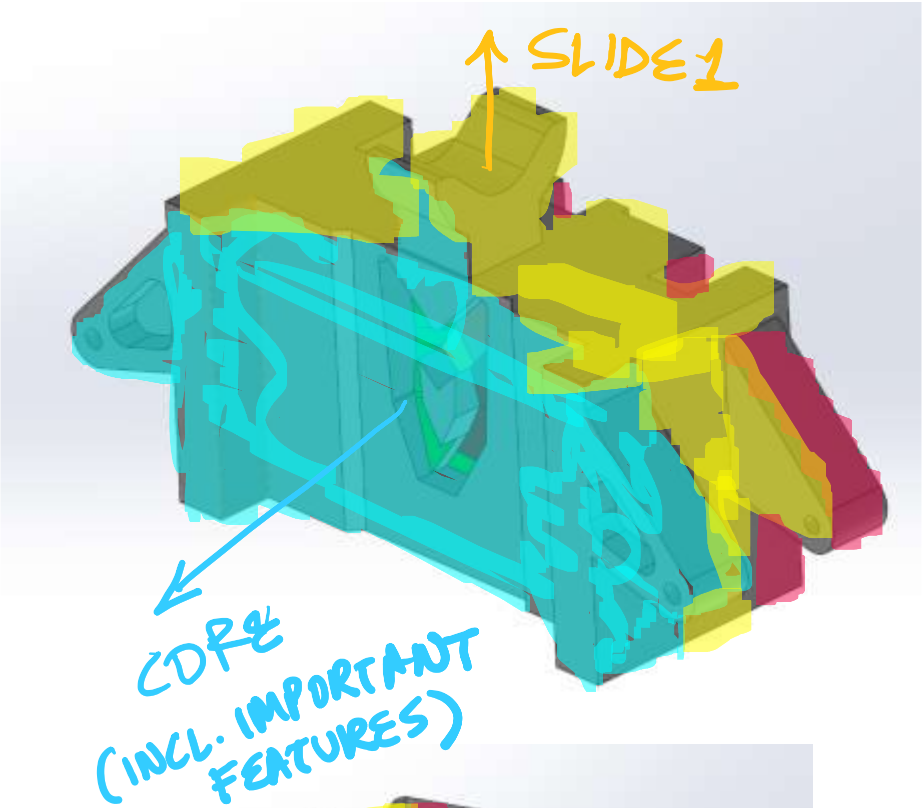
Other key aspects of design- Door design

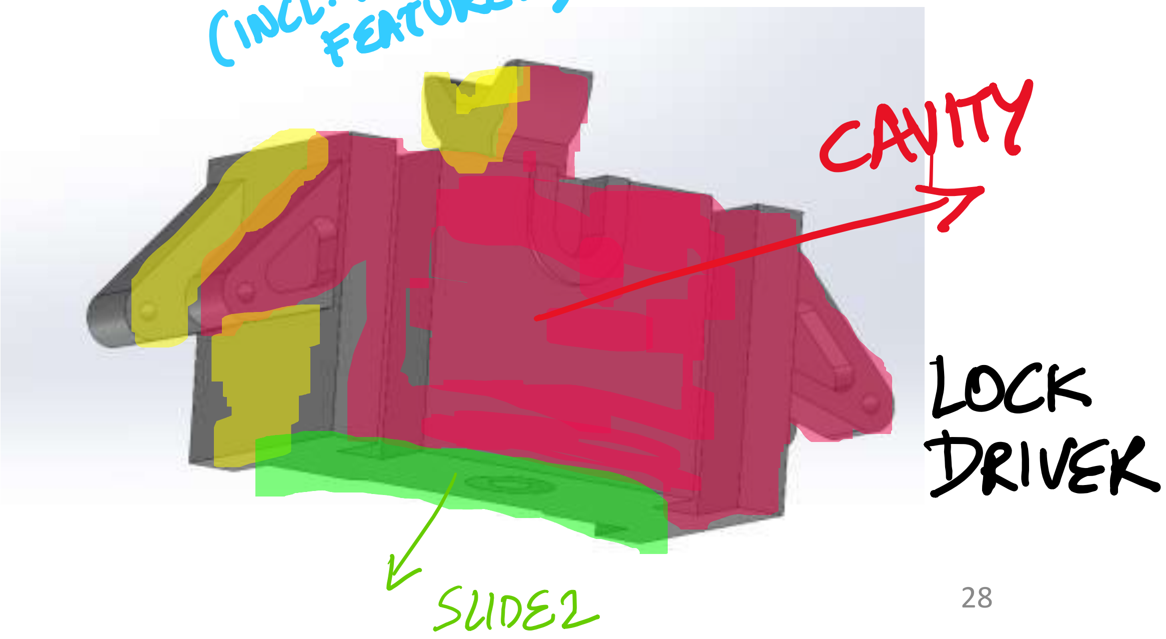


A door design with a living hinge next to the locking mechanism was considered. This provides the benefit of not rotating the complete door (~2.5”) and can help save overall thickness by preventing need for clearance while the door swings inwards. The downside with polypropylene living hinge is that over time, it will take a set at a bent configuration which may cause issues while locking. Therefore, the living hinge design was not incorporated.

DFM of complex parts







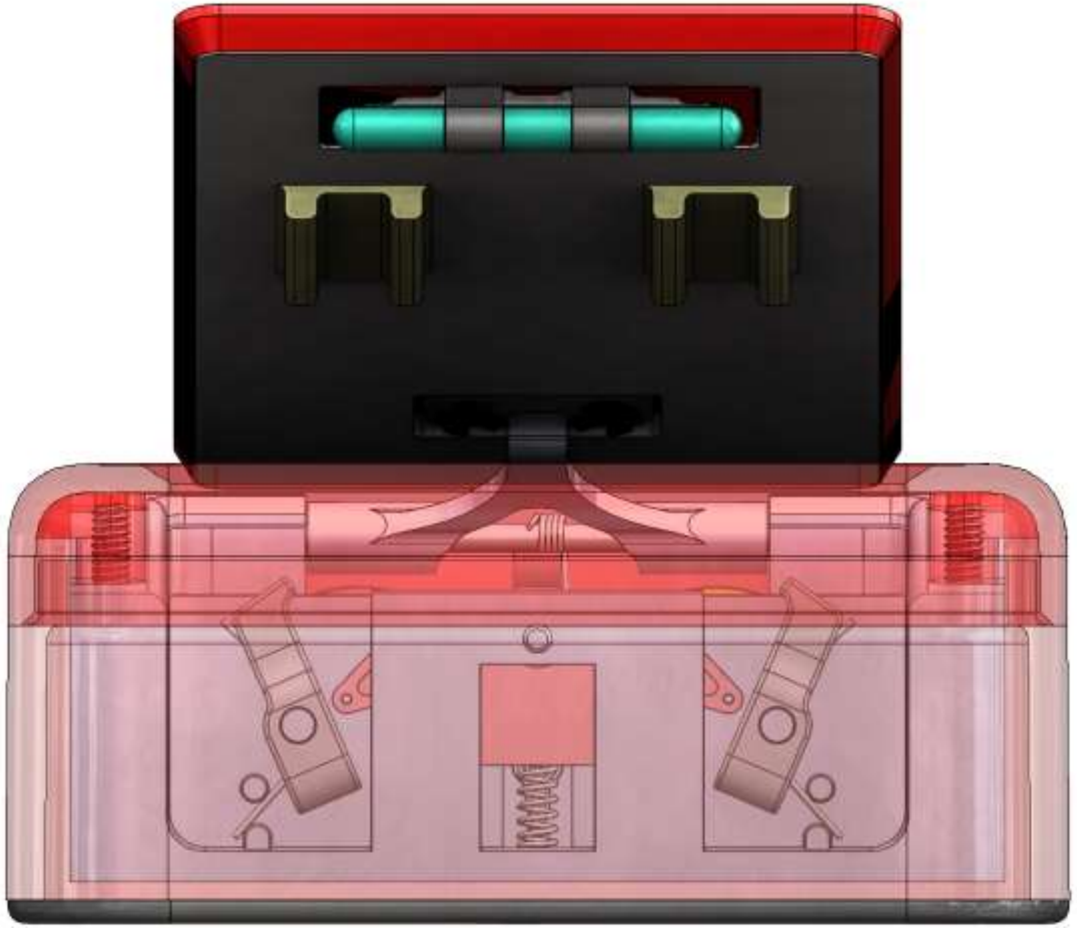
BOM

#	PART NUMBER	MATERIAL	QTY.	MFG. METHOD IM: Injection Molding	EST. COST (considering> 100k units/year)
1	iPod-SideFrame	PC/ABS blend	1	IM	$1.00
2	iPod-AA*	-	2	-	-
3	iPod-BackFrame	6063 Aluminum	1	CNC Machined	$10.00
4	iPod-Screen	-	1	-	-
5	iPod-BatteryCase	PC/ABS 20% GF (e.g. RTP 2505) or Nylon with 20% GF	1	IM	$1.50
6	iPod-DoorHinge	Stainless Steel	1	MIM	$1.50
7	iPod-BDoor	6063 Aluminum	1	CNC Machined	$7.00
8	iPod-DHook	Acetal (POM/ Delrin)	1	IM	$0.40
9	iPod-Catch	ABS/ PC	2	IM	$0.50
10	iPod-DoorBase	Polypropylene/ ABS	1	IM	$0.70
11	iPod-HSpring	301 SS FH (fully hardened)	1	Stamping	$1.00
12	iPod-LockDriver	Acetal	1	IM	$1.00
13	iPod- DriverSpring (8969T111)	316 SS	1	OTS	$0.10
14	iPod- CatchSpring (9287K550)	316 SS	2	OTS	$0.10
15	iPod-LatchRod	304V SS	1	Manual press bending	$0.20
16	iPod- LatchRodSpring (8969T101)	316 SS	1	OTS	$0.10
17	iPod- BaseScrew (92703A109)	18-8 SS	4	OTS	$0.10
18	iPod- DoorPinKnurled	316 SS/ 304 SS	1	OTS	$0.10
19	iPod-DriverLimitPin	316 SS/ 304 SS	1	OTS	$0.10
20	iPod- HingeSpring (9287K226)	316 SS	1	OTS	$0.10

* May not be part of the BOM. Also, many other parts not relevant to this mechanism aren't included.

References

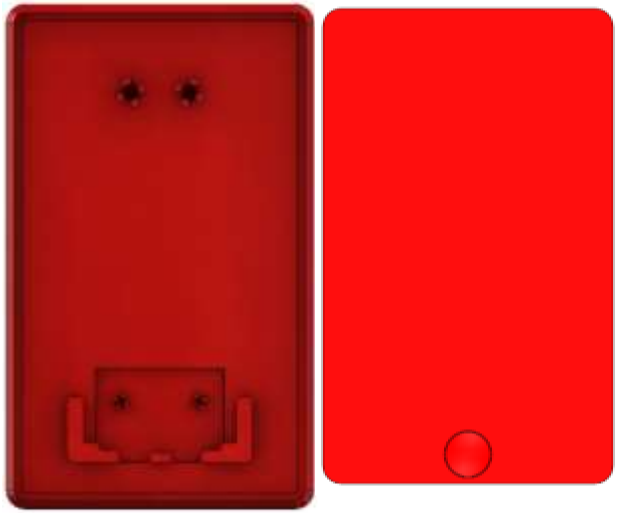
1. Push button force: Link 1 (<2lbs push button force), Link 2
2. Button displacement between 2- 3mm (0.080”-0.1”). Study link
3. Latest iPod touch has 1030mAh battery (iFixit Teardown) with upto 40hrs of music playback time. Each AA cell is 2000-3000 mAh (Polulu link)
4. Thickness of the latest iPod Touch is 0.24in. Adding 0.55” cell to it along with other parts, thickness is expected to be 0.9in. iPod Link
5. AA cell’s diameter averages 0.55in. Weight of the cell varies based on cell type (approx. 15g for Lithium, 23g for Alkaline and 31g for rechargeable). Wikipedia Link
6. RTP 2505: Material link



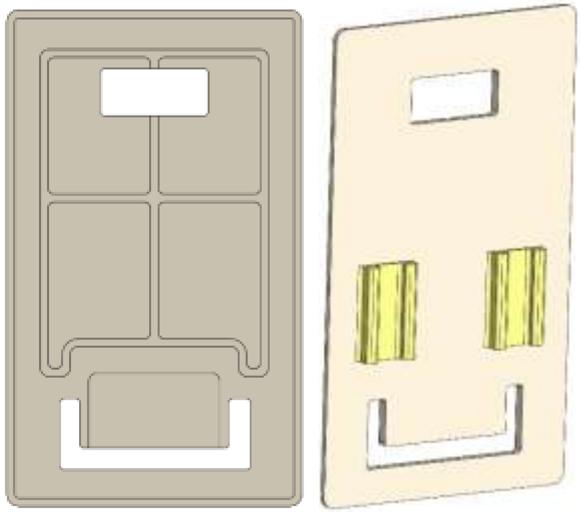
Thanks very much for listening!

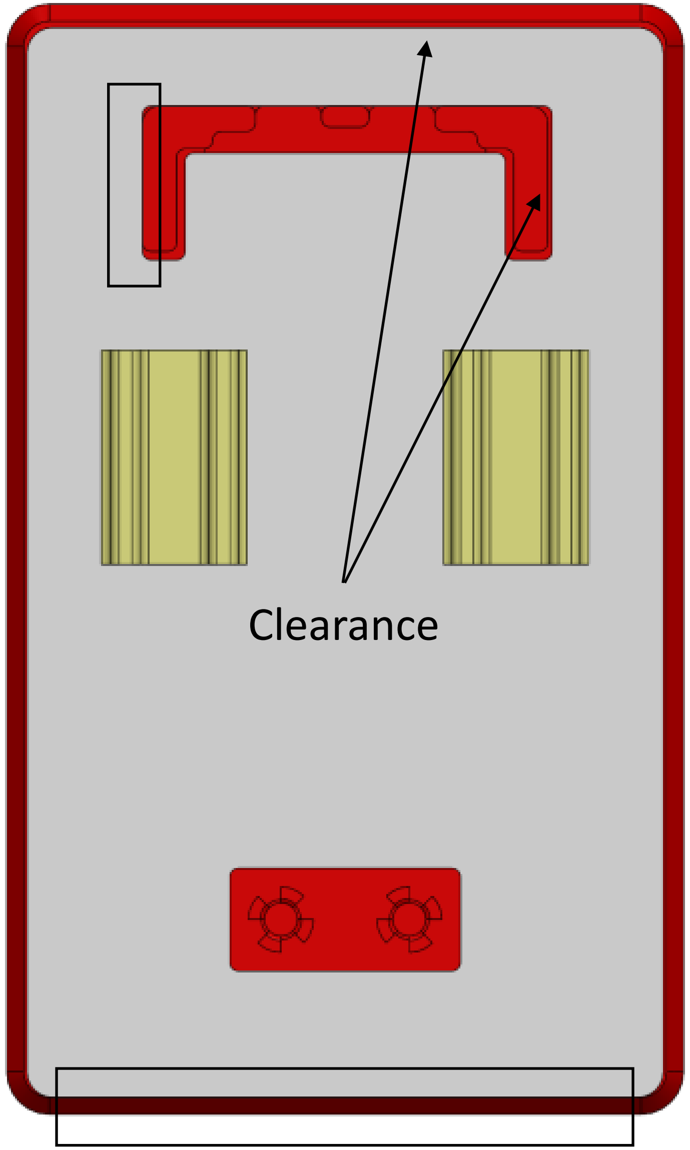
Back Frame

Door



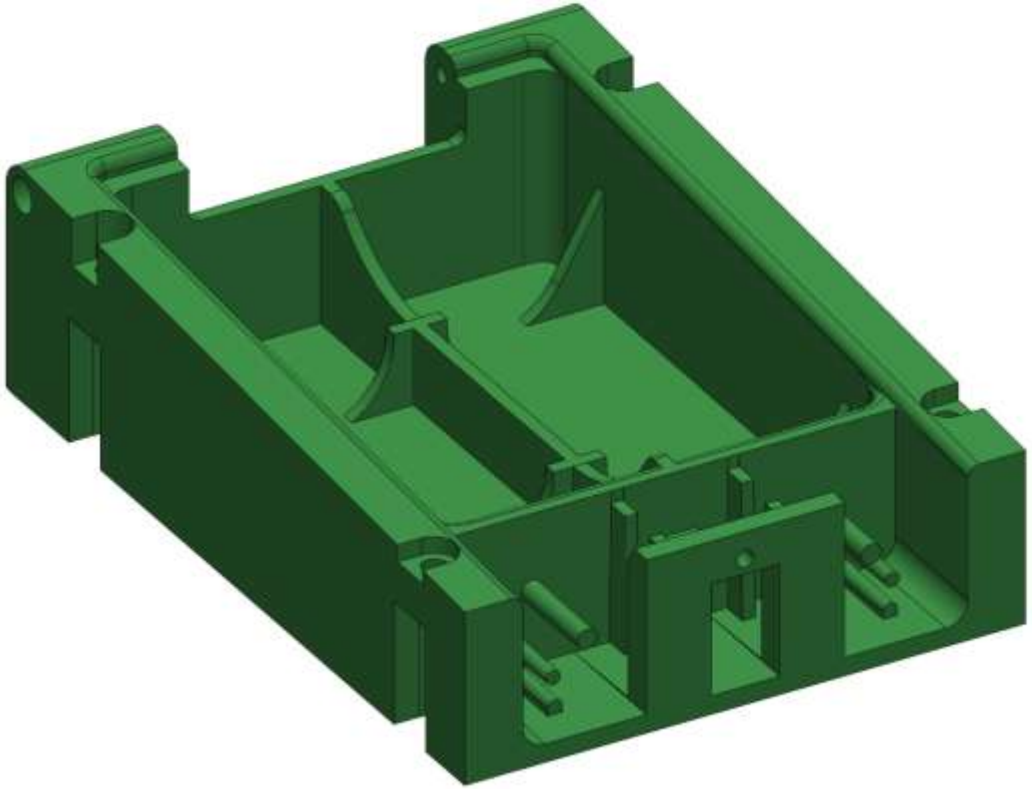
Door Base

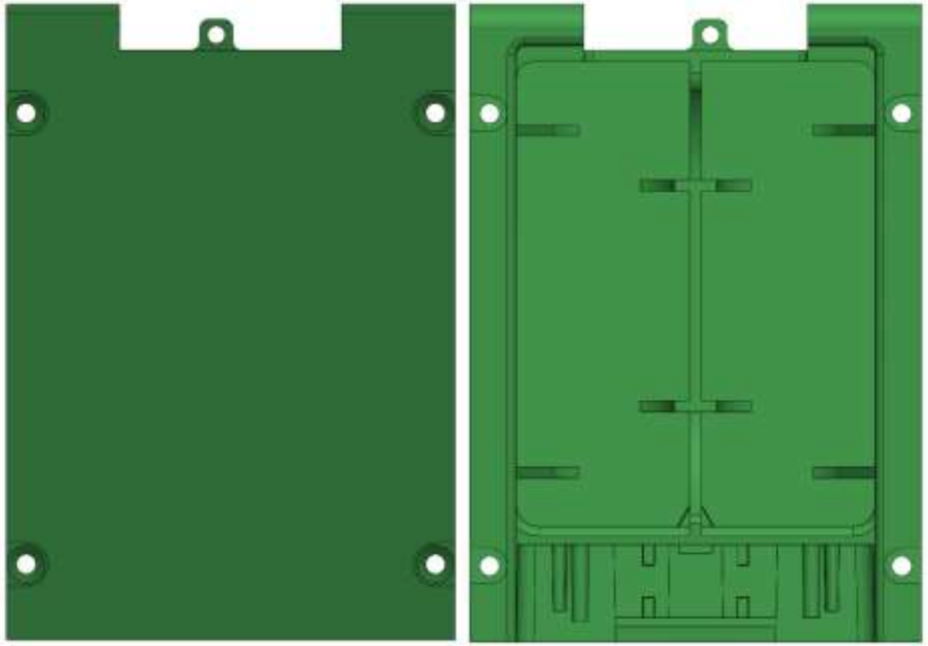


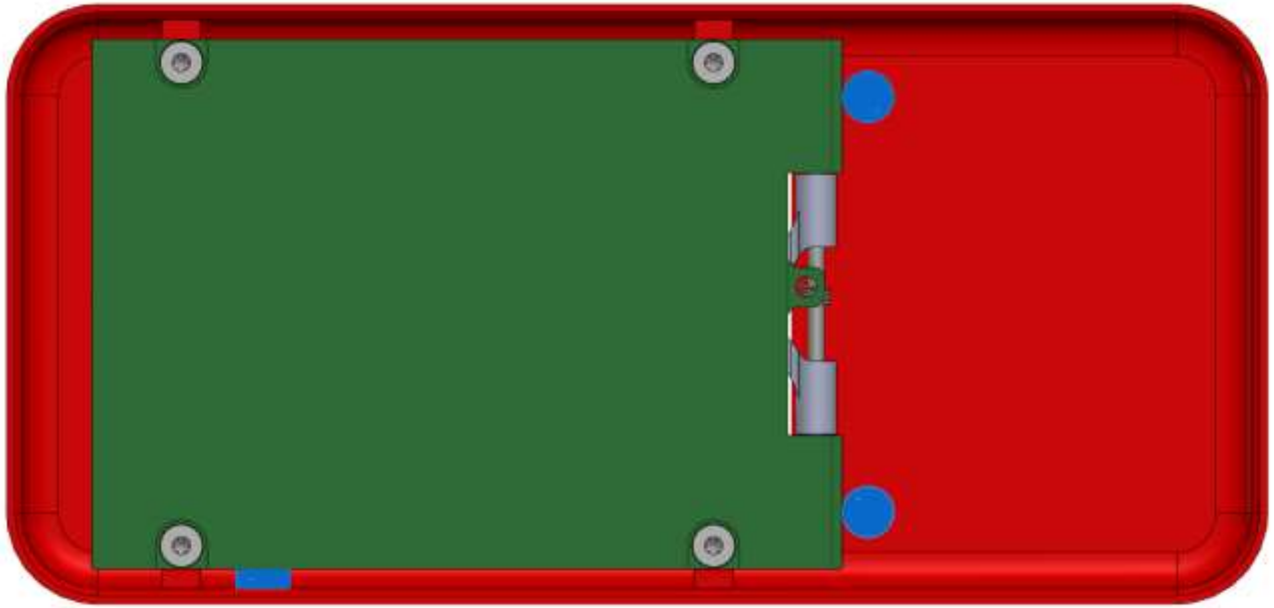


X-Y Datums for Door Base

Battery Base



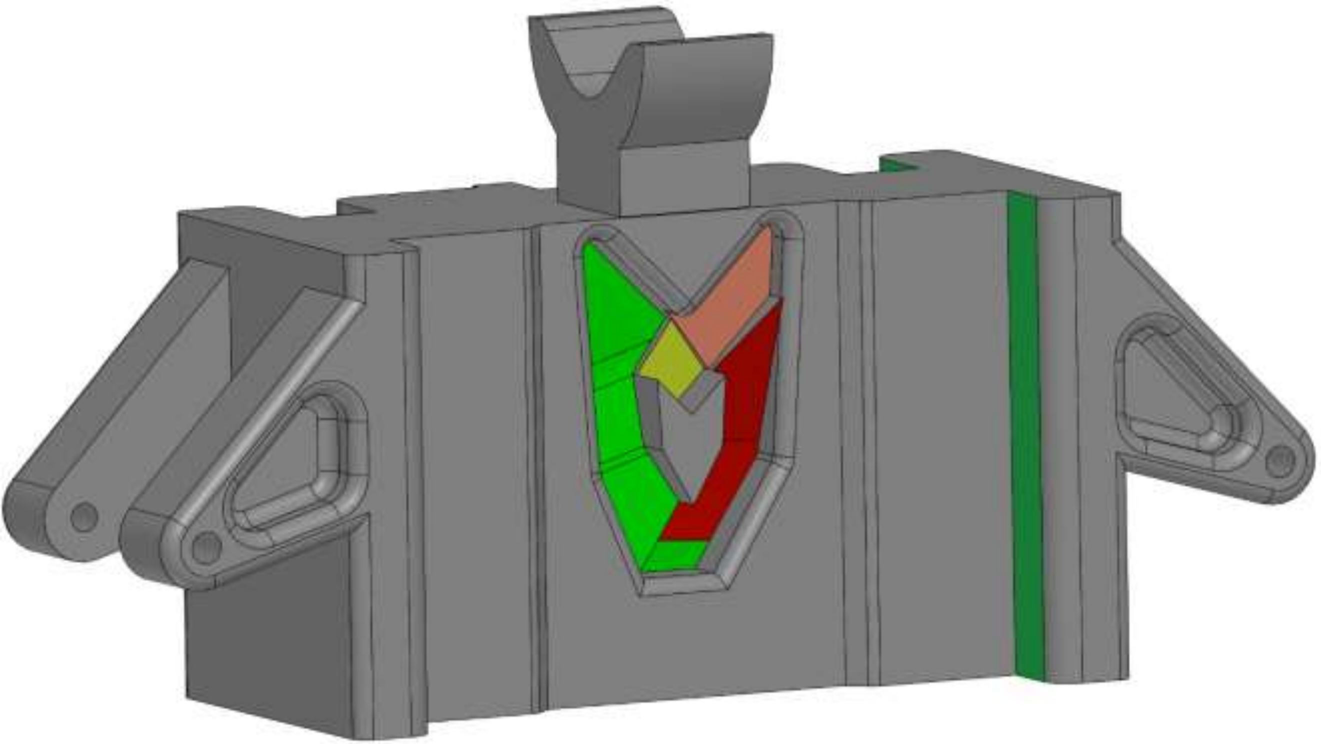


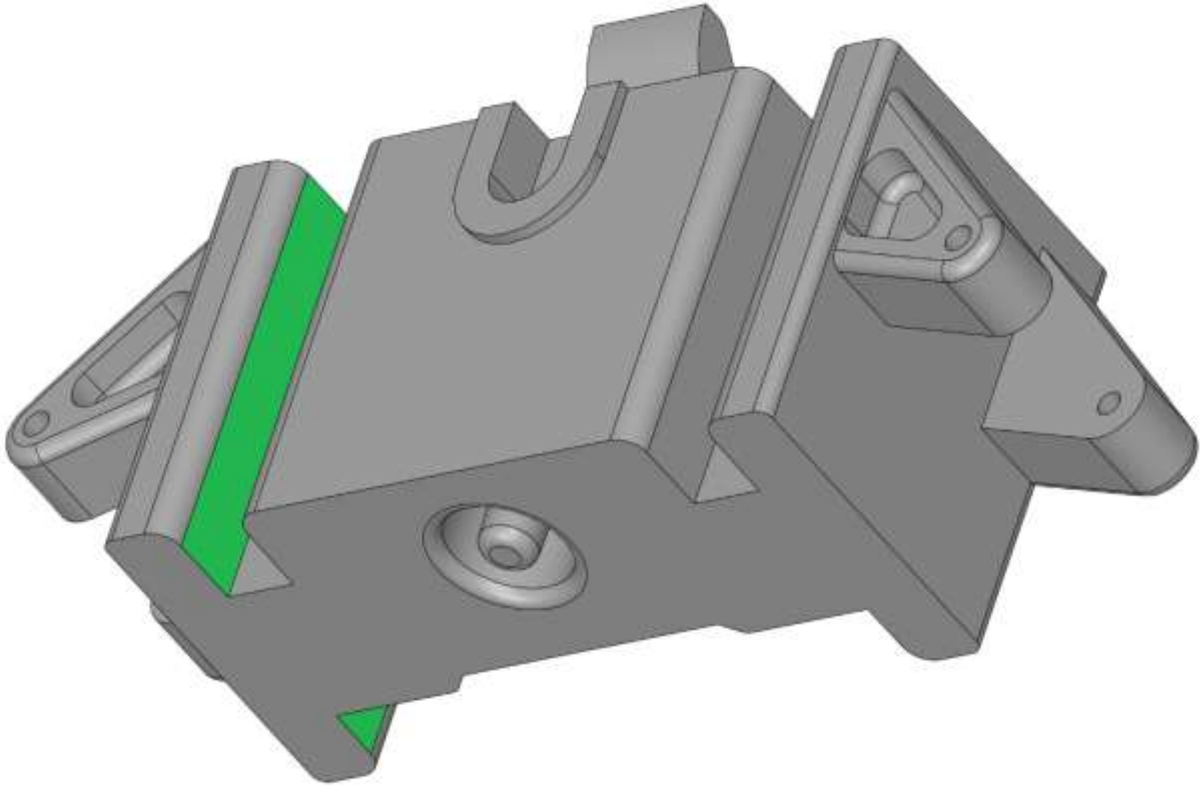


2-56 Torx (T6) Flat Head screw

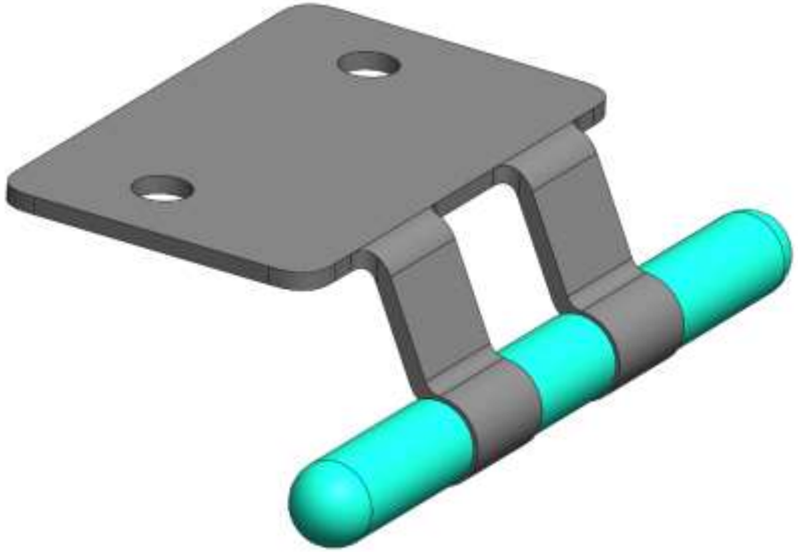
X-Y Alignment with respect to Back Frame

Lock Driver

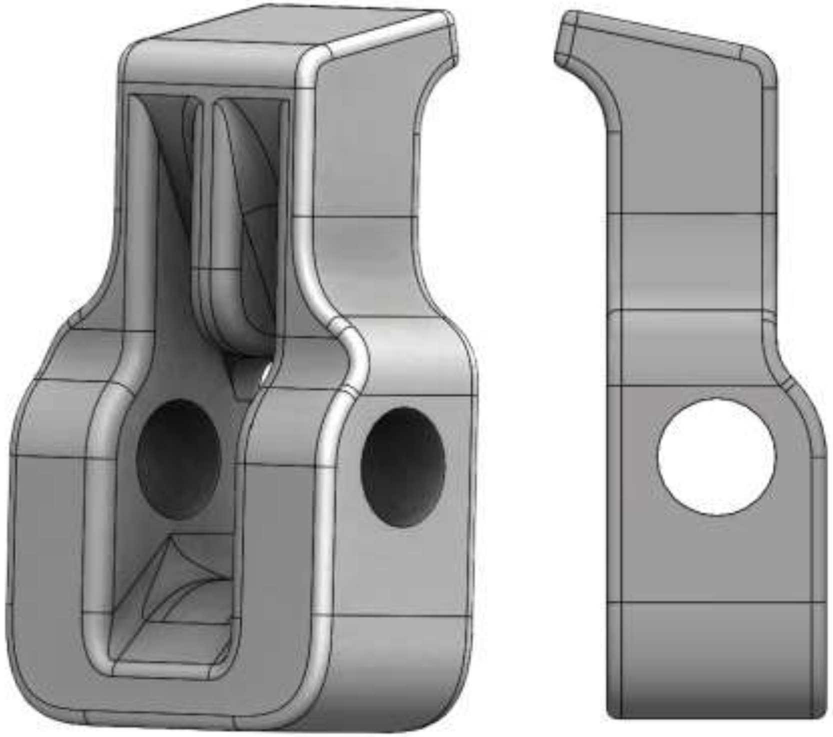




Hook Spring



Catch

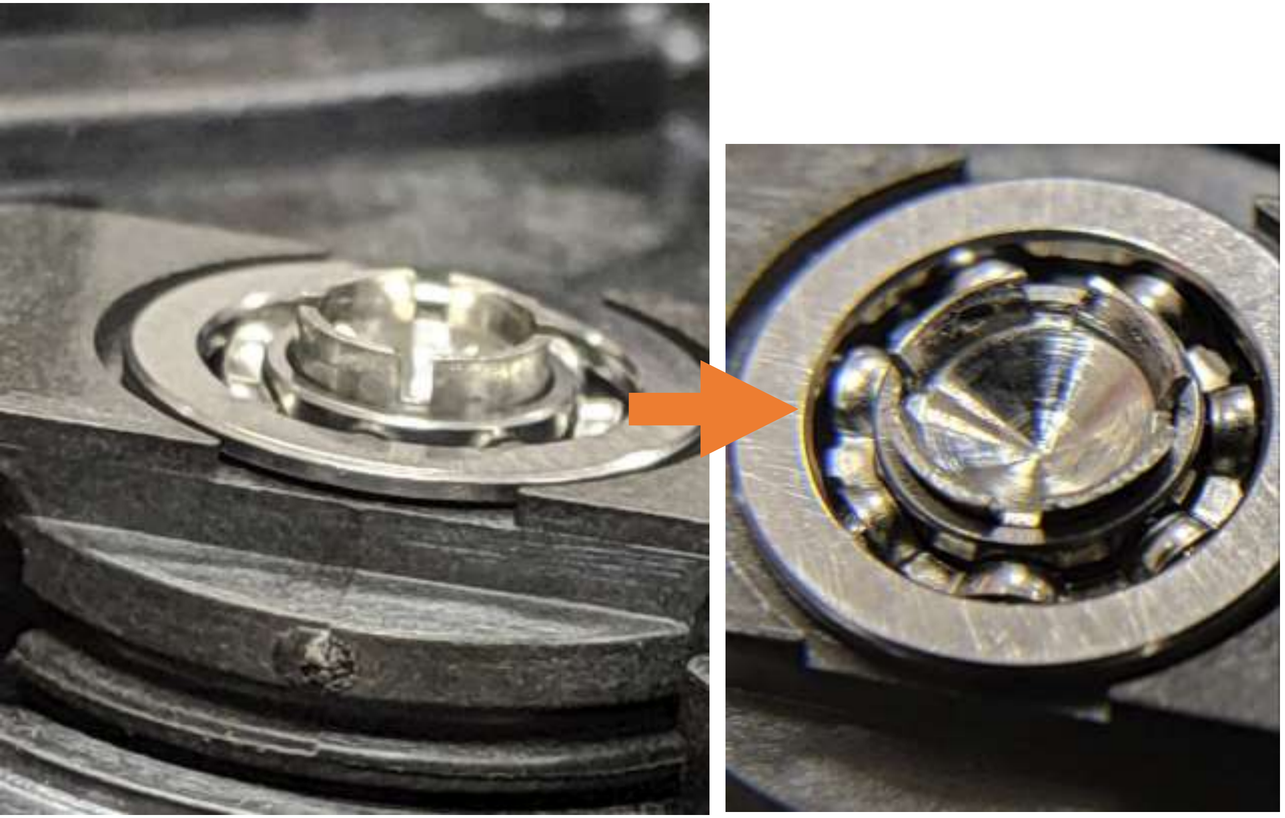


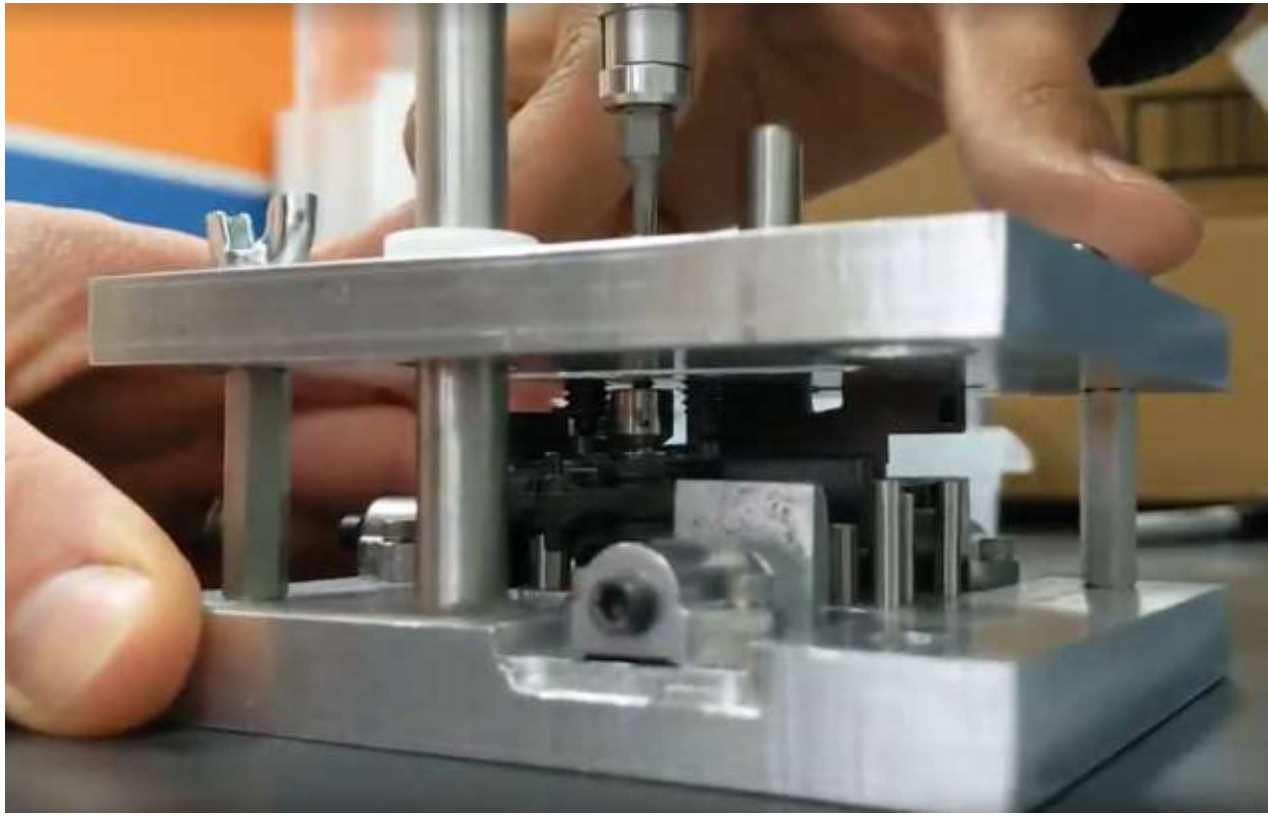
Door Hinge

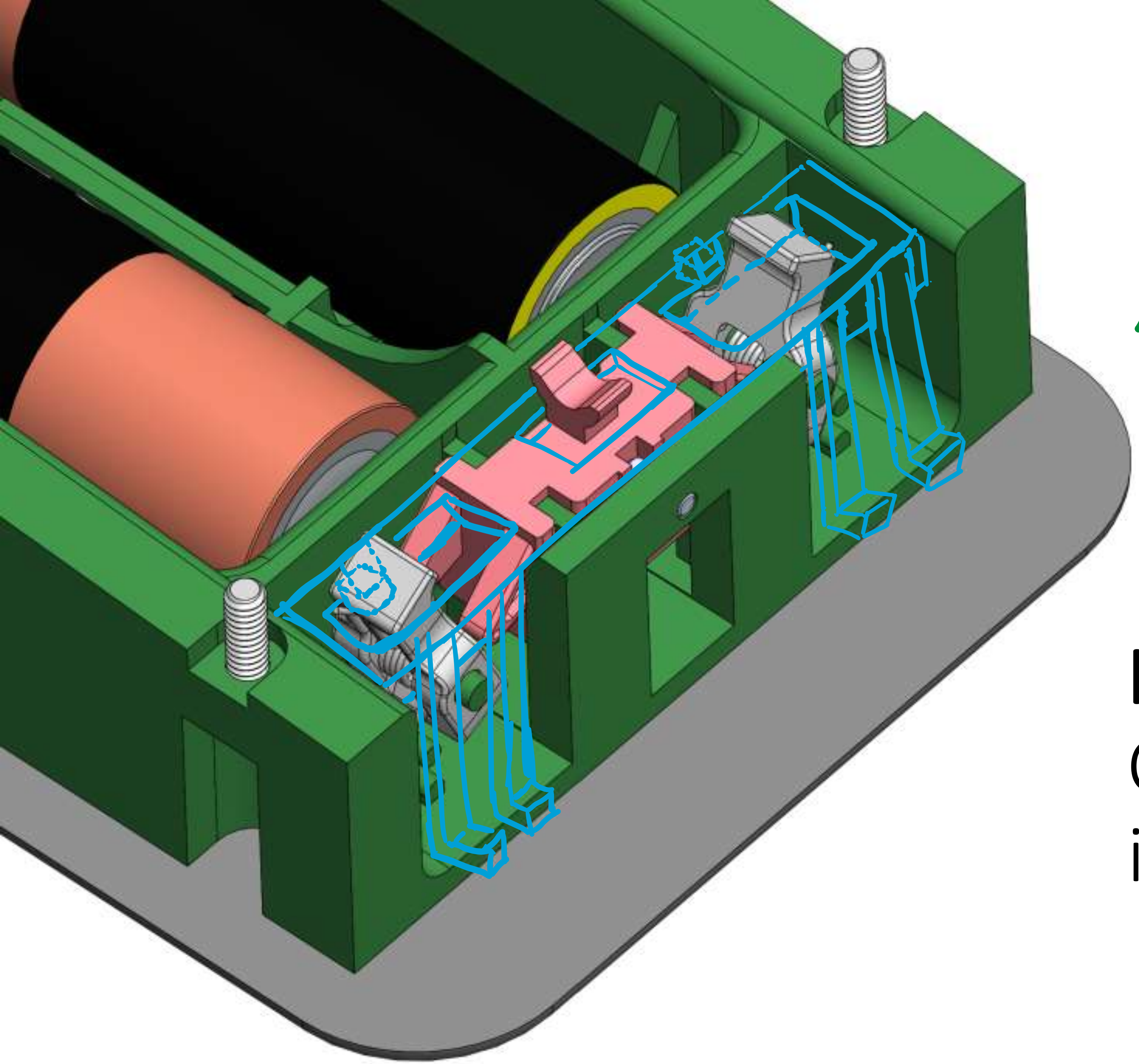
Questions

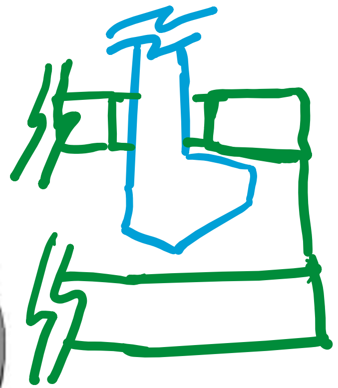
1. What will you change in your design to improve it further?
   i. Improve the design to have a better enclosure for internal mechanism so that the details beneath the enclosure aren't visible at all.
   ii. Consider the ways of reducing the overall thickness of the iPod.
2. Why choose FH 301SS for the spring? **High Tensile Strength, greater FoS.**
3. What grade of Aluminum chosen for the door? **6063T6 with Type III Anodization Hard Coat**
4. What could go wrong in the design?
5. What will be the force required to flare the aluminum tabs?
6. Are there concerns about the catch material strength?
7. How would you bond intermediate body to back shell?
8. Why choose such low value for drop test? How will you convert the drop test value into technical spec.

Pin Flaring Example (past experience)









Improvement 1
Casing for the internal mechanism

Force Loop

Testing for back-drivability, when the hook is pulled up, the forces are eventually transferred to battery back frame via the following loop:
Hook->Catch->Driver->Battery Base->Battery Back Frame