POLITECNICO DI TORINO

Corso di Laurea magistrale
in Ingegneria Meccanica

DESIGN OPTIMIZATION AND MANUFACTURABILITY OF AN E-SCOOTER HANDLEBAR FRAME

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APRILE 2021

Overview

1 Introduction

The thesis explains, almost in a chronological way, the prototypal development of a component for the e-scooter LYNX. This activity has been carried out together with the start-up TO.TEM, which LYNX is its first electrical scooter. The start-up goal is to launch on the market this e-scooter, that differs from the already existing ones, with three wheels and the integration of artificial intelligence.

The activity starting point has been the LYNX prototype alpha with the focus on a component called upper support. Upper support is a junction element between the main tube, the handlebar, and the smartphone holder.

The first part of the thesis has been focused on specifying all the design changes requests that have been managed and made, to satisfy the project specification.

A kinematic analysis has been carried out to realize and verify the upper hook locking configuration. Upper hook is a component connected to the rear zone of the upper support to allow the functioning of the e-scooter folding system.

The upper support has been subjected to a material definition analysis, necessary to choose the final manufacturing process and material. The upper hook has been subjected to a static load analysis to simulate the contact with rear hook, placed on the rear e-scooter fender, and to verify the reliability of the folding system.

Geometric tolerancing and dimensioning according to AMSE Y14.5-2018 has been used to create engineering drawings for the upper support and upper hook. The functional modelling has been described step by step.

The last part of the activity has been the study of the upper support functional gage to check and validate the component at the end of the manufacturing line. A model of the upper support gage fixture has been created.

2 Lynx E-scooter

2.1 Characteristics

Lynx is a last generation e-scooter, made in Italy and designed for an urban use.

Lynx has a different number of unique features:

- 3 large wheels for maximum agility and stability, even when stationary.
- Honeycomb run-flat tyres for weight reduction and anti-tyre puncture.
- Direction indicators for optimal visibility and better safety in an urban environment.
- A wide and comfortable platform that allows to drive the e-scooter with parallel feet.
- Geolocation and burglar alarm.
- Improved security while driving and reduction of road accident thanks to a camera.
- An anti-collision system based on artificial intelligence.
- Manageability and ease of transport, it can used as a trolley or as a suitcase.
- Modular removable battery and dashboard smartphone location.
- Smartphone connectivity for a complete management of the vehicles

Figure 2.1

2.2 Component to develop

Lynx is made assembly of several components; each one is fundamental and has a specific function.

After the design, the realization and the test of the first Lynx prototype (alpha), the start-up has been focused on the realization of an improved prototype version of Lynx (beta), through the resolution of the main issues identified and the optimization of critical parts.

The development of a particular component has been the main subject of the activity: the “upper support”. It is a junction element between the main tube, the handlebar, and the smartphone holder, that can be considered as a handlebar frame. In the first part of the thesis, a description through all the process and modification that element came across has been conducted, to satisfy the new product specification of Lynx beta-prototype.

Originally the upper support consisted of two different elements fixed together with screws:

- A metallic lower support tube. It was intended to be made by casting in serial production, for the alpha prototype it was manufactured by Aluminium 3D printing. It presents a hook in his design that allows the e-scooter folding and the transport (figure 2.4).
- A plastic upper cover, realized in additive manufacturing, that contains the electric cables and the printed circuit board (figure 2.5).

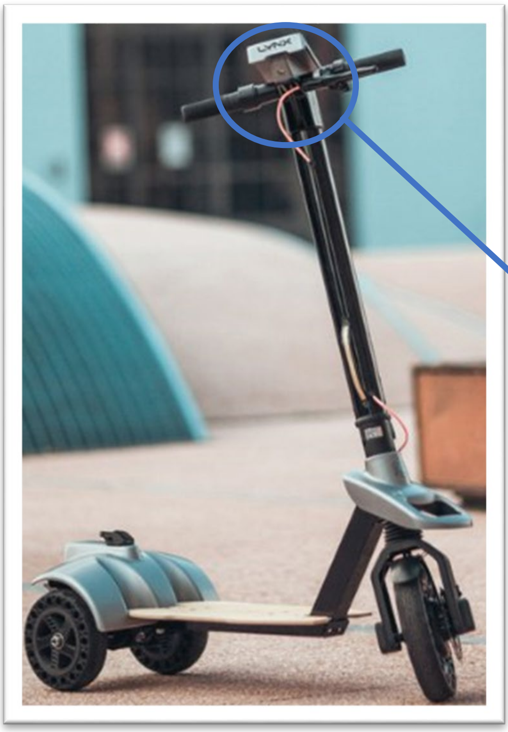
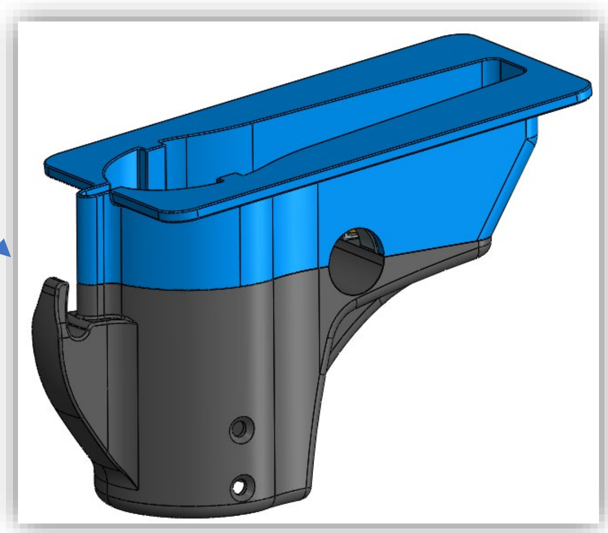


Figure 2.2



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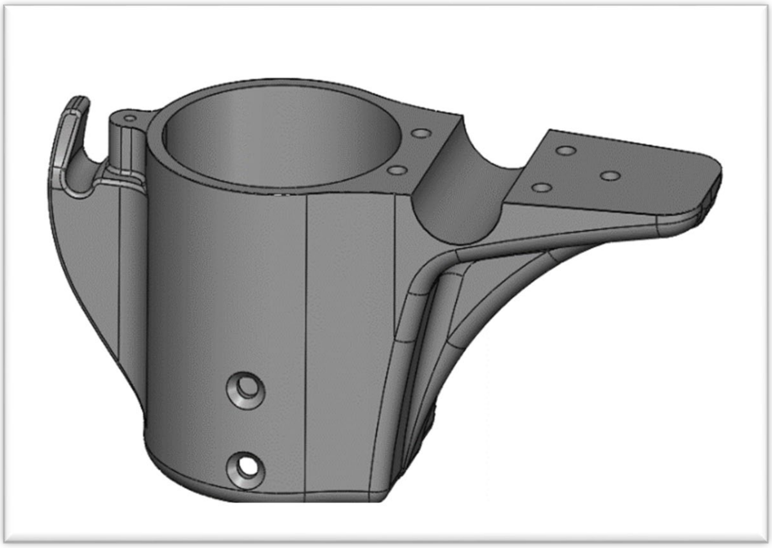

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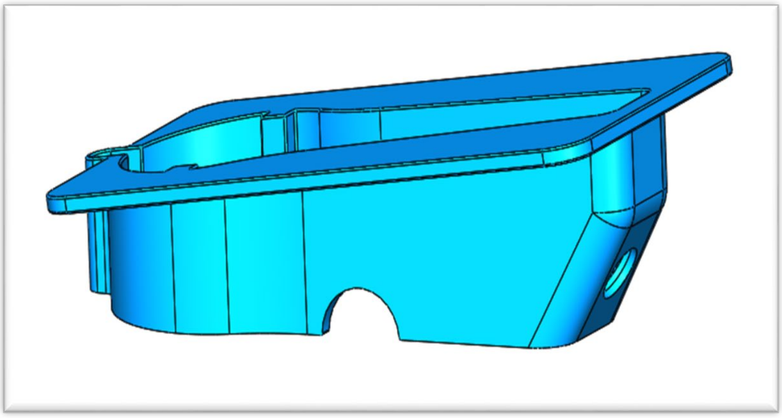


Figure 2.5

3 Development and changes in the upper support design

3.1 Starting models

The first task has been to merge the two elements, previously described, making a single component. This operation allows a reduction of the manufacturing costs and an easier assembly.

Initially a series of models have been made, combining the two parts, and making the first changes:

- Removal of all the screw seats.
- Removal of the hook.
- A change in the main pipe cavity, specifically an increase in size and a slot-shaped section has been introduced, to guarantee the assembly of the new pipe.

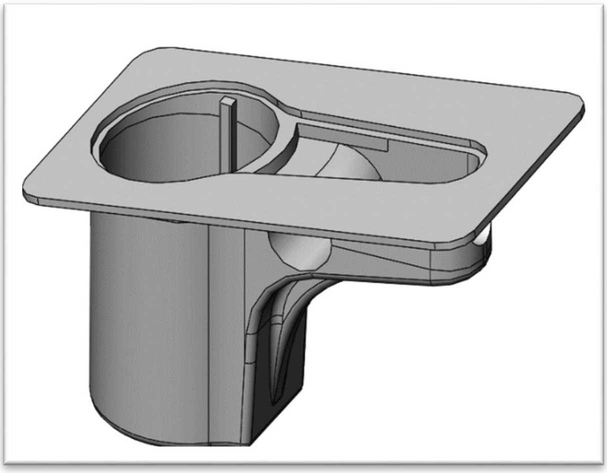


Figure 3.2

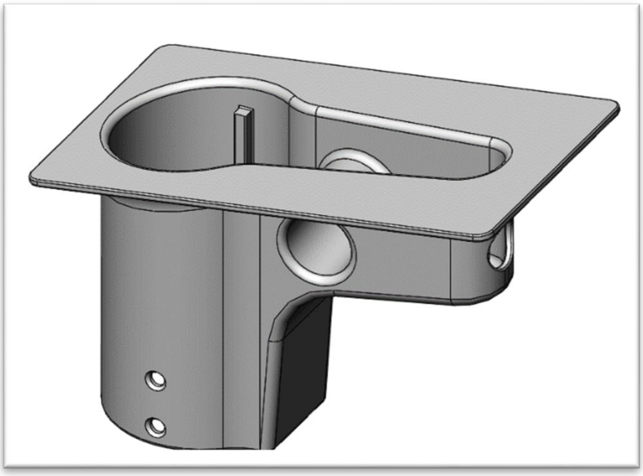


Figure 3.3

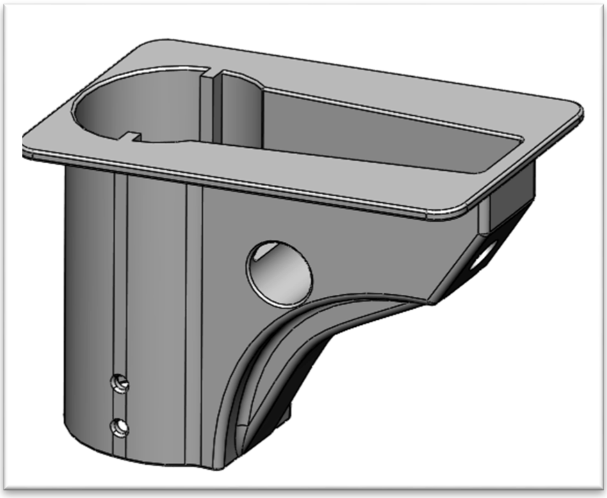


Figure 3.1

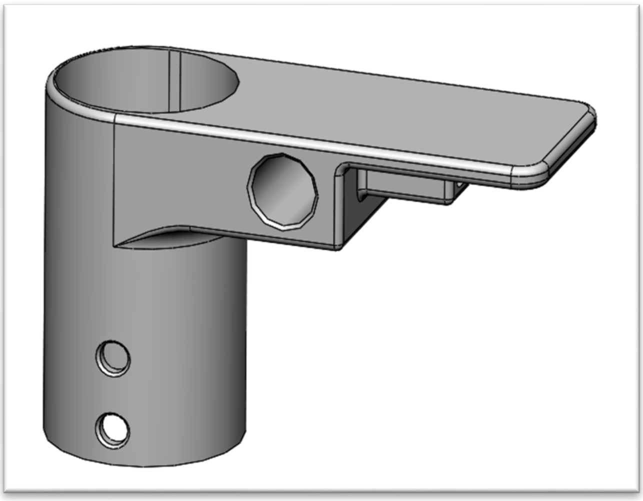


Figure 3.4

In this phase some proposals have been rejected because of the intention to maintain the same aesthetics of the previous design and not to completely overturn it.

3.2 Design changes n.1

3.2.1 Cable passage duct

A significant change has been the realization of a duct inside the upper support. It has been used as a hidden passage for the electric cables, that provides a proper and functional connection between the dashboard and the control unit installed inside the main tube. It also allows reduction in weight and in costs. Originally it has been realized a rectangular section passage (figure 3.5), then it has been changed with a slot section and proper fillets (figure 3.6). The duct has been realized carving out space in the upper support rib.

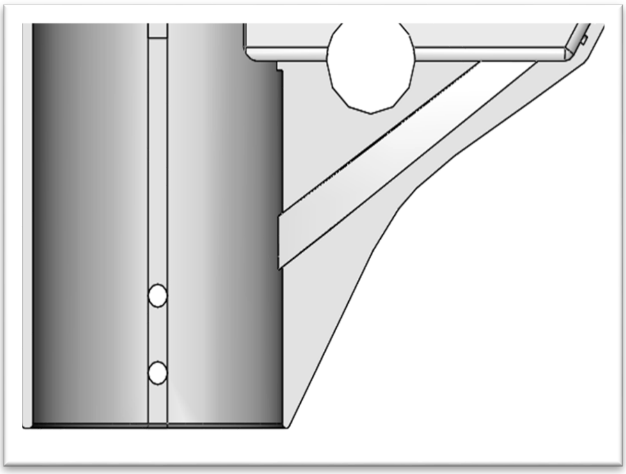


Figure 3.5

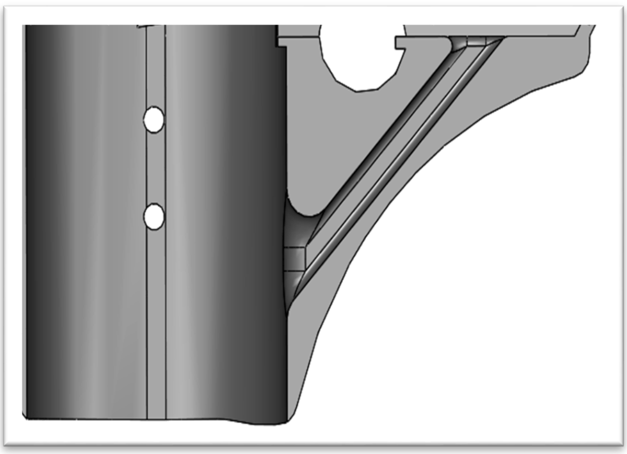


Figure 3.6

3.2.2 PCB placement

The Lynx prototype alpha dashboard was provided with two printed circuit board (PCB) separated and located in the upper zone:

- The first circuit board: it interfaces with the control unit, located in the lower part inside the main tube. The PCB also present connections with the led headlight, the brake, and the accelerator.
- The second and smaller circuit board: it interfaces with five small led lights, that work as battery charge indicators. An issue was the unpleasant visual effect of this circuit while opening the smartphone holder to insert the battery.

It has been decided to unite the two PCB. The result has been a new circuit board with a T-shape (figure 3.8). The upper support has been modified to contain the new PCB. A T-shape placement has been realized on the inclined planar surface. Four small screws have been used to secure the PCB to the upper support. It has been also necessary to add new material for making two perforated turrets (figure 3.7), that allow a proper connection with the screws.

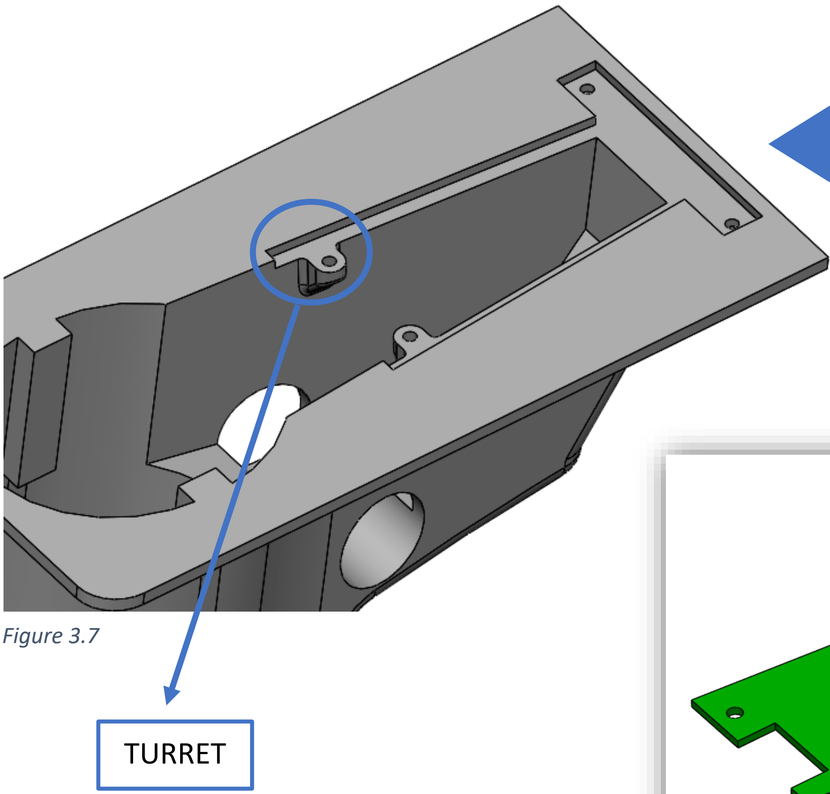


Figure 3.7

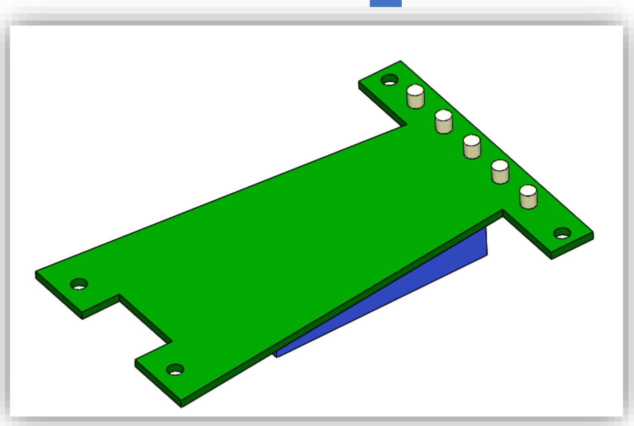


Figure 3.8

3.2.3 Upper hook prototype

Lynx prototype alpha had a particular folding system: the hook was part of the previous upper support and, by folding the e-scooter, it attached on a device placed on the centre of the rear fender.

The hook and the device, that connected to each other, were entirely designed from the ground and that meant high production costs.

To solve the issue, it has been decided to introduce a new system, taking inspiration also from the e-scooters made by the big Companies and using “off the shell” parts to reduce customizations costs.

Two different hooks, that engage each other, have been used:

- The rear hook: it is a standard piece available online, installed on the centre of the rear fender (figure 3.9).

Figure 3.9

- The upper hook: it has been built from the ground and shaped to fasten properly onto the rear hook. A protrusion has been conceived and realized on the back of the upper support to connect this hook.

The very first idea was to find not only the rear hook but also a standard upper hook online, to reduce the costs. Unfortunately, the hook available on the market did not satisfy the project demand.

A series of different upper hook prototype have been designed, starting from those existing on the market and adapting them to the project needs.

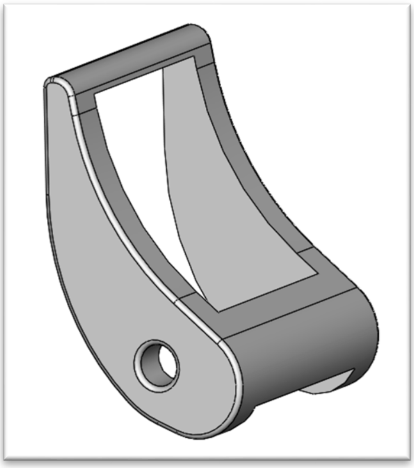


Figure 3.10

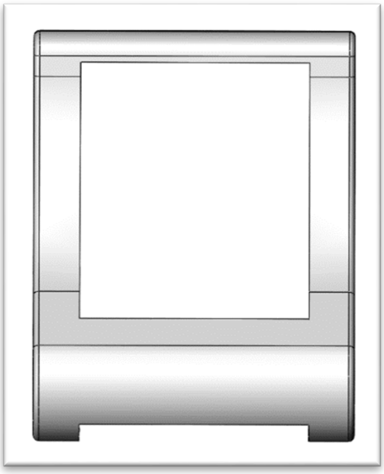
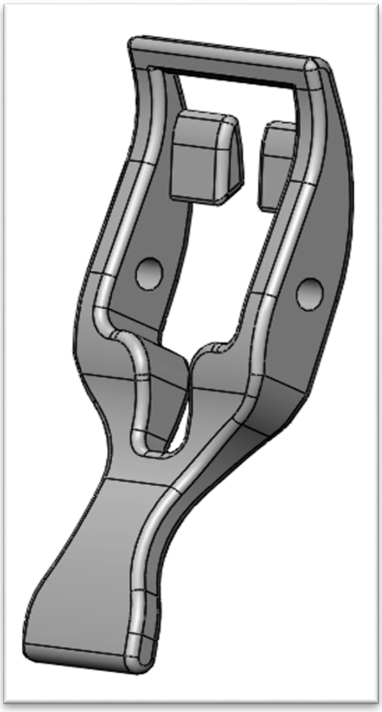


Figure 3.11

The resulting models have been developed by adding a flap in the lower part, allowing the e-scooter user to unfold the upper hook easily. Two small lateral wings have also been added, essentials for the spring installation (figure 3.13).



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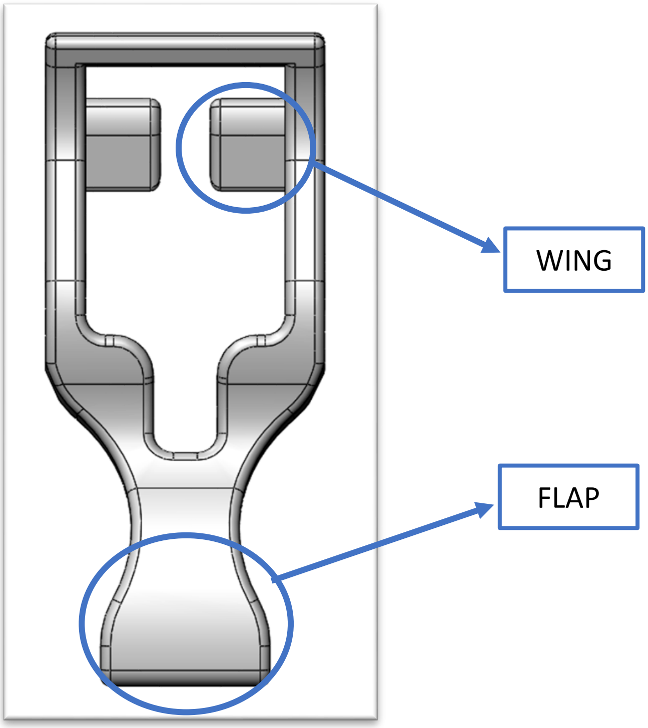


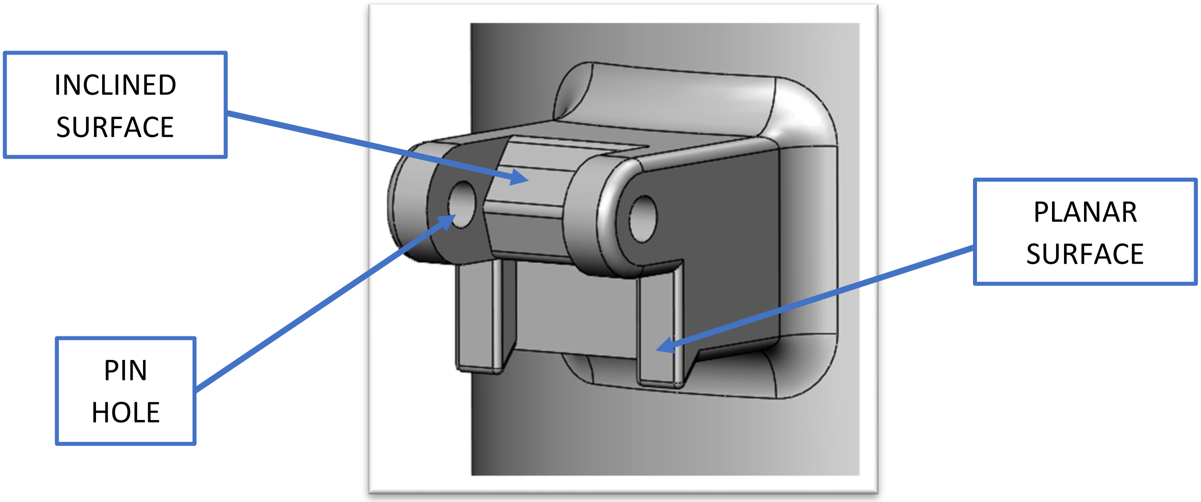
Figure 3.13

The upper hook design has been the result of a kinematic study, that has been displayed in the chapter 4 of the thesis.

3.2.4 Upper hook protrusion

A protrusion has been realized on the back of the upper support to connect the upper hook to the upper support. The specific design allows the proper functioning of the upper hook. It consists of:

- Two holes: they permit the pin and the spring installation and consequently the connection with the hook (figure3.14).
- Two plane surfaces: they allow to keep the contact with the upper hook, in nominal position (figure 3.14).
- Two inclined surfaces: they allow the rotation of the hook without any material interference (figure 3.14).



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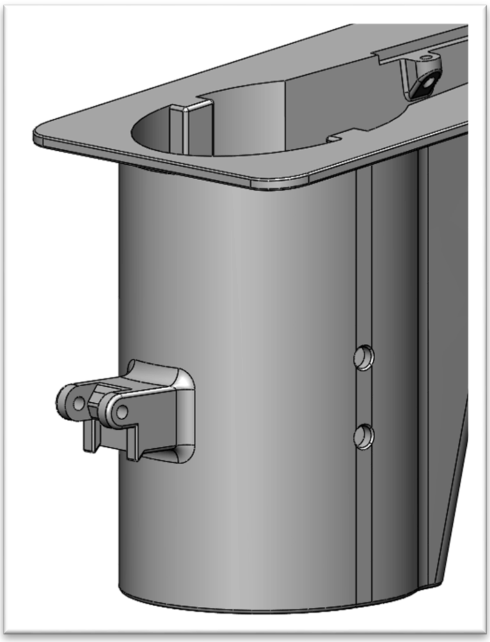


Figure 3.15

3.2.5 Handlebar fastening system

Lynx prototype alpha handlebar was inserted through a cavity, leaning on the material above the rib.

A system that allows to abut the handlebar against its accommodation was required, preventing any rotation or translation. To secure the handlebar, preventing any rotation or translation, two C-shape holders and four screws were adopted (figure 3.16).

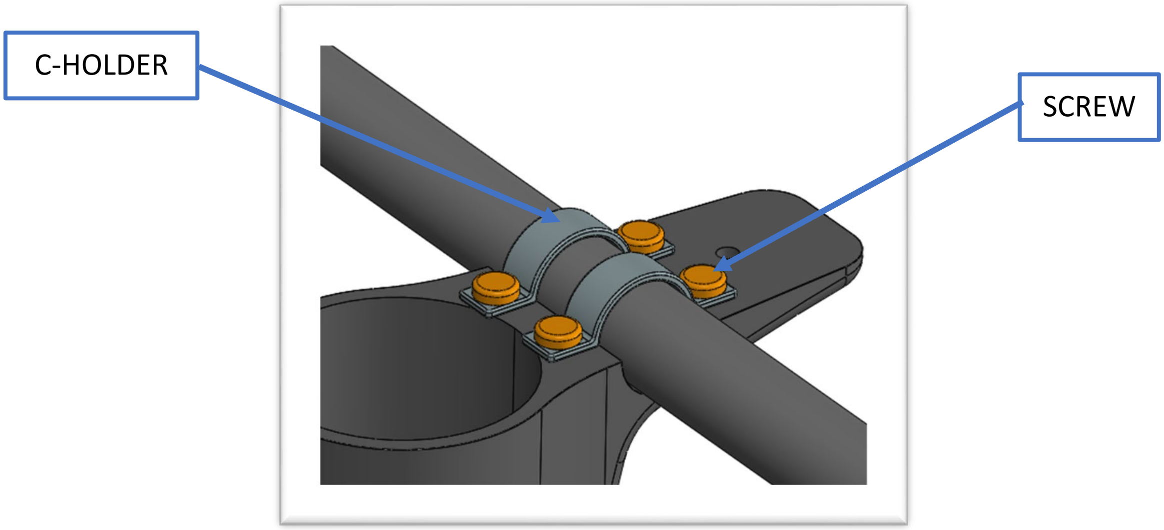


Figure 3.16

The very first idea, to improve the handlebar fastening system, has been to find standard solutions online and try to adapt them to the geometry of the upper support. However, it has not been found any valid options. It has been considered a completely different solution: the integration of a ledge

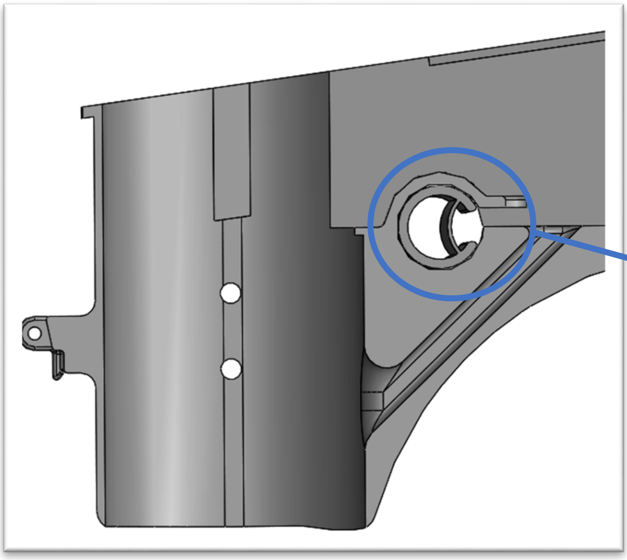


Figure 3.18

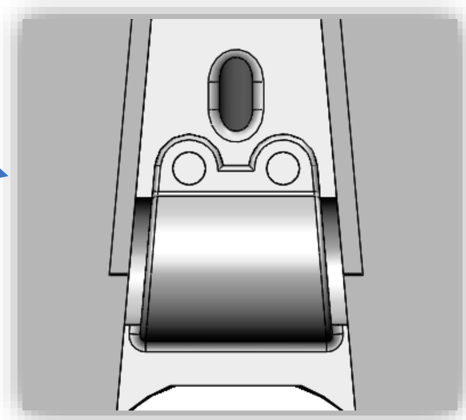


Figure 3.17

to the upper support. It starts from the flat surface near the pipe cavity, wraps around the handlebars and ends with two holes prepared for the screws (figure3.18). The two parallel surfaces, that of the ledge and the one of the upper support, present a space of 5 millimeters between them, to allow the insertion of a polymeric material. By tightening the screws, the ledge compresses the handlebar preventing any movement.

Even this solution has been rejected: it would have been considered if the upper support had been made with the casting technique. This hypothesis has been discarded due to the high production costs.

It has been decided to make the component in plastic, via injection molding. A solution with the C-shape holders has been reconsidered, even if some changes have been applied. It has been added some materials in the space between the handlebar seat and the pipe cavity, to tuck the threaded inserts. They are commonly implemented to plastic components to consent the fixing of the screws. The holders shape has been changed too (figure 3.20).

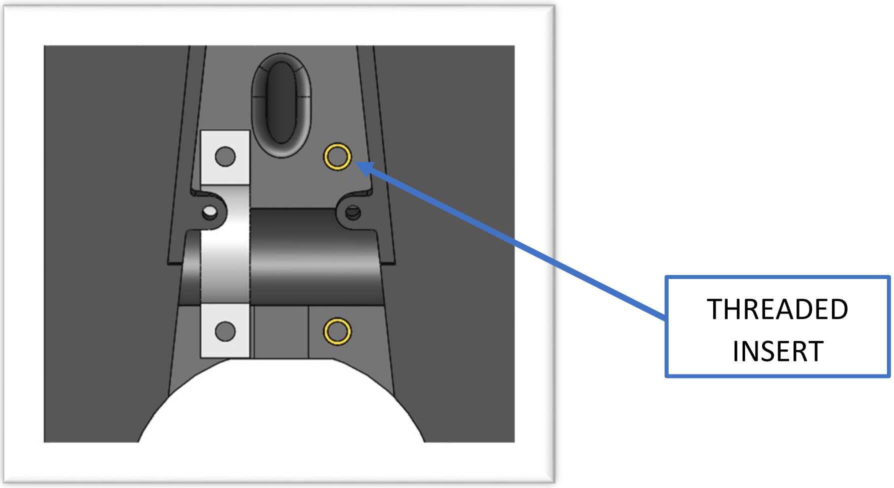


Figure 3.19

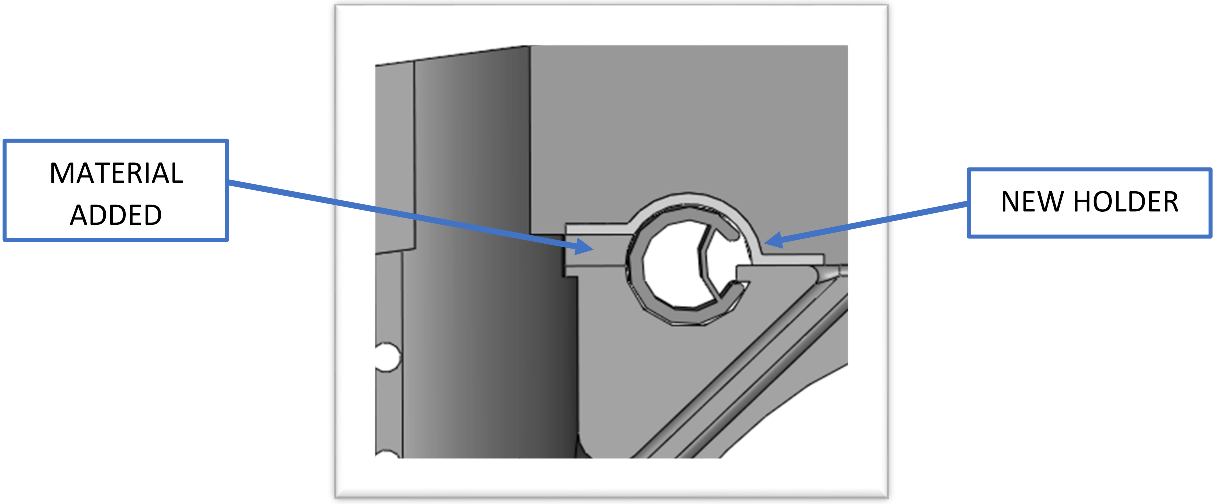


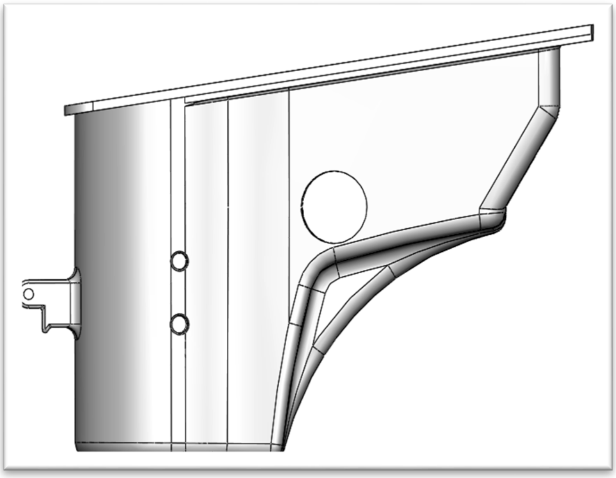
Figure 3.20

3.3 Design changes n.2

3.3.1 Headlight led placement

Lynx prototype alpha was equipped with a circular shape headlight led, slight and connected to the main PCB with a thin cable. This system pointed out issued related to reliability and safety. The cost was also a critical point because the headlight was not a standard component.

It has been decided to use a standard LED headlight, the same model destined for a commercial e-scooters. It has been difficult to adjust the actual design and to place the new headlight. A housing has been created in the front area of the upper support, leading to a noticeable change in the external design: larger fillets in the lower area and more pronounced rib and "nose" of the support (figure 3.21).



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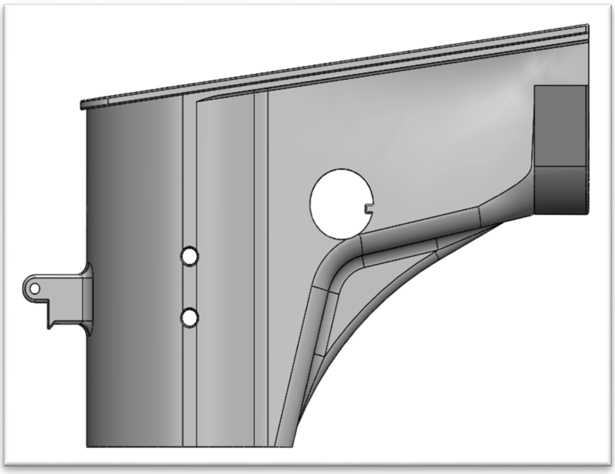

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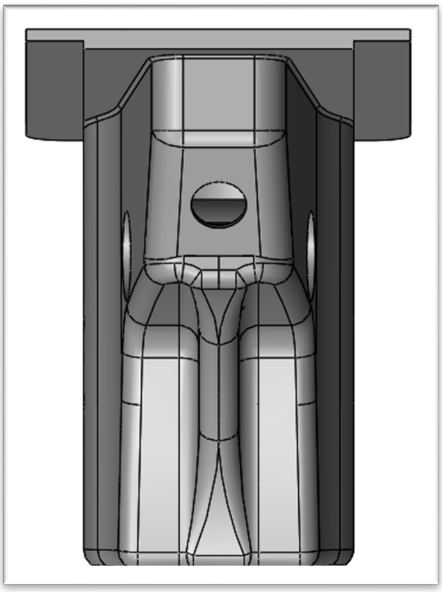

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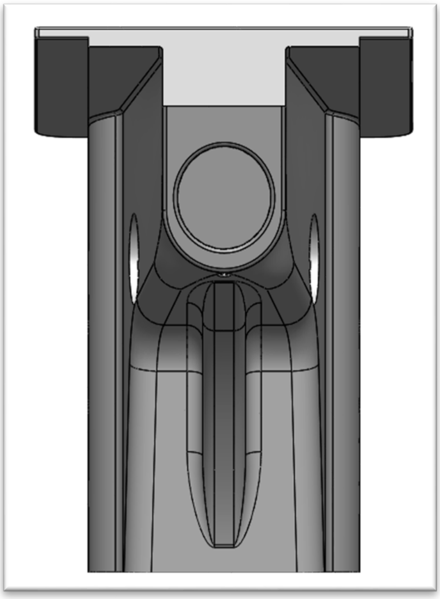


Figure 3.24

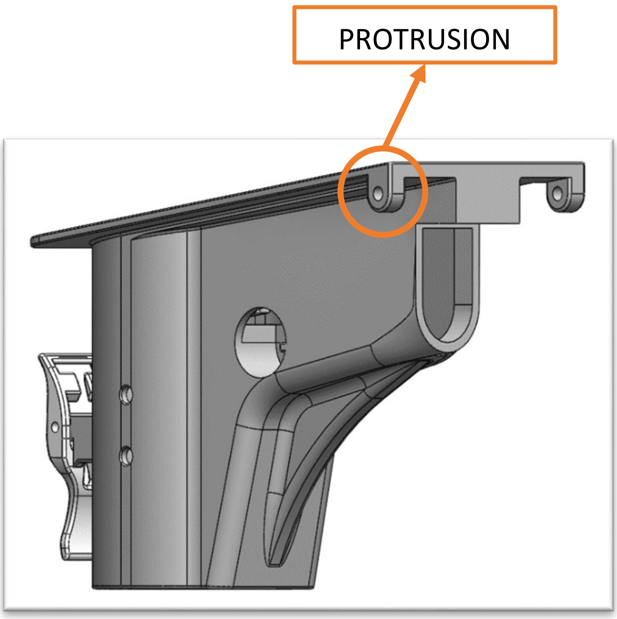
3.3.2 Connection between pipe and cover (smartphone holder)

Above the upper support has been placed a cover that essentially ensures two functions:

- It holds and keeps firm the smartphone, that has a dashboard functioning, thanks to a magnet.
- It hides and protects the printed circuit board inside the upper support and the cables.

The connection between the upper support and the cover has been set using partially threaded screws and inserts. In particular:

- Two perforated protrusion have been realized on the rear part of the upper support inclined surface (figures 3.25). Two threaded inserts are then inserted (figure 3.28). The interaction between the insert and the screw allows the cover opening and closing.
- Two holes have been made on the cover and inserts without threads have been used (figure 3.26). The not threaded screws tips have been passed through these holes, guaranteeing the connection with the pipe (figure 3.28).



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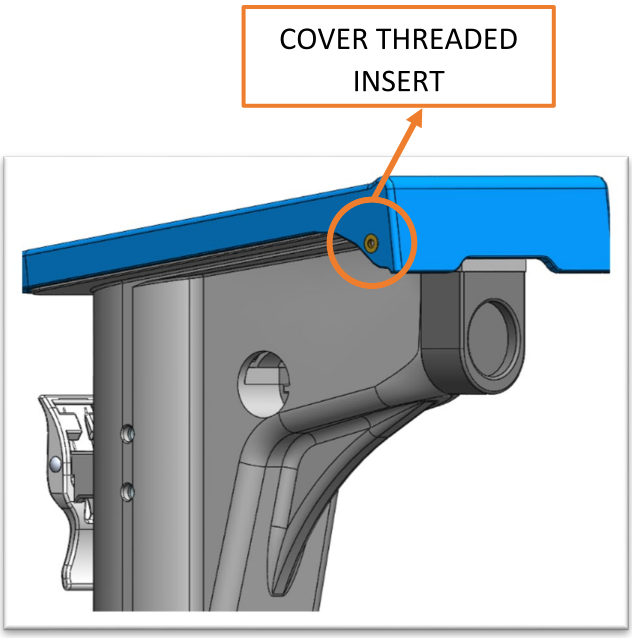

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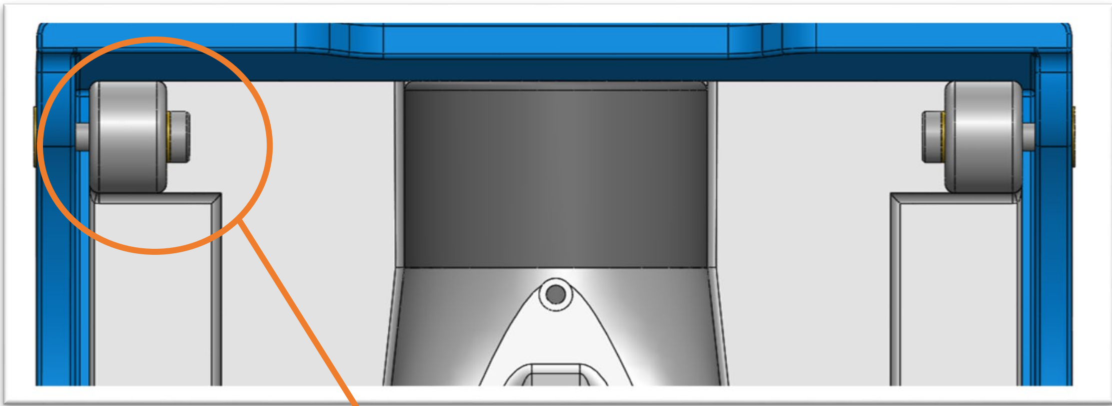

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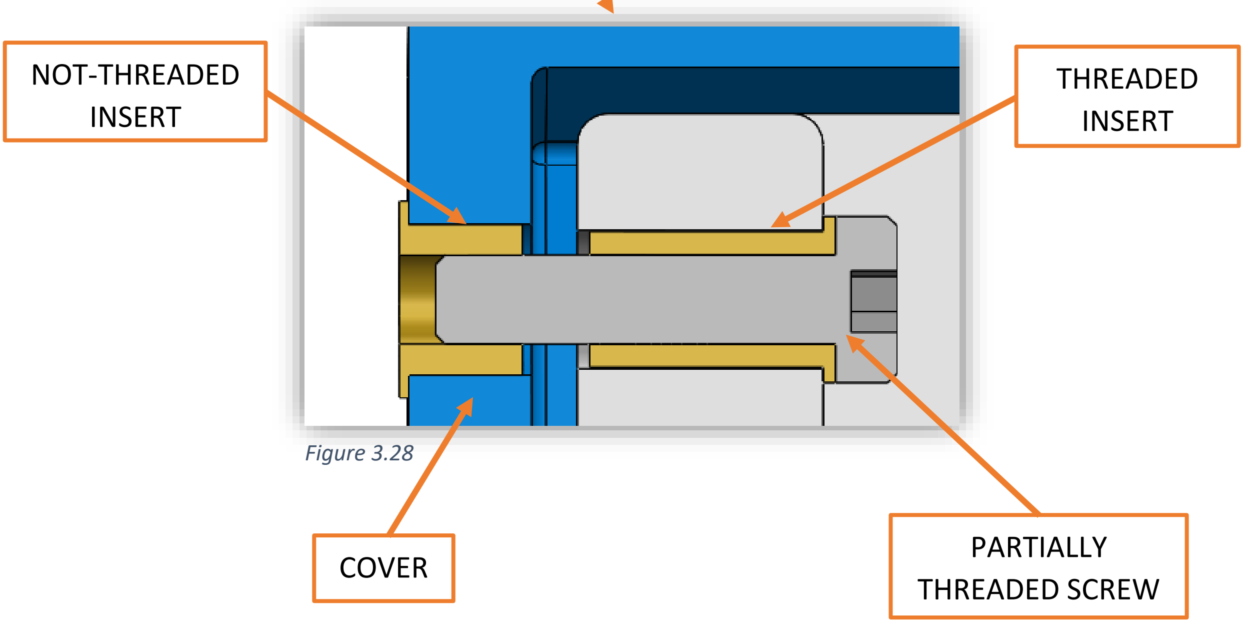


Figure 3.28

3.4 Final design

The final upper support design has undergone further changes due to the manufacturing technology chosen and the idea of having an injection moulded part.

- Optimization of the front lighting system: a new headlight has been selected (figure 3.29) due to aesthetic reason, lower costs and to comply with lighting regulation (the previous headlight led has been considered too small). The headlight housing has been modified, leading to major change in the design of the lower part of the pipe: smaller rib and wider fillets for a proper aesthetic harmony.

Figure 3.29

- The cable passage hole has been modified: the material, above the passage, has been removed (figure 3.30). This allows the process to reduce the number of molds sliding elements in the injection molding tool. Moreover, the presence of undercuts is prevented, and a reduction of weight is obtained.

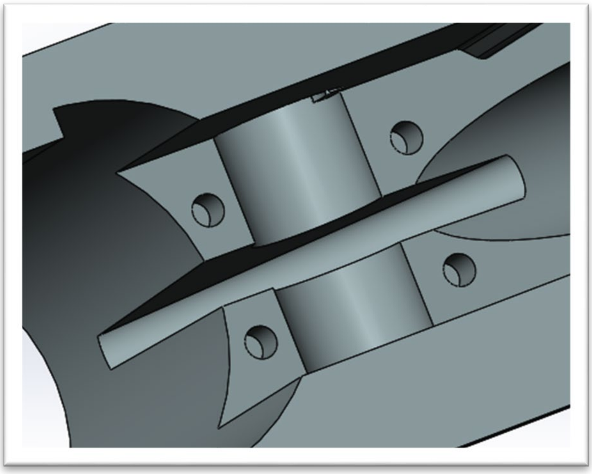


Figure 3.30

- The rear protrusion, that allowed the connection of the upper hook, has been disunited from the upper support surface: it is now a separate element, mounted with screws on the rear back of the pipe (figures 3.31). Optimization of the injection mold and service reasons have been the main purpose of this change.

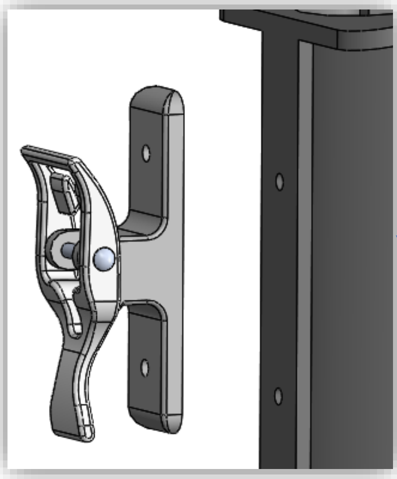


Figure 3.31

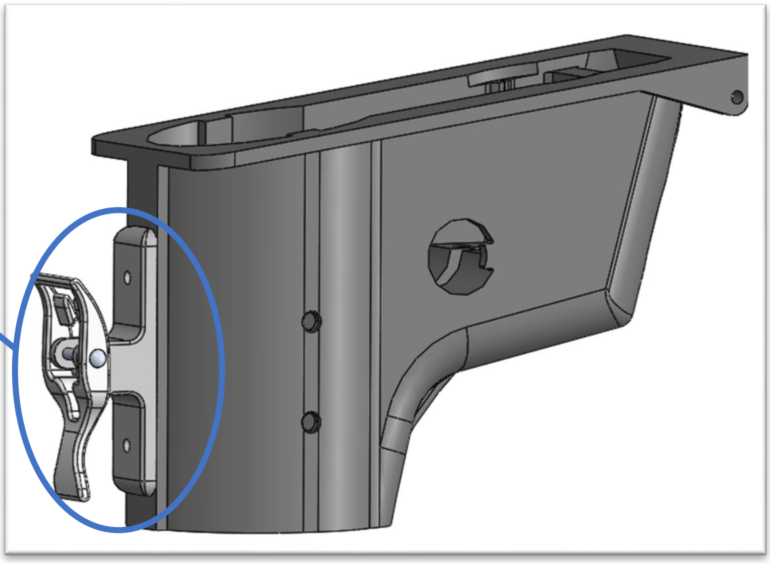
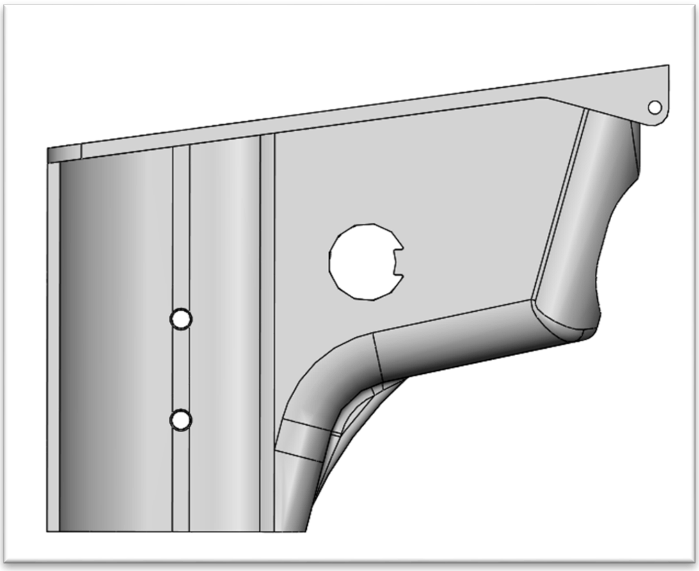


Figure 3.32

- Another important revolution is the integration of a circular display (figure 3.33): it indicates the speed and it has various indicator lights. It is connected to a new PCB, that is located in the same area as the previous one. The PCB placement has been modified: the charge indicator LEDs have been removed (now the display indicates the battery charge). The PCB has been installed to the upper support with screws passing through two perforated columns, instead of the previous protrusions: this, to avoid undercuts during injection.

Figure 3.33

- The shape of the protrusions, that allows the connection with the smartphone holder, has been changed. Sharp edges have been abandoned in favor of softer lines to reduce load concentrations (figure 3.34).



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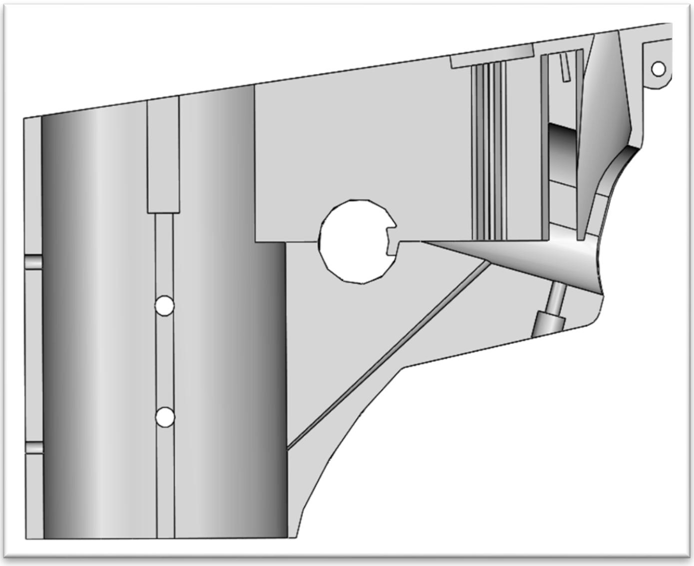

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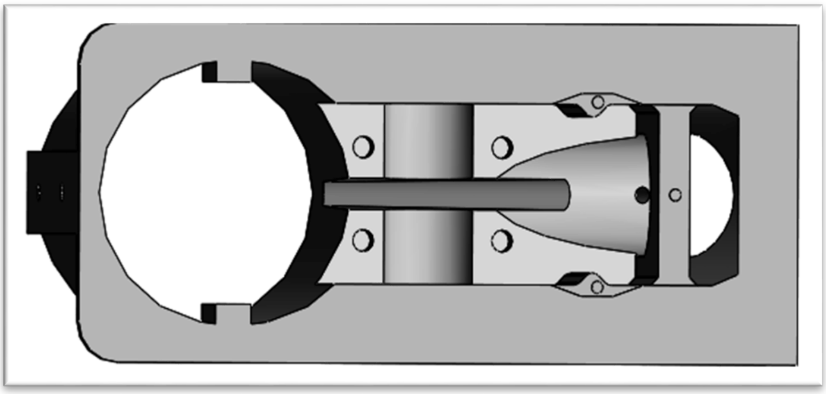


Figure 3.36

4 Kinematic analysis

For a purely urban use, the idea of portability is resulting in increasingly versatile folding electrical vehicles and Lynx is part of this concept.

The integration of a folding system is fundamental: it allows to attach and secure the handlebar frame to the rear frame, resulting a vehicle easy to be carried.

To reduce the manufacturing costs, the very first idea was to look for standard hooks. The specific design of the handlebar area has not allowed its use. Instead, no problems have been encountered in using a standard rear hook.

It has been necessary to pursue a kinematic study: the purpose has been to set the upper hook design and verify the functioning. The boundary conditions that have been defined are:

- The geometry of the vehicle, like the handlebar height and the wheelbase, has been considered fixed.
- The geometry and the position of the rear hook has been kept fixed.
- The geometry and positioning of the upper hook have been left variable.

The sequence consists of two phases:

- Engaging phase. The handlebar frame and consequently the upper hook rotate, with the hinge pin axis as center of rotation, until they reach the rear hook (figures 4.1). The upper hook touches the rear hook and rotate clockwise until it is release from the contact and moved back to the nominal position (figure 4.2). The nominal position is kept by the action of the spring.
- Releasing phase. By moving the flap, the upper hook rotates clockwise until it is outside the rear hook rotation path.

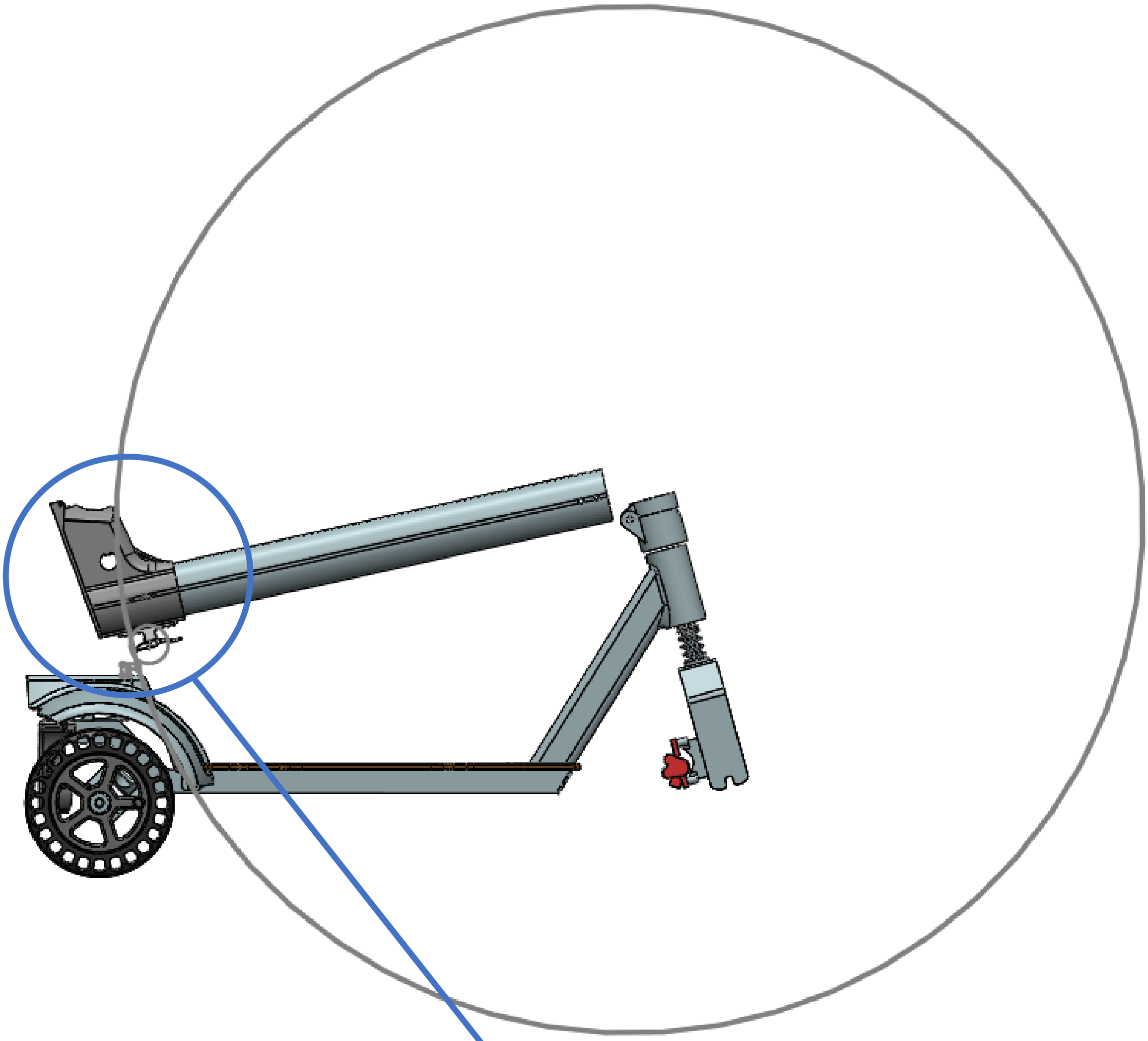


Figure 4.1

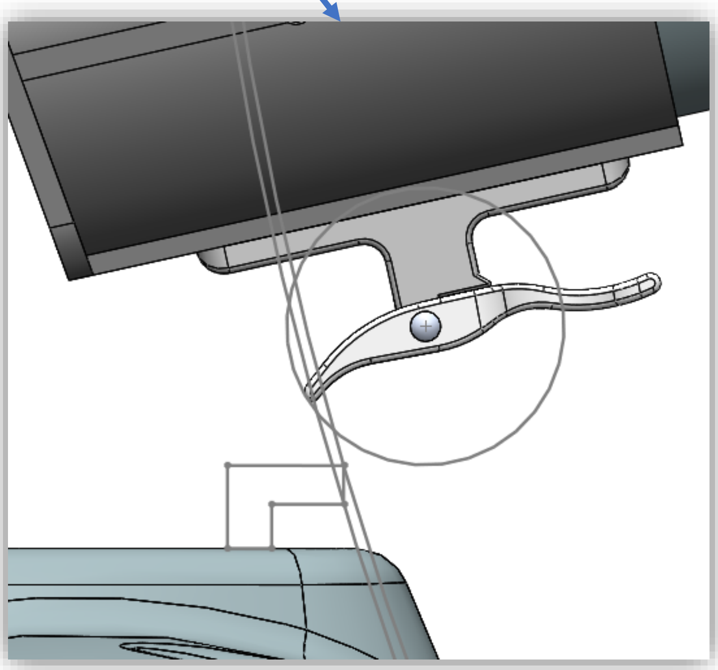


Figure 4.2

5 Structural analysis

Once the design development phase has been completed, a stress analysis check has been requested to evaluate the behaviour of the upper support and of the upper hook, if subjected to certain loads.

Two structural analysis have been carried out, simulating different conditions:

1. Load applied on the handlebar: it has been carried out a material definition analysis. Two different upper support materials have been considered to verify the strength in both cases and then making a comparison.
2. Upper hook- rear hook contact check: it has been verified the reliability of the upper hook when the e-scooter is folded and carried.

5.1 Distributed load handlebar seat

5.1.1 Materials

The two materials chosen for the analysis are: PA66 and aluminum 4032. They match with two different manufacturing technique: the injection molding for the first and the casting method for the second one.

PA66 came from the polymerization of hexamethylenediamine and adipic acid and it is a technical thermoplastic material. Compared to PA6, PA66 has higher stiffness but lower resilience.

PROPERTY	VALUE	UNIT
Modulus of elasticity	2877	N/mm^2
Poisson's ratio	0.3871	N/A
Shear modulus	1037.06	N/mm^2
Density	1140	Kg/m^3
Yield strength	62.25	N/mm^2

Figure 5.1

PA66 is a semi-crystalline-crystalline material that has one of the highest melting points among commercially available polyamides. It keeps good rigidity and consistency, even at high temperatures.

Aluminum 4032 belongs to the Group 4000 (Al - silicon alloys): alloys with a silicon percentage between 4.5% and 20% are used to produce pistons, while a silicon percentage equal or greater than 13% make them suitable for complex-shaped castings.

The main characteristics of the aluminum 4032 alloy are:

- low density: the specific weight is among the lowest of structural materials.
- high ductility due to their cubic crystalline structure F (centered faces): this property makes it possible to make very thin aluminum sheets.
- high thermal and electrical conductivity.
- low melting point (about 660C): aluminum melting point limits the structural applications.
- corrosion resistance in the atmospheric environment: light alloys resist well to generalized corrosion, but suffer from some other types of corrosion, as they are previously treated.

PROPERTY	VALUE	UNIT
Modulus of elasticity	79000	N/mm^2
Poisson's ratio	0.33	N/A
Shear modulus	26000	N/mm^2
Density	2680	Kg/m^3
Yield strength	315	N/mm^2

Figure 5.2

5.1.2 Constraints

Constraints have been applied to:

- the base of the upper support.
- the through holes: they allow the passage of the screws in order to fix the upper support to the main pipe.

- the internal surface of the main cavity, to simulate the presence of the main pipe (figure 5.3).

The constraints eliminate all six degrees of freedom.

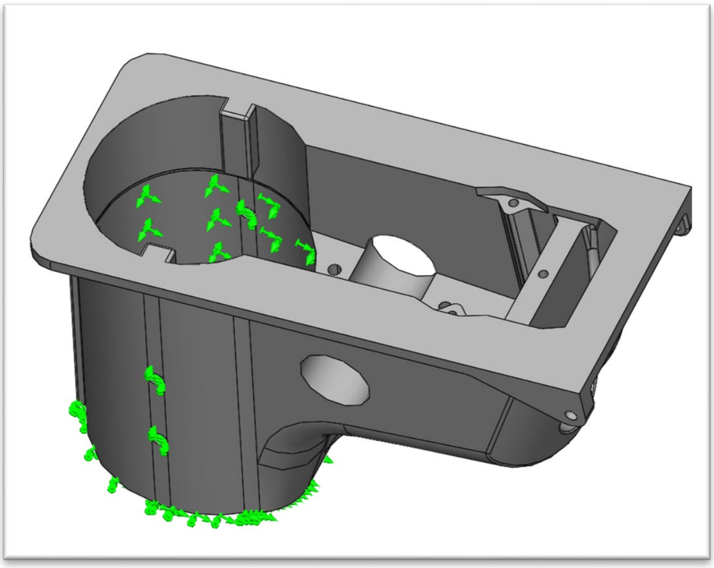


Figure 5.3

5.1.3 Loads

Two distributed loads have been applied simultaneously to the surface seat of the handlebar (figure 5.4):

1. Magnitude: 4000 N; Direction: perpendicular to the surface.
2. Magnitude: 4000 N; Direction: parallel to the surface.

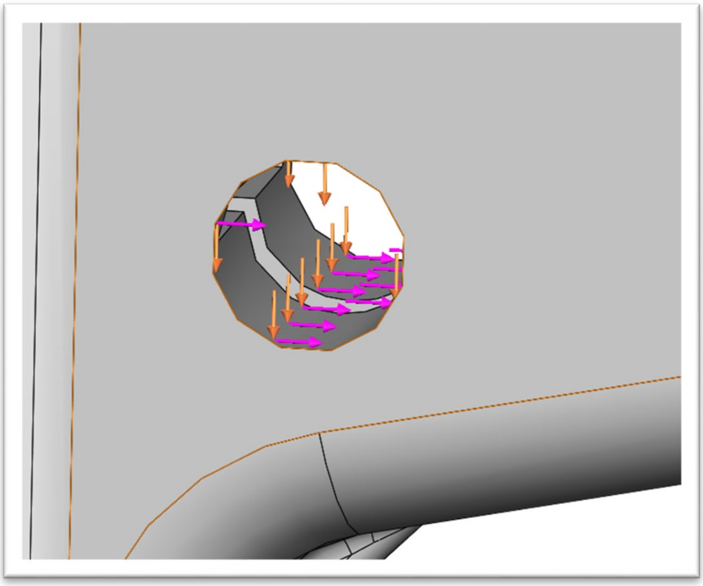


Figure 5.4

5.1.4 Mesh

It has been applied a curvature-based mesh with a maximum element size of 11mm.

A local mesh control has been also implemented on the surfaces near the handlebar seat with an element size of 3,5mm.

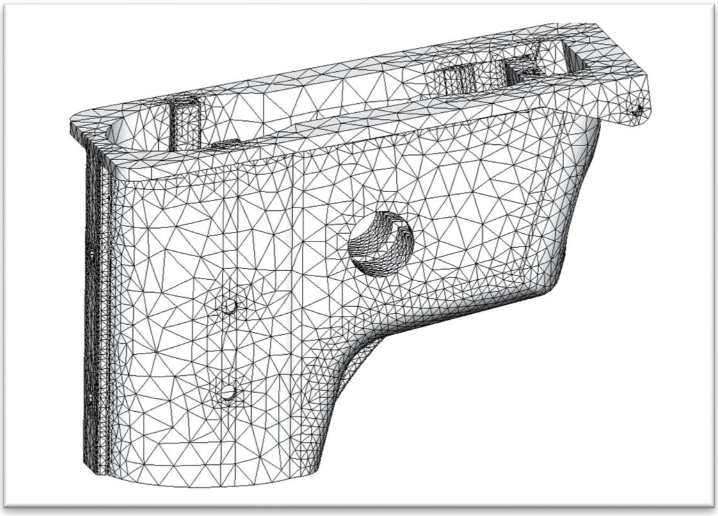
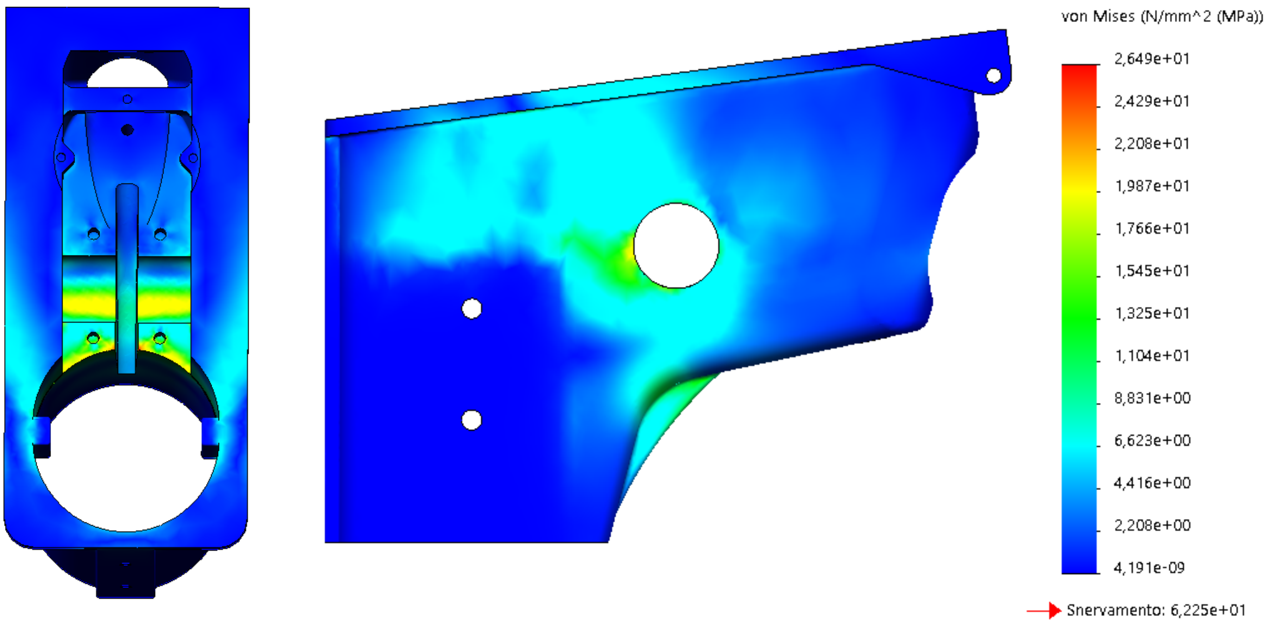


Figure 5.5

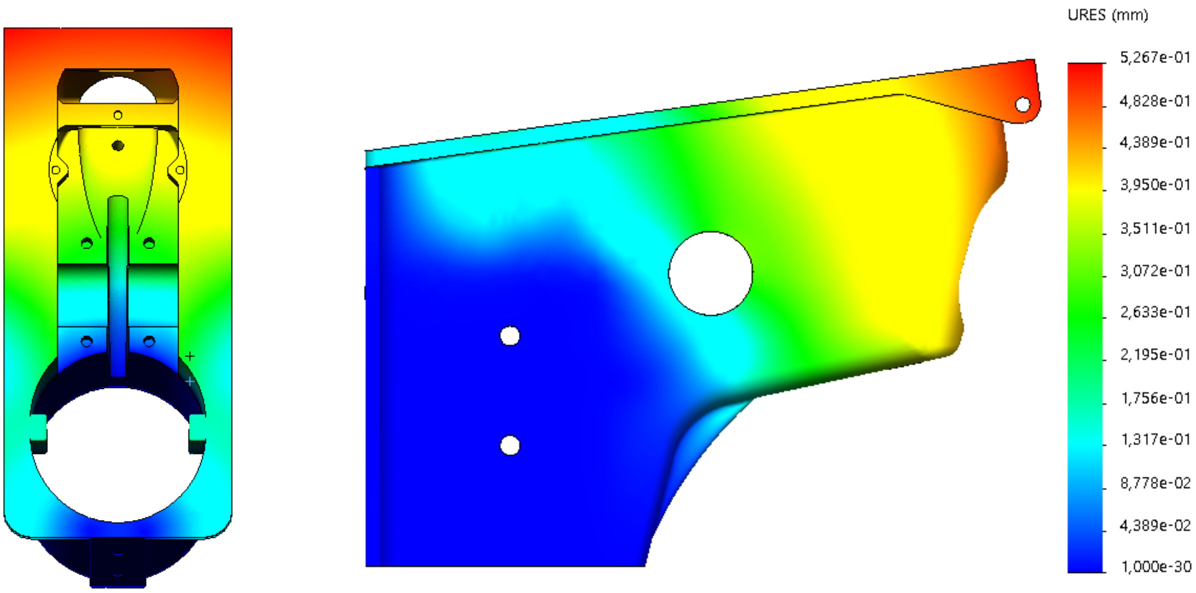
5.1.5 Results (PA66)

- Static analysis of nodal stress:



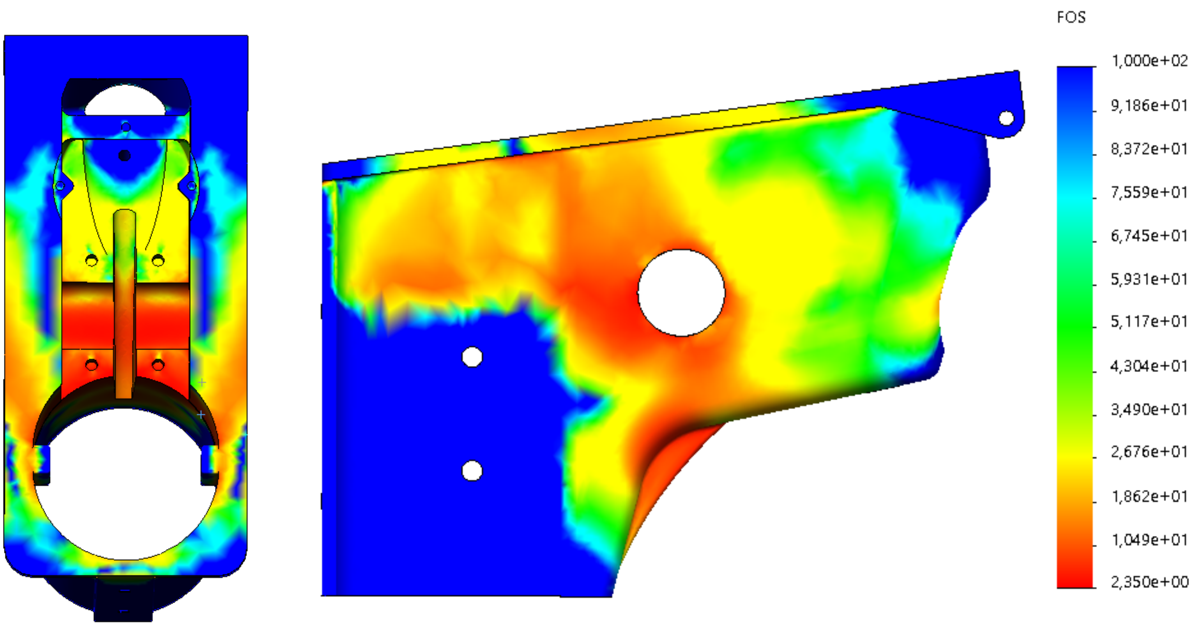
The highest stress values have been detected in the handlebar housing area, with a maximum value of 27 MPa in the notches.

- Static displacement



It represents the material displacement as a result of the load applied.

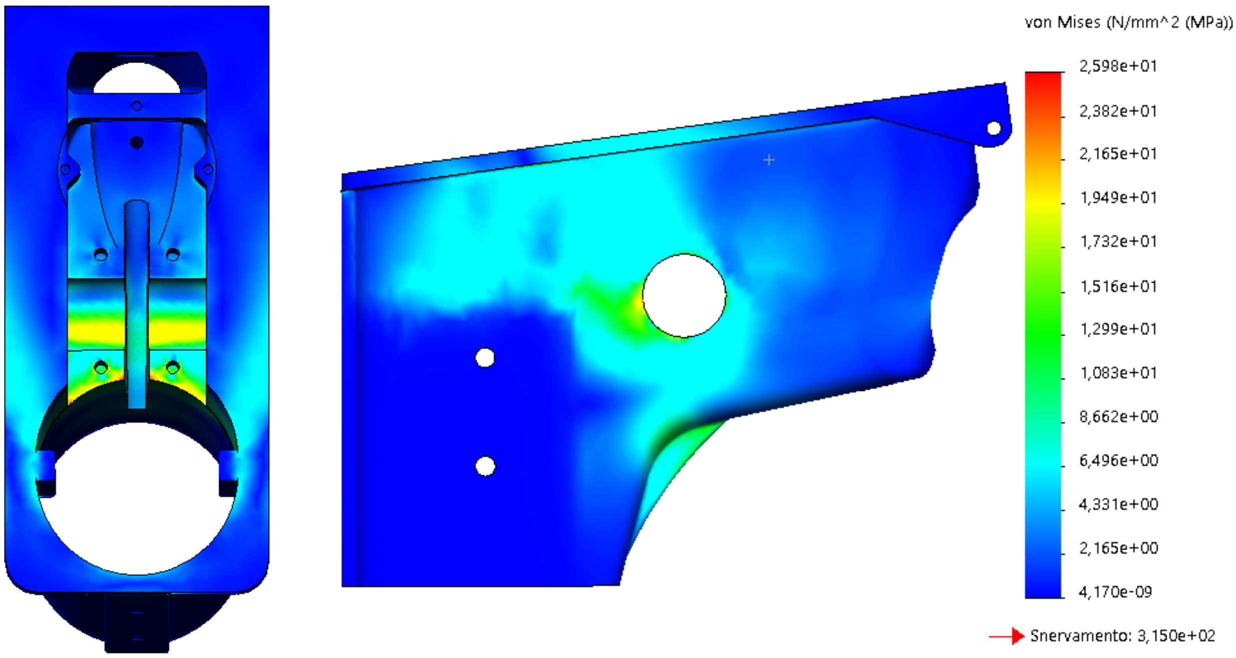
- Factor of safety (FOS):



It represents the variation of the factor of security. FOS (minimum value) = 2,35.

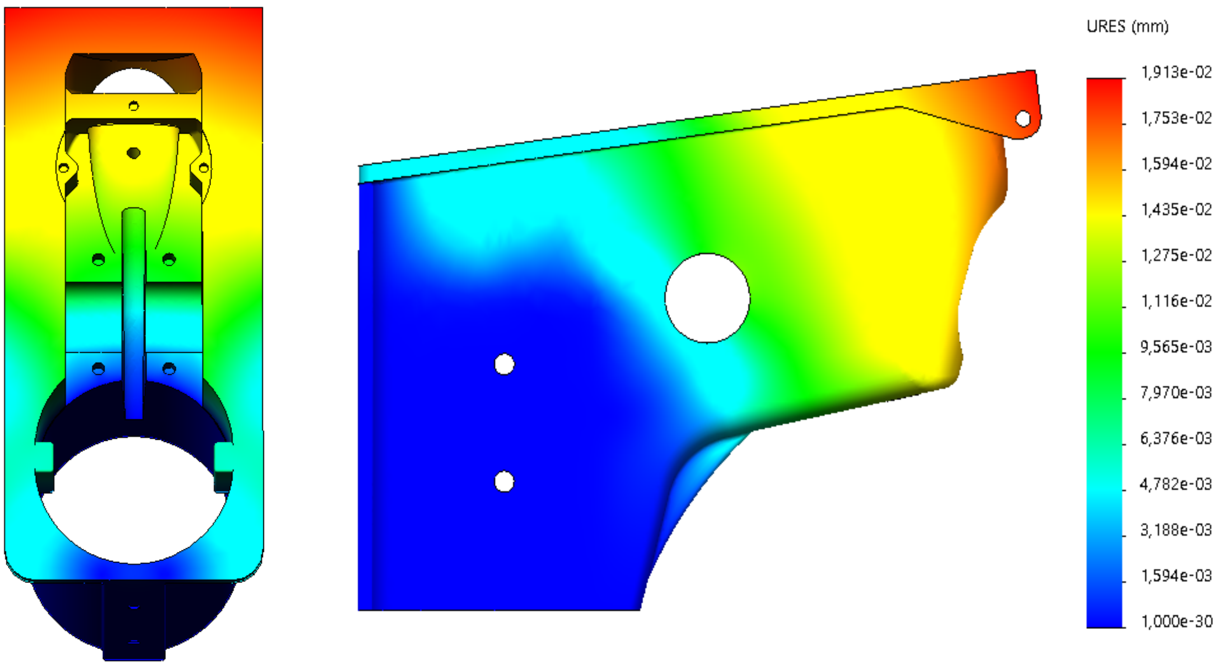
5.1.6 Results (Aluminum alloy 4032)

- Static analysis of nodal stress:

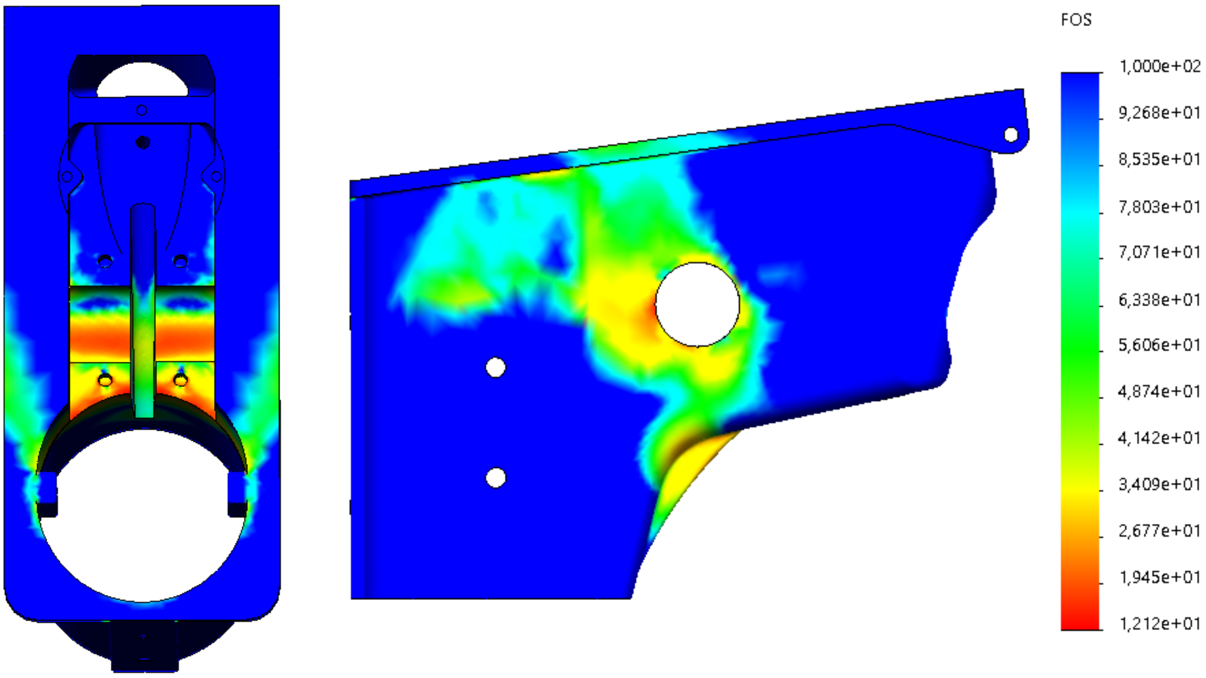


The highest value detected is 26 MPa, with respect to a yield stress value of 315 MPa.

- Static displacement



- Factor of safety (FOS):



FOS (minimum value) = 12

5.1.7 Comparison

The analysis results have not shown relevant differences between the two materials: the maximum stress detected, in both cases, has an approximate value of 27 MPa that is way lower than the two materials Yield stress.

It has been an important outcome because of its contribute to the choice of the upper support manufacturing process. Making a casting component was the original concept. The idea has been rejected for two reason:

- High initial manufacturing cost (the molds, the machine, etc.)
- No big strength differences between the aluminum and the plastic, in this case.

Injection molding has been the preferred option: the plastic material guarantees a significant reduction in costs and a good strength, in relation to the upper hook specific loads.

5.2 Upper hook-lower hook contact

The analysis has been carried out by making these assumptions:

- It has been considered only the upper hook.
- The contact surface with the rear hook has been assumed.
- A load has been applied on this surface.

5.2.1 Material, Constraints and loads

PA66 has been the material chosen for the analysis.

Constraints have been applied to the surfaces of the pivot passage holes and to the plane rear surfaces, that maintain the hook in its nominal position.

A distributed load has been applied to the hypothetical contact surface (figure 5.6):

- Magnitude: 250N; Direction: perpendicular to the surface.

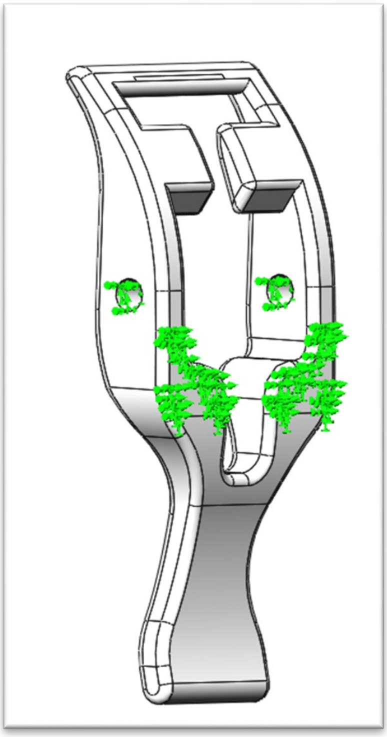


Figure 5.7

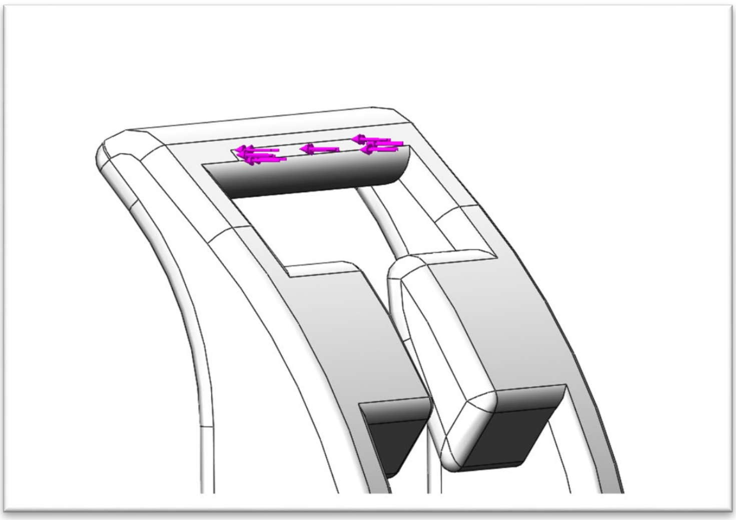


Figure 5.6

5.2.2 Mesh

It has been applied a curvature-based mesh with a maximum element size of 11mm.

A local mesh control has been also implemented on the surfaces near the handlebar seat with an element size of 3,5mm.

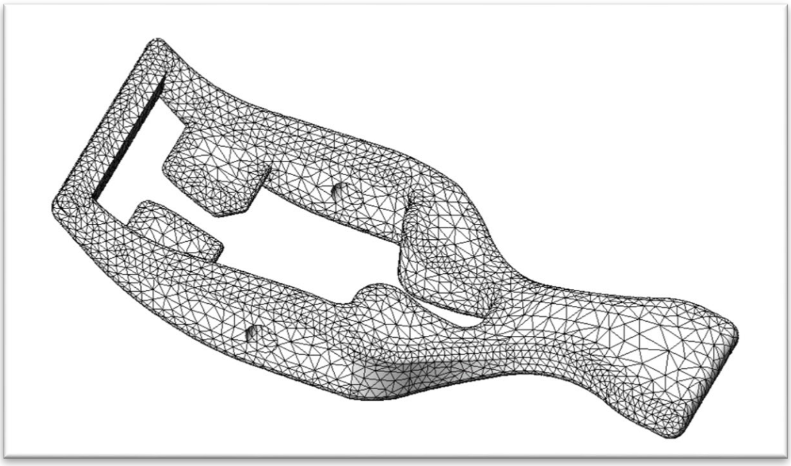
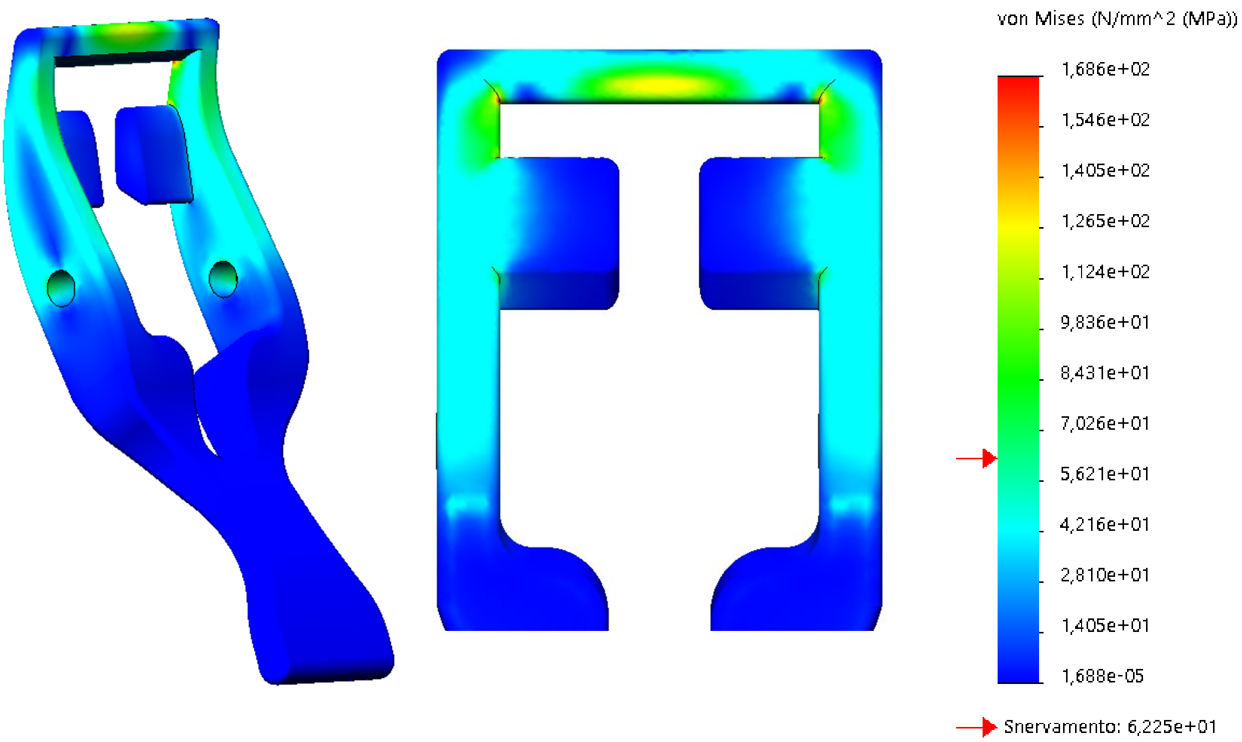


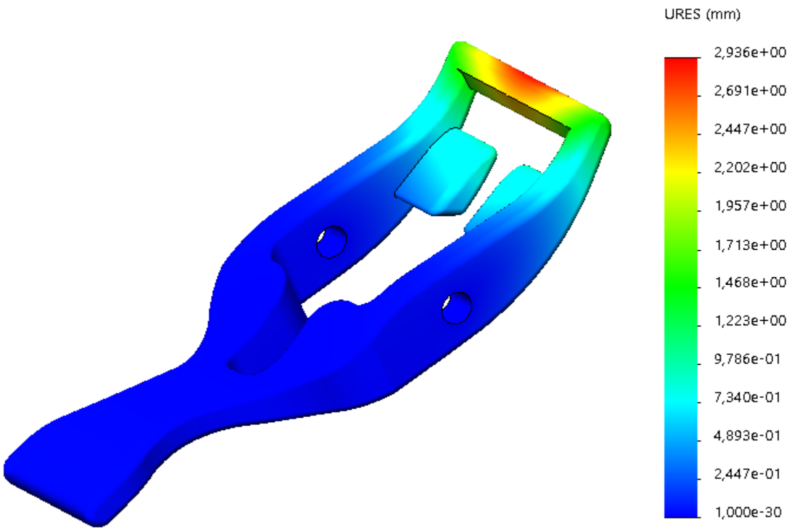
Figure 5.8

5.2.3 Results

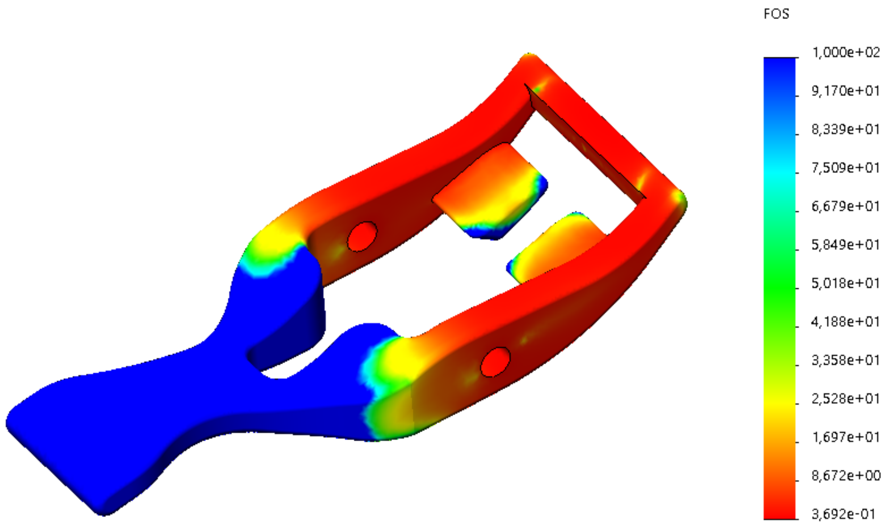
- Static analysis of nodal stress:



- Static displacement



- Factor of safety (FOS):



FOS (minimum value) = 0,36

The previous representations show how the upper hook analysis fails because the hook is not able to sustain the initial load conditions. The issues can be solved by the following changes:

- The material: PA66 presents a low yield stress value for the application.
- The design of the hook: the thickness of the material, in the zone that interact with the rear hook, is too thin.
  Moreover, edge blends can be increased in size to reduce the notches severity and consequently to lower the stress.

6 Drafting

6.1 GD&T and GPS

Geometric Dimensioning and Tolerancing (GD&T) or Geometric Product Specification (GPS) are symbolic languages that can be used to research, define and codify the function of all the features that present a component. The main aim is to always guarantee the correct assembly and functionality, to indicate the manufacturing objectives, to reduce the production costs and to transform the inspection in a reliable process with determined steps to follow.

It can be considered also as a design tool that define unambiguously the limits of imperfect produced parts, that cannot be exceeded. In fact, real surfaces can be different from the exact geometric form, because of various factors. Each workpiece feature has a function and has to be determined in terms of size, location, orientation and form.

The drawings of the workpiece should not be ambiguous: the use of the ISO GPS or ASME Y14.5 standard can satisfy the specific requirements of different companies and can eliminate, with simple and coherent standardized rules uncertainties and confusion in the design, manufacturing and verification phases.

The ISO GPS and ASME Y14.5 standards differs to each other, the first is mainly adopted in Europe while the second one is born and used in the USA. However, each company is free to choose the best language to suit your needs. The main differences are:

1. Interdependence between form and dimension: ISO uses the Independency Principle by default, while ASME uses the Envelope Requirement.
2. The ISO standards use by default the Gaussian dimensioning notion to define the size of a feature; the points of any surfaces do not have to violate an envelope, defined by the least squares method. The ASME standards adopt the mating size approach to describe the size of a feature. In this case, the envelope to not violate has the maximum material dimensions.
3. The ISO standards give importance to the “duality principle”: the specification process and measurement phase are connected each other. Every change in the specification is due to satisfy the inspection phase. The ASME standard limits itself to describe the admissible geometry of a parts and is not interested in how a component can be measured.

4. The ISO standard uses as control system the coordinate measurement machines (CMM). The control sequence “extracts” the geometry of the physical component to elaborate the geometrical features associated with the surfaces (planes, spheres, cylinders) and to evaluate the measurement of interest. The ASME standard idea is that the real surface of a piece should not violate the geometrically perfect zone specified.
5. The GPS language is defined by more than 150 distinct standards. Instead, GD&T is based on only a single standard that has been developed in a series of fundamental rules defining a consistent normative system.
6. The ISO standard is in constant evolution with the addition of rules and standards that may contradict the existing ones. ASME standards are modified each 10-15 year.
7. While tolerancing a feature of size, the two languages behave differently: ISO applies its standards to an extracted median line and surface while ASME define a derived and ideal feature such as an axis or a centerplane.
8. The ISO standards use indistinctly the position and the profile tolerance to locate and orientate a surface. In the ASME, position tolerance is applied only to features of size.

6.1.1 Geometrical tolerances

Size and form errors can be caused by an imperfect production phase but can also derive from a wrong orientation or location between two features of a part.

Geometrical tolerances can be distributed and classified in:

1. Form tolerances, which determine the variation limits of a surface or a single feature from the ideal form, defined in the drawing. A form tolerance is respected when the distance of each point between a real surface and an ideal geometric surface is equal to or less than the tolerance defined on the drawing. Form tolerances are independent from the datum, they do not depend on the orientation and location relations with the datum.
   Profile Tolerances are mainly used to check location of a feature of size, but it is not their only application. They could also control indirectly orientation and form based on the datum configuration specified in the feature control frame.
2. Orientation tolerances, which define the variation limits of a feature surface with respect to one or more features indicated as a datum.

3. Location tolerances, which establish the variation limits of a surface (only in GPS) or a single feature of size with respect to a theoretically exact position.
4. Runout tolerances, which determine the variation limits of a surface or of a single feature with respect to a datum, established in the design phase, during the rotation of a piece around a specific datum.

TOLERANCES	DATUM	GEOMETRICAL CHARACTERISTIC	ISO 1101 SYMBOL
Form	NO	Straightness	⏤
		Flatness	⏥
		Circularity (Roundness)	○
		Cylindricity	⌭
Size, orientation and location control	YES/NO	Profile of a Line	⌒
		Profile of a Surface	⌓
Orientation	YES	Angularity	//
		Perpendicularity	⊥
		Parallelism	∠
Location Orientation and location of a feature of size	YES	Position	⌖
		Concentricity	◎
		Symmetry	⌯
Runout Coaxiality and surface deviation of revolution surface	YES	Circular Runout	↗
		Total Runout	⌰

Figure 6.1

It results that a geometrical tolerance is used to define a bidimensional or three-dimensional boundary that a feature or a feature of size, that has to be controlled, must not violate.

The table (figure 6.1) shows the characteristic geometrical symbols used to represent the geometrical tolerancing and define two categories:

- The non-associable tolerances: they do not relate to any feature or feature of size used as a datum. The form tolerances represent the main example.
- The associable tolerances: they may associate to other features to allow their correct orientation and positioning on the drawing.
  The profile tolerance is a valid example.

Geometrical tolerances are indicated on a drawing by using a rectangular frame. It consists of a series of compartments, having each one a specific function. In order from left to right there is (figure 6.2):

1. The symbol of the geometrical tolerance.
2. The tolerance numeric value. This value is preceded by the sign Ø if the tolerance zone is round or cylindrical. Another indication that can appear is a modifier, expressed by a capital inscribed letter.
3. The letter indicating the datum features and together representing the datum reference frame. Even in this case, the modifier symbol can be inserted.

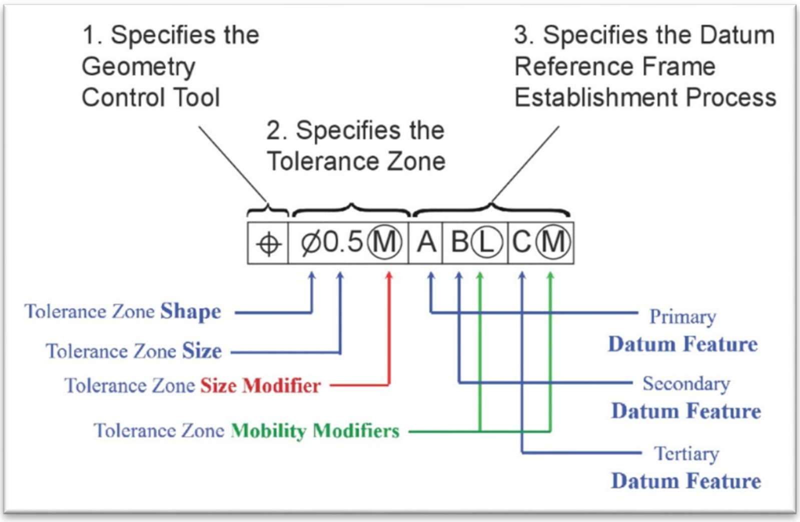


Figure 6.2

6.1.2 Fundamental principles

The fundamental principles are rules that can be applied to all the geometrical property categories. They are:

- The **envelope principle** is rule #1 of the ASME Y14.5 standard. Rule one could be summarized as "perfect form at MMC", it means that a feature of size when it is produced at MMC, it has perfect form. When it is moving from MMC to LMC, the feature of size could have form errors. For external feature of size MMC means "biggest" size, for internal feature of size it means "smallest" size.
- The **principle of independence** states that each dimensional and geometric tolerance requirement in a design shall be respected in itself, independently, unless special conditions are prescribed. This principle has been introduced with the normative UNI EN ISO 8015 of 2011. It means that the geometric tolerances have to be evaluated and applied without taking into account the dimensions of the element.

This principle is at the base of the ISO standard, and it contrasts the ASME standard approach, i.e. perfect shape at the maximum material.

- The **principle of simultaneity** indicates that position and shape controls located by the same datum and with the same material modifiers must be applied simultaneously.

6.1.3 Material modifiers

The standard UNI ISO 8015 states the independency between the dimensional and the geometric tolerances. There are, however, two exceptions:

- Envelope requirement
- Application of the maximum or minimum material

The **Maximum Material** Principle, also called as the Maximum material requirement (MMR), represents one of the fundamental rules on which geometrical dimensioning with tolerances is based.

When components need to be assembled, the mating process is determined by both the form and position dimensions errors. Imagining a mating with clearance, the clearance has the minimum value when the mating elements are at the maximum material conditions. If the geometric tolerances do not reach the maximum value and consequently the elements dimensions differ from the maximum one, it means that the mating clearance is increasing. When this scenario occurs the prescribed form and position tolerances can be extended.

This condition constitutes the MMR. It is indicated on a drawing with the symbol M next to the numeric tolerance value inside the feature control frame. The benefits result in an increase in the tolerance limits ergo less pieces are rejected during the production phase.

Least Material Requirement, LMR, instead refers to the holes at the maximum possible diameter and to the shafts at their minimum diameter. In this case, if the element is not at the LMC, there is a gaining in the form and position tolerances. The symbol L is used for the indication on the drawing, and it used to protect minimum distances and to guarantee the existence of resistant section. It is important to mention that (L) is an internal material tolerance, so it could not be checked with functional gages.

6.1.4 Datum

The datum system allows the description of the features functional relations and indicates, at the same time, the unambiguous inspection sequence to follow. A datum should always be chosen by considering the function of a part and not because of the technological production process. In fact, it can lead to a reduction in the available tolerances.

A distinction between the datum, the datum feature and the datum feature simulator should be done:

- The **datum features** are particular surfaces of real and imperfect parts. They limit some degrees of freedom during the assembly process.
- The **datum** are abstract geometrical elements, and they represent the ideal counterpart of the datum feature or the axis of the ideal geometric counterpart. They do not exist, but they are simulated by the machine coordinate system.
- The **datum features simulator** are theoretically perfect and represent the connection between the imperfect datum feature and the ideal datum. They also define the datum reference frame.

A particular typology of datum are the datum targets. They are inserted when only a portion of a feature is used as a datum feature. They describe the location and the form of the control features that simulate a datum plane. In the upper hook drawing, the datum target has been identified with two planar contact areas, characterized by cross hatch. These areas are portions of the feature surfaces, which ones keep in contact the hook, that is pushed itself by the spring. Datum targets are indicated by a circle divided in two compartments by a horizontal line. The lower space is reserved for a letter, which represents the datum feature, and for a number that indicates the number of the datum target. The upper compartment is used for complementary information, such as the dimensions of the datum target zone and the shape.

One major datum objective is to identify one or more cartesian reference systems in order to orientate and locate the three-dimensional tolerance zones. The datum reference frame or DRF can be obtained by following a specific sequence of six phases:

1. The decoding of the feature control frame, in a drawing.
2. The identity of the datum features among all the component features.
3. The construction of the datum feature simulator.

4. The extraction of the datums from the datum feature simulator.
5. The use of the datums to define the DRF.
6. The transfer of the DRF to the real component.

6.2 Upper support drafting

6.2.1 Functional requirement of the component-Assembly sequence

It is fundamental to understand how to upper support is mounted on the e-scooter and how it interfaces with the different components. The resulting functional relations have to be respected, in order to display the assembly sequence and consequently to determine the datums and the geometric tolerances.

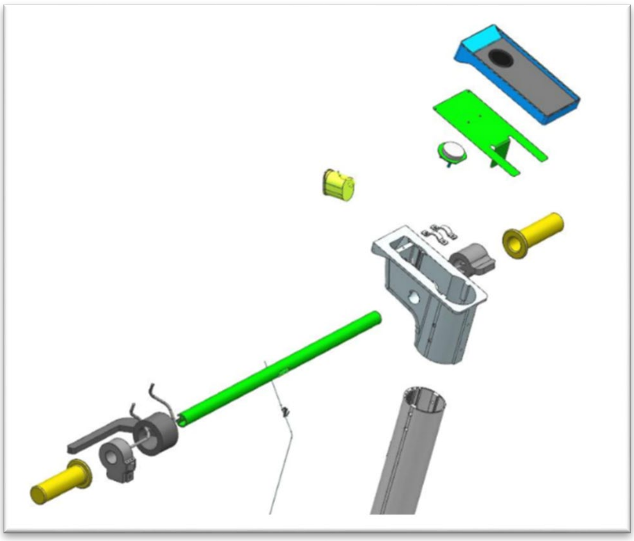


Figure 6.3

The upper support has to:

1. Be connected to the main pipe (figure 6.4).
2. Fixed with four screws inserted in the through holes, placed on the upper support (figure6.5).

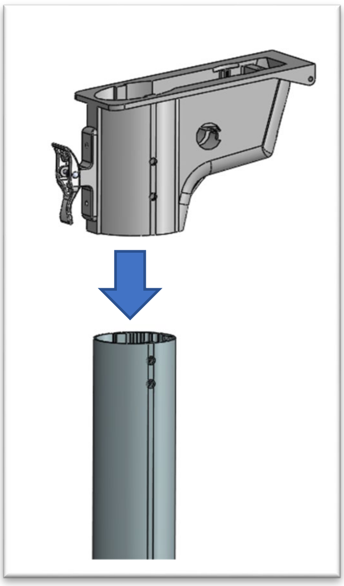


Figure 6.4

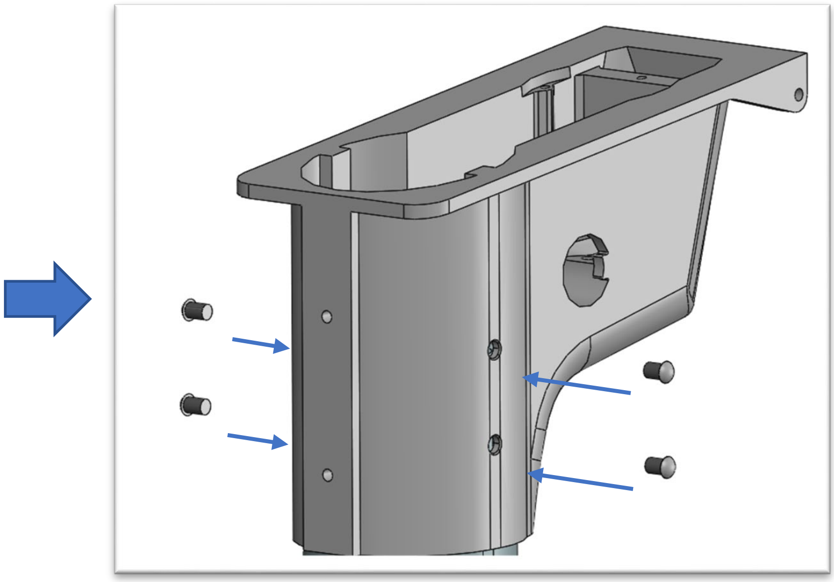


Figure 6.5

The Drawing has to:

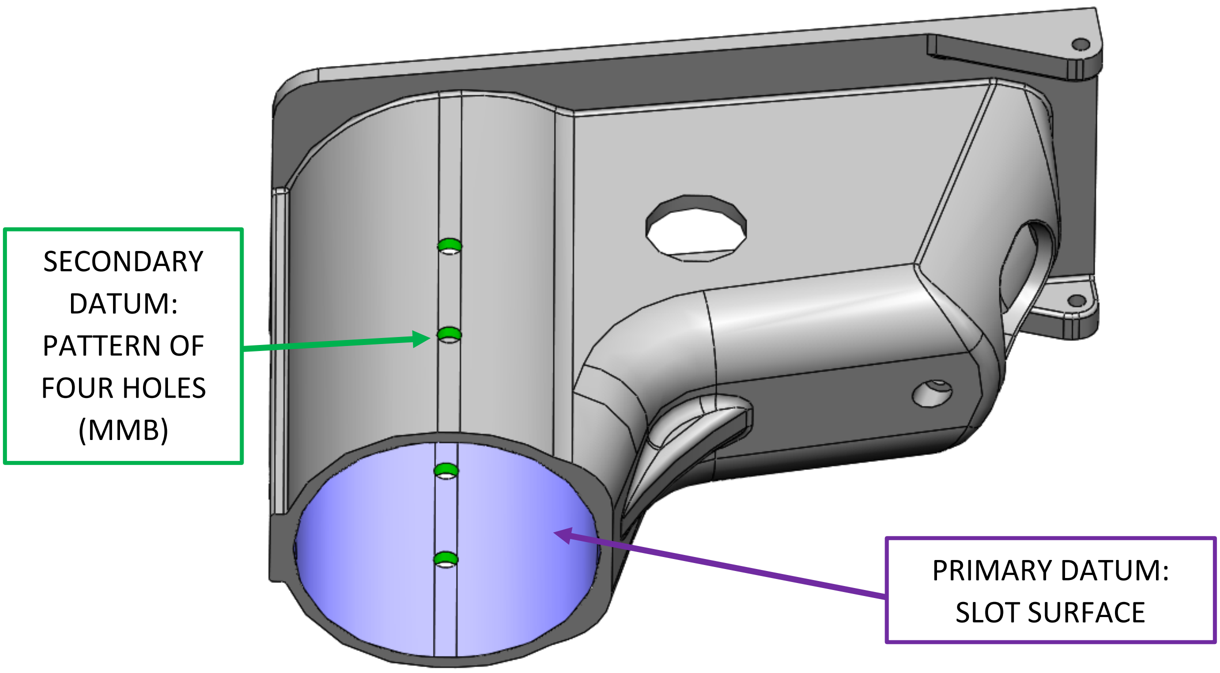
1. Ensure correct assembly.
2. Satisfy the functional requirements of the component.
3. Use largest tolerance admissible in order to satisfy point 1 and 2 and lower the cost as much as possible.

6.2.2 Datum selection

Once the assembly sequence has been identified, it has been possible to extrapolate the datums.

It is important to identify:

1. Datum Feature: the physical surfaces of real and imperfect parts
2. Datum sequence: it is defined by the assembly sequence.
3. Material Condition (RFS or MMC/LMC)



DATUM SEQUENCE	A Ⓜ B Ⓜ

- **Datum A**: it has been defined by using the profile tolerance on a pattern of surfaces, to simulate the mating condition with the main tube (figure 6.7). The profile tolerance, in this case, controls the form of the profile of the patterns but not the orientation nor the positioning because the profile control is specified without any datum references. Moreover, the circle present in the arrow (all around modifier), indicates that the control is applied to the whole surfaces.

  The surfaces, attached together, create a feature of size and, in this particular case, the maximum material condition can be used.
- **Datum B**: It represent a pattern of 4 holes and it has been identified by using the position tolerance (figure 6.6). Particularly, it has been utilized the virtual boundary condition methodology: a theoretical boundary controls the positioning of the surface of a feature of size. In fact, when there is a mating through hole-screwed hole, like this case, and here the screw is screwed, what matters it is not if the screw axis is aligned to the through-hole axis, but that the through-hole allows the passage of the screw. In this way, a more expensive axis control is not necessary, and it is controlled only if the hole satisfies the mating requirement.

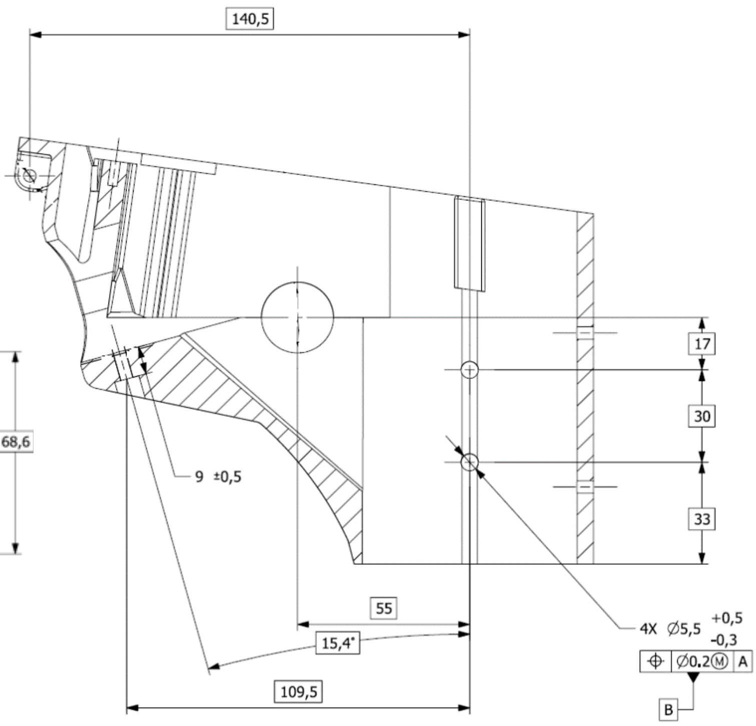


Figure 6.6

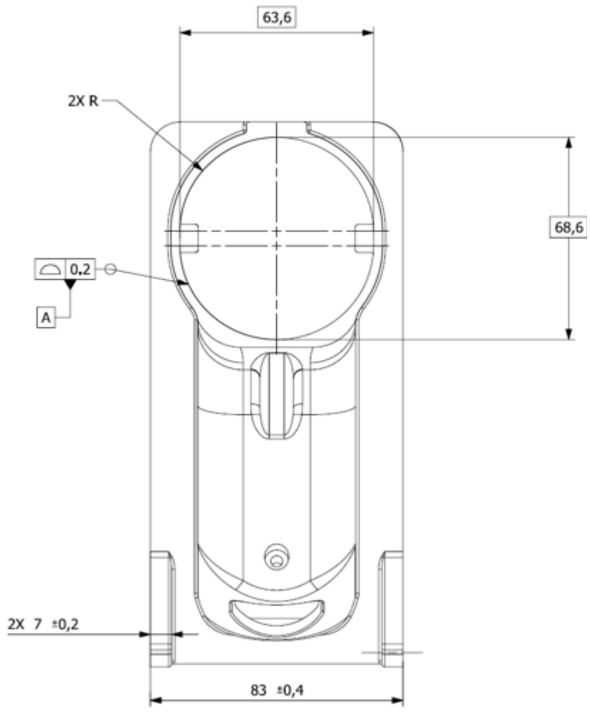


Figure 6.7

6.2.3 Geometric tolerances

The datum references frame (DRF) has been completely identified: it is a system of three perpendicular planes and represents the starting point for measurements and for a correct geometric dimensioning.

A control of the upper support features has been conducted by using the geometric tolerances to respect the features functional requirements and to indicate their position with respect to the DRF system. The features that have been controlled are:

- **Handlebar hole**: the function is the passage of the handlebar, during the assembly stage. It has been used a location tolerance and the basic dimensions to determine the theoretical location of the feature with respect to the datum planes. Moreover, if the holes are produced with a larger diameter, the maximum material condition (MMC) inserted allows an additional tolerance, called bonus, allowing the mating and preventing the rejection of the working piece (figure 6.8).
- **Cover connecting holes:** the function is to center the pins to allow the connection with the smartphone holder. It has been used a location tolerance, adding the MMC (figure 6.8).
- **Fixing headlights hole**: the function is to allow the screwing of the screw to maintain still the headlight led. It has been utilized a location tolerance, adding the MMC (figure 6.8).

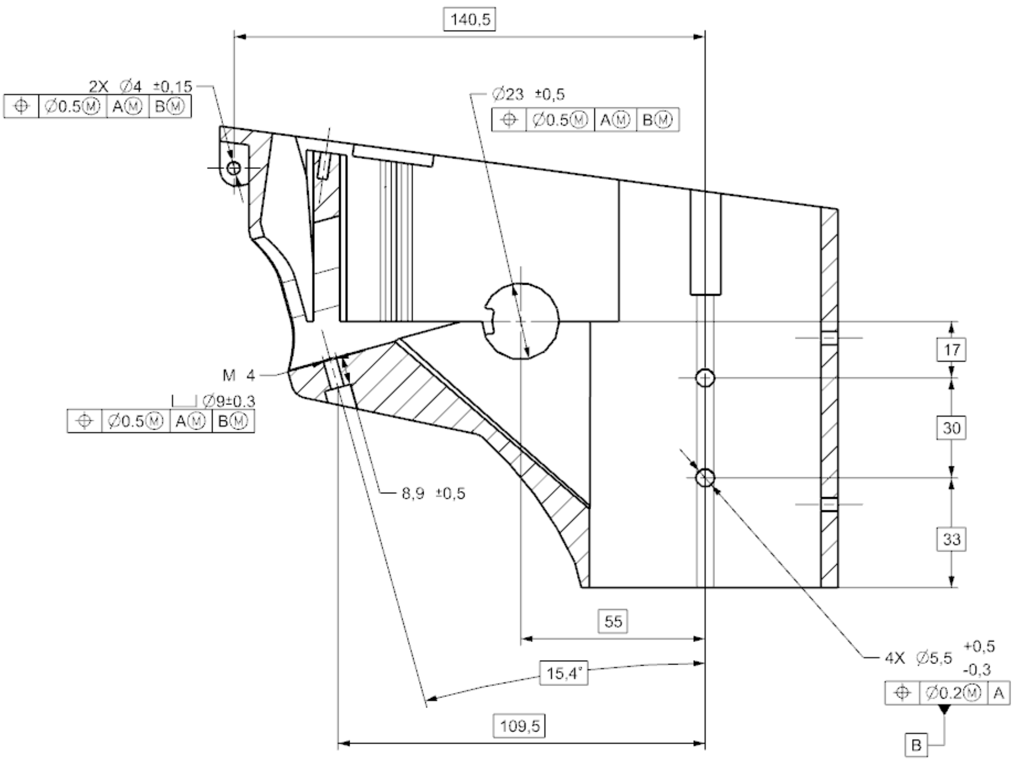


Figure 6.8

- **Headlight led slot**: the function is to allow the integration of the led headlight. Due to the slot-shape, two location tolerances have been used. The MMC is also present (figure 6.9).

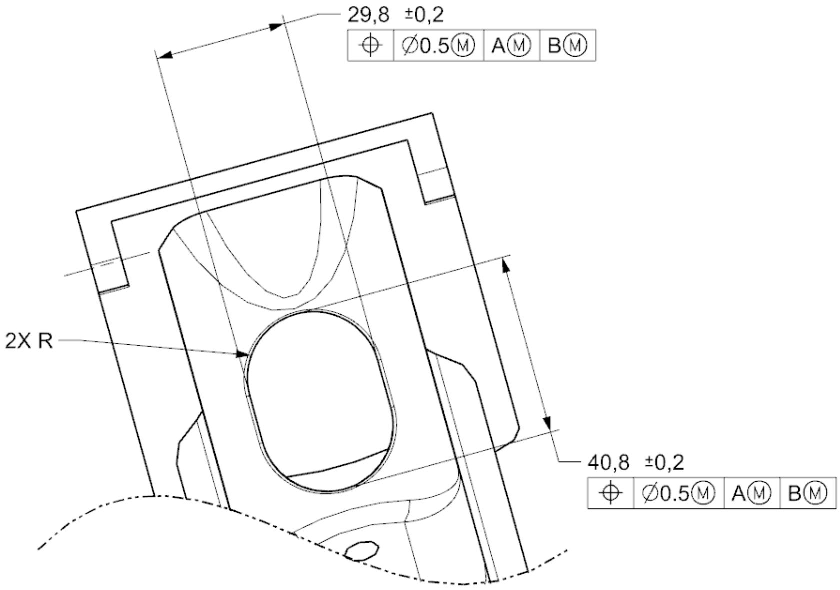


Figure 6.9

- **Battery guide**: the function is to allow and guide the passage of the battery pack. Two location tolerances have been required (figure 6.10).

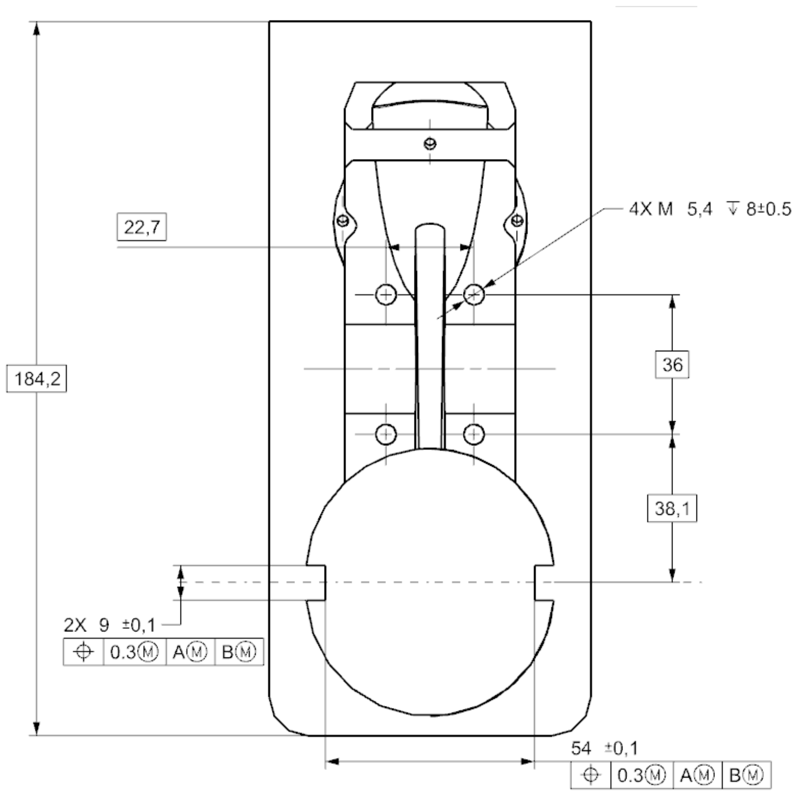


Figure 6.10

- **Fixing Dashboard holes**: the function is to allow the screws passage, securing the display to the upper support inclined surface. It has been necessary a new DRF to fully control the holes tolerances.

  Datum C represents the upper inclined surface (figure 6.11) and it has been identified by using a profile tolerance. This datum is used to better control the orientation and location of the fixing dashboard holes. A multiple single segment position tolerance has been applied to the pattern of the three holes (figure 6.12). The upper segment has been used to locate the pattern with respect to coordinate system AB. The lower segment frame has been used to have a tighter tolerance to control the spacing of the pattern.

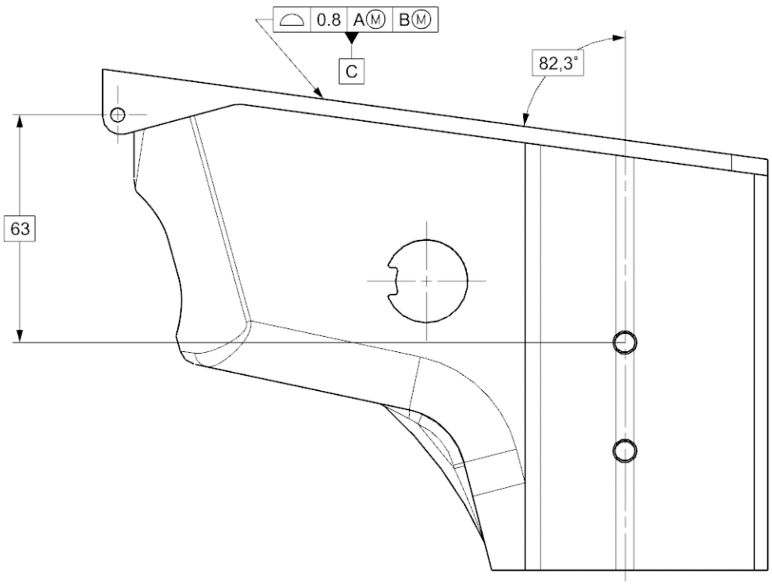


Figure 6.12

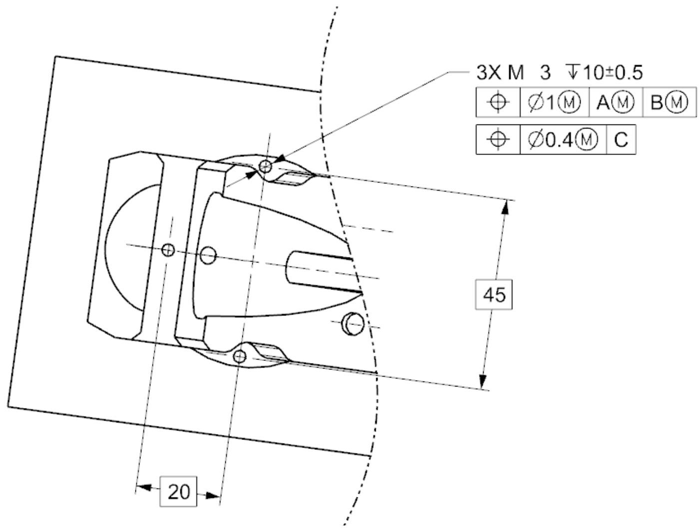


Figure 6.11

Moreover, a general profile and position tolerance has been applied to all the surfaces.

6.3 Upper hook drafting

6.3.1 Assembly sequence

The device, which allows the connection of the upper hook on the upper support, has been considered already assembled. The upper hook drafting and tolerancing is related to the assembly sequence.

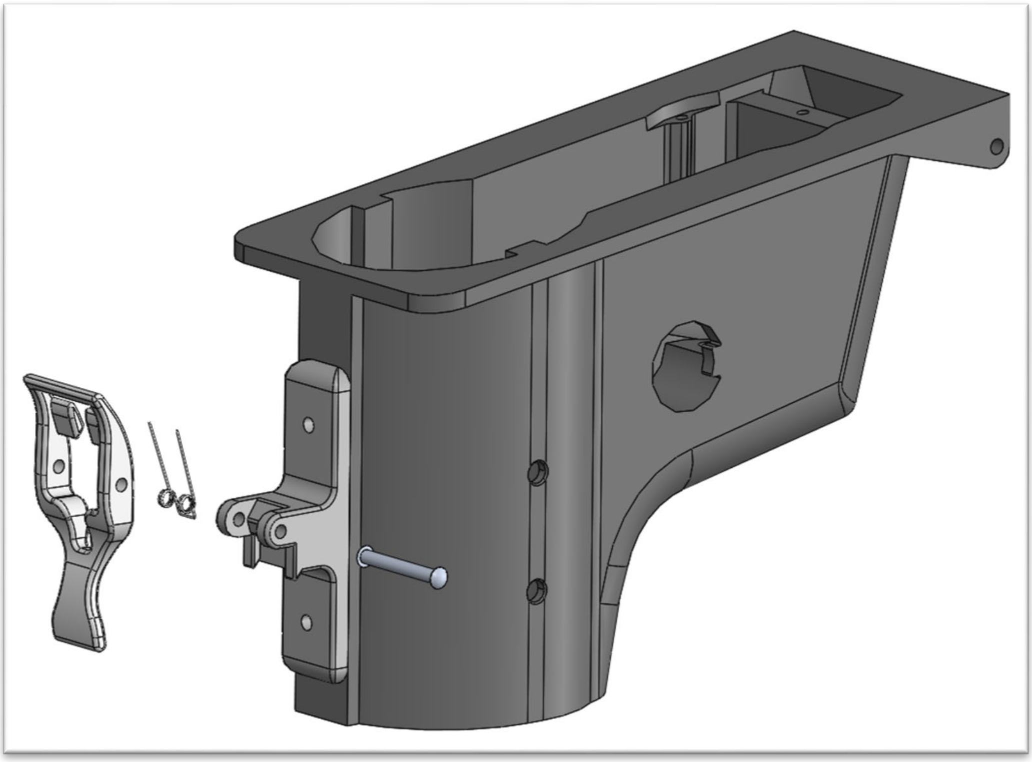


Figure 6.13

The upper hook has to:

1. Be inserted in his nominal position (figure 6.14).
2. Be connected to the hook lodge thanks to a pin (figure 6.15).

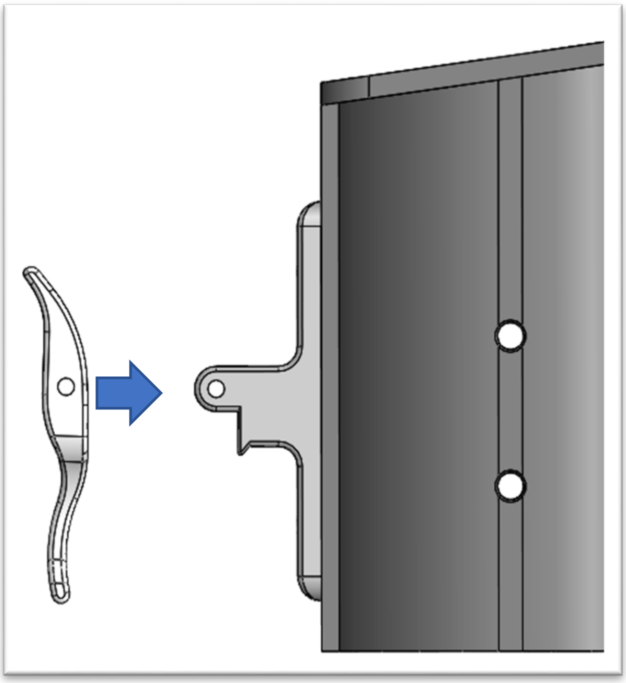


Figure 6.15

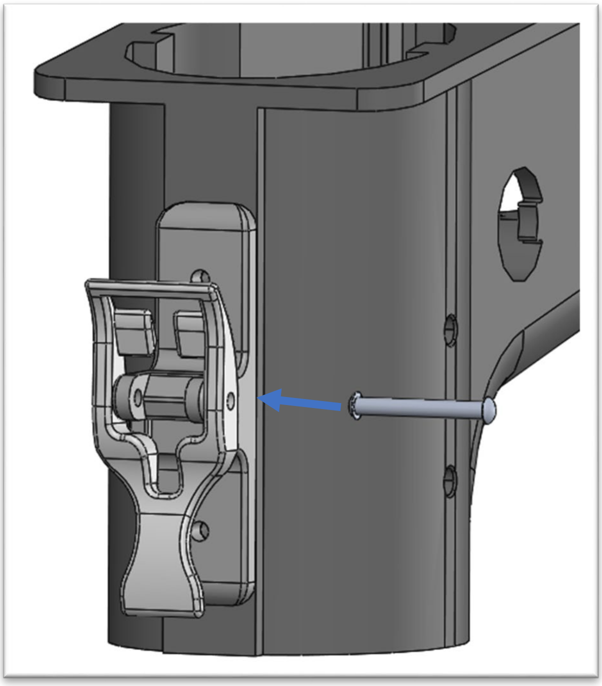
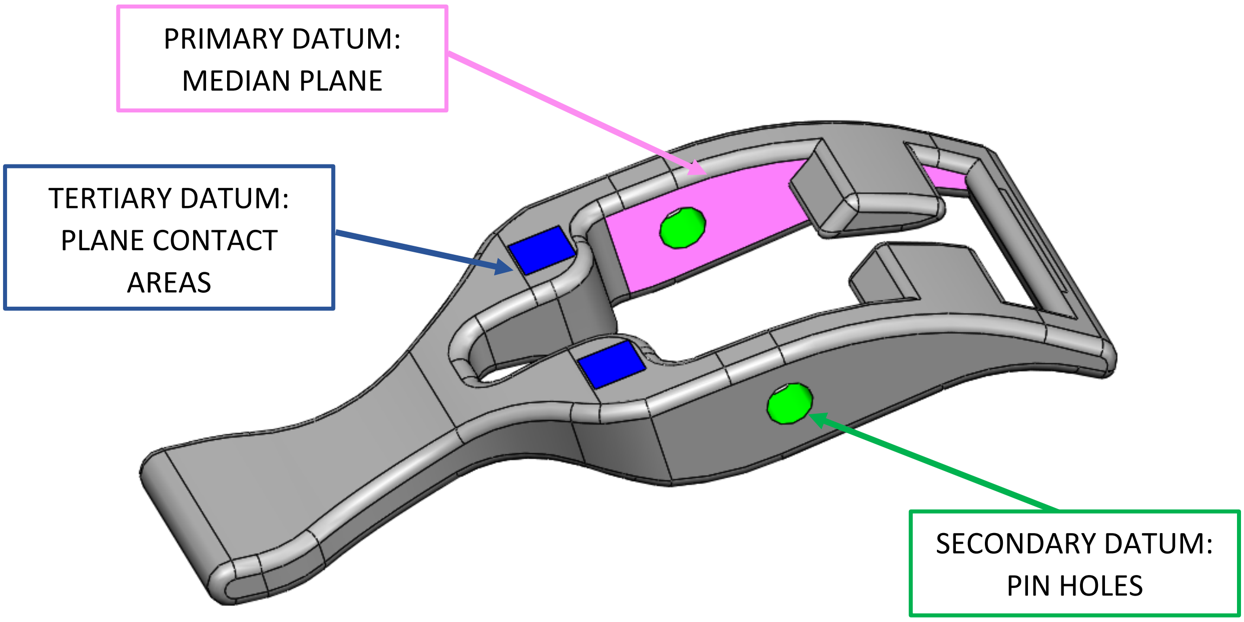


Figure 6.14

6.3.2 Datum selection

Once the assembly sequence has been identified, it has been possible to extrapolate the datums.



DATUM SEQUENCE | A | B Ⓜ | C |

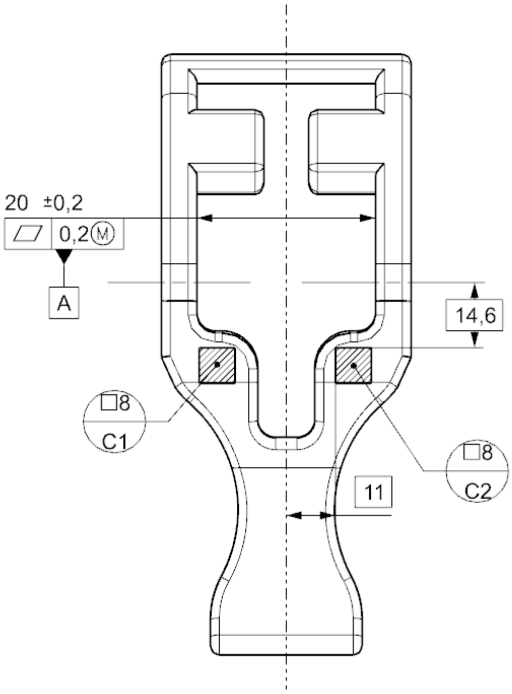


Figure 6.16

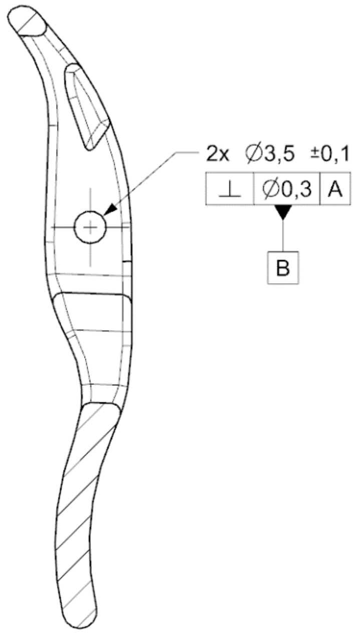


Figure 6.17

- **DATUM A**: it has been defined by using a form tolerance (figure 6.16). The addition of the modifier M means that the median plane surface, defined as datum A, has not to violate the maximum material condition boundary. The flatness of the median plane has been controlled indirectly.
- **DATUM B**: it has been defined by using an orientation tolerance (figure 6.17). Particularly, it has been applied a perpendicularity control of the hole axis with respect to the median plane. The control defines the deviation of the geometrical singularity from the condition of perfect perpendicularity. In this case, no MMC have been applied to the boundary: the two holes have to be aligned and a stricter axis control has been required.
- **DATUM C**: By choosing the following datum system, the upper hook can still rotate around the pin axis. In order to eliminate any movement and to allow a correct validation of the component, datum C has been defined using datum target.

  .

When the geometry, the form and surfaces of the upper hook are controlled, datum C must be used because all six degrees of freedom need to be constrained. When the component is controlled under operating conditions, datum C is not necessary: five degrees of freedom are enough.

6.3.3 Geometric tolerances

The DRF system has been completely defined. The workpiece features, that have been controlled are:

- **Wings distance**: the function is to allow the torsional spring installation and functioning. It has been used a location tolerance to control the resulting median plane (figure 6.18). The MMC has been added.
- **Central rectangular hole**: the function is to eliminate unnecessary material. It has been adopted a location tolerance to control the median planeb(figure 6.18). The MMC has been also applied.
- **Upper hook interacting surface**: the function is to allow the connection between the upper and the rear hook. It has been applied a multiple single segment profile tolerance and besides a double-direction arrow (figure 6.18). The last one indicates that the surfaces, from the letter A to B, are combined in one single feature and controlled together as one creating a pattern of feature. The first segment has been used to locate the surfaces with respect to coordinate system AB. Datum C has not been used because even if the upper hook rotates, the measurement does not change. The second segment has been applied to control the form of the surfaces.
- **Flap surface**: the function is to facilitate the operation of rotation of the upper hook. It has been used a multiple single segment profile tolerance (figure 6.19). The first segment has been used to locate the flap surfaces, fixed together thanks to the double arrow symbol, with respect to the ABC coordinate system. The second segment has been applied to control the form of the surfaces.

Moreover, a general profile and position tolerance have been applied to all the surfaces.

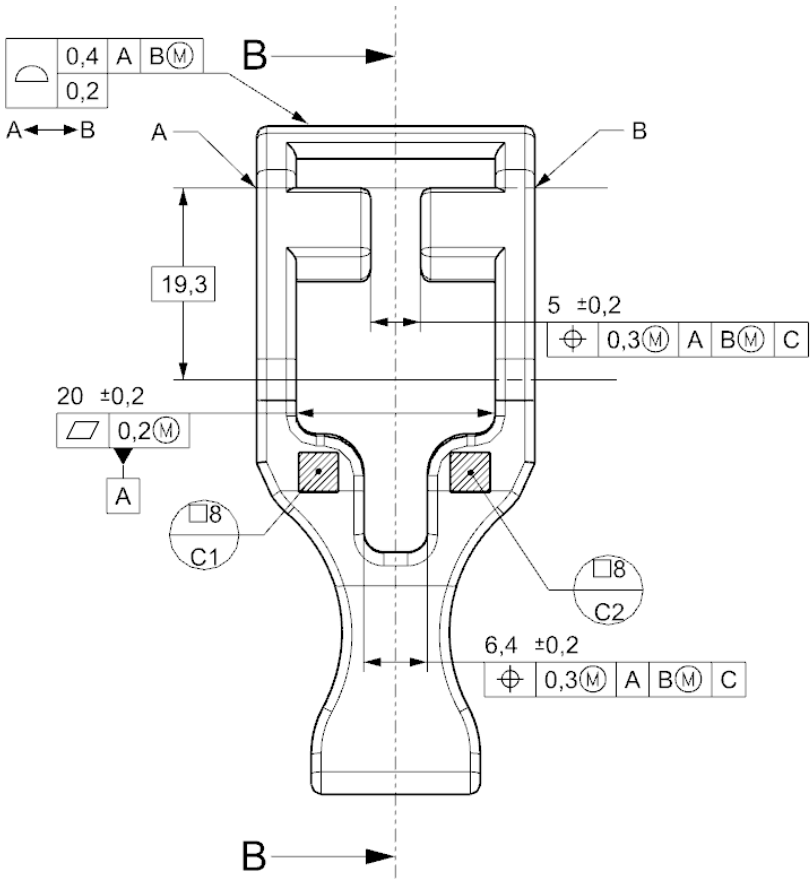


Figure 6.18

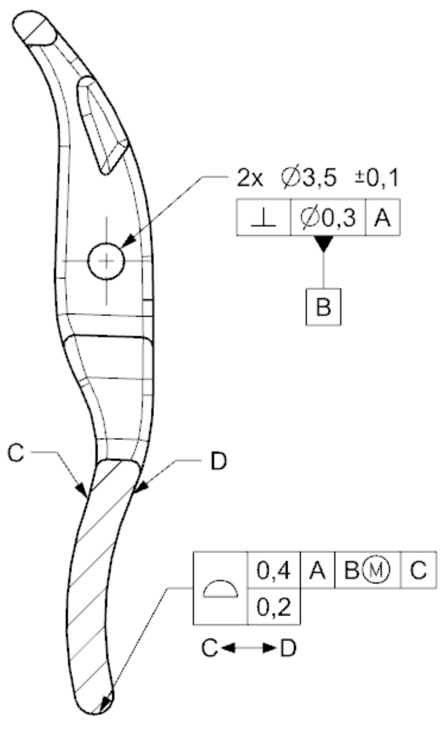


Figure 6.19

7 Functional gage overview

Functional gages are essentially realized and utilized to verify and validate a component, once the production phase is finished.

A functional gage is built starting from the simulated datums, that represents the perfect geometry counterpart of the datum features. Simulated datums allow to extract the datums, establish the datum reference frame (DRF) and to finally transfer the coordinate system to the real component.

7.1 Gage Dimensioning

Upon the fixture base it has been placed:

- **Gage slot-shape block**: it is the physical datum simulator of the datum A. The block section dimensions have been defined by using the upper support drafting: it has been realized at the slot maximum material conditions, considering the presence of a form tolerance (figure 7.1).

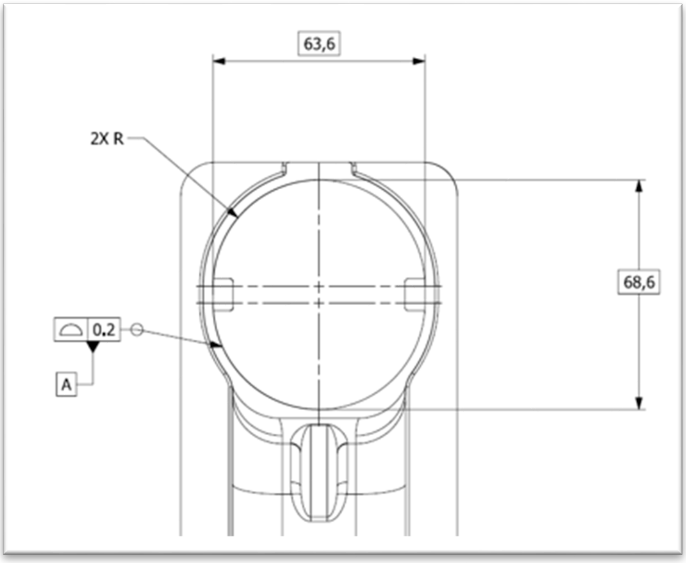
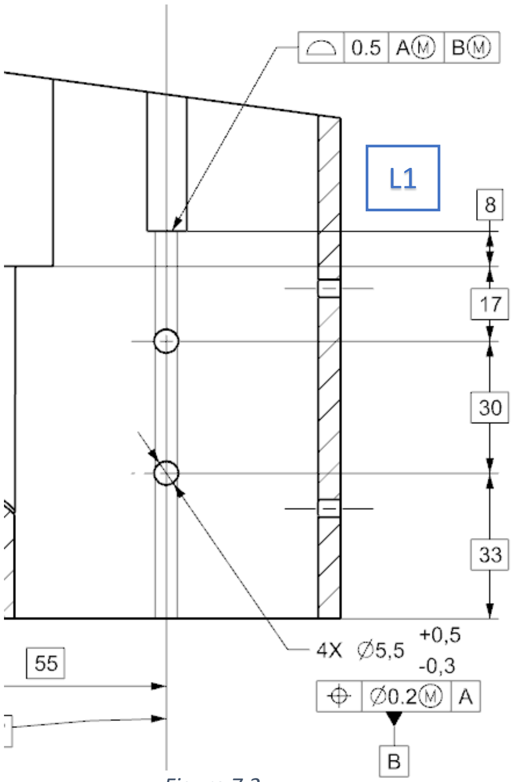


Figure 7.1

WIDTH= 63,6-2*0,1 = 63,4mm

LENGHT = 68,6- 0,2*1 = 68,4mm

- **Battery guides slots**: the upper support presents two battery guides, and to fit them into the block two slots have been realized on it. They have been defined as the physical simulator of these features. A profile tolerance has been applied to the lower battery guides surfaces, that have been located with the basic dimension (figure 7.2).
  The other battery guides dimensions have been controlled by the location tolerances (figure 7.3). The block has been made to come out from the upper support slot hole and the height has been fixed at 130 mm.
- **Pins**: they are the real representation of the simulated datum B. They are made considering the holes at the MMC. Four holes have been realized on the gage block and their positions are indicated by the basic dimensions (figure 7.2).



PIN DIAMETER: 5,5-0,3-0,2 = 5mm

L1: 33+30+17+8-0,25 = 87,75mm

L2: 54-0,1-0,3 = 53,6 mm

L3: 9+0,1+0,3 = 9,4 mm

Figure 7.2

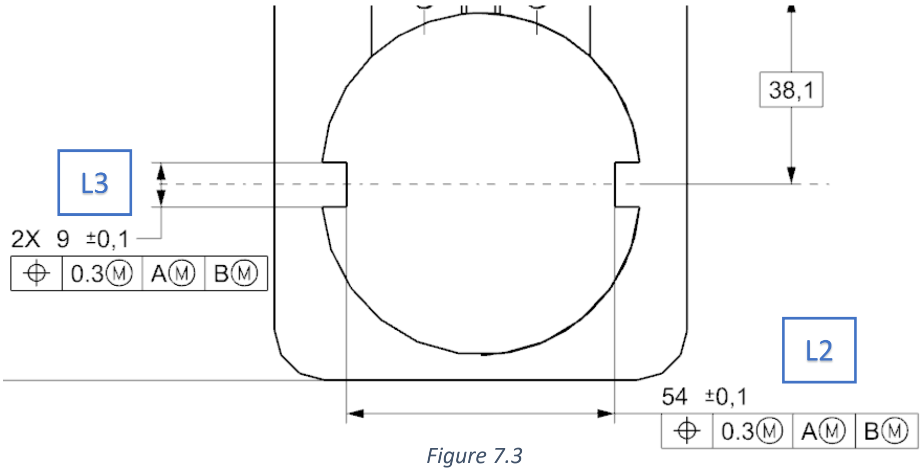


Figure 7.3

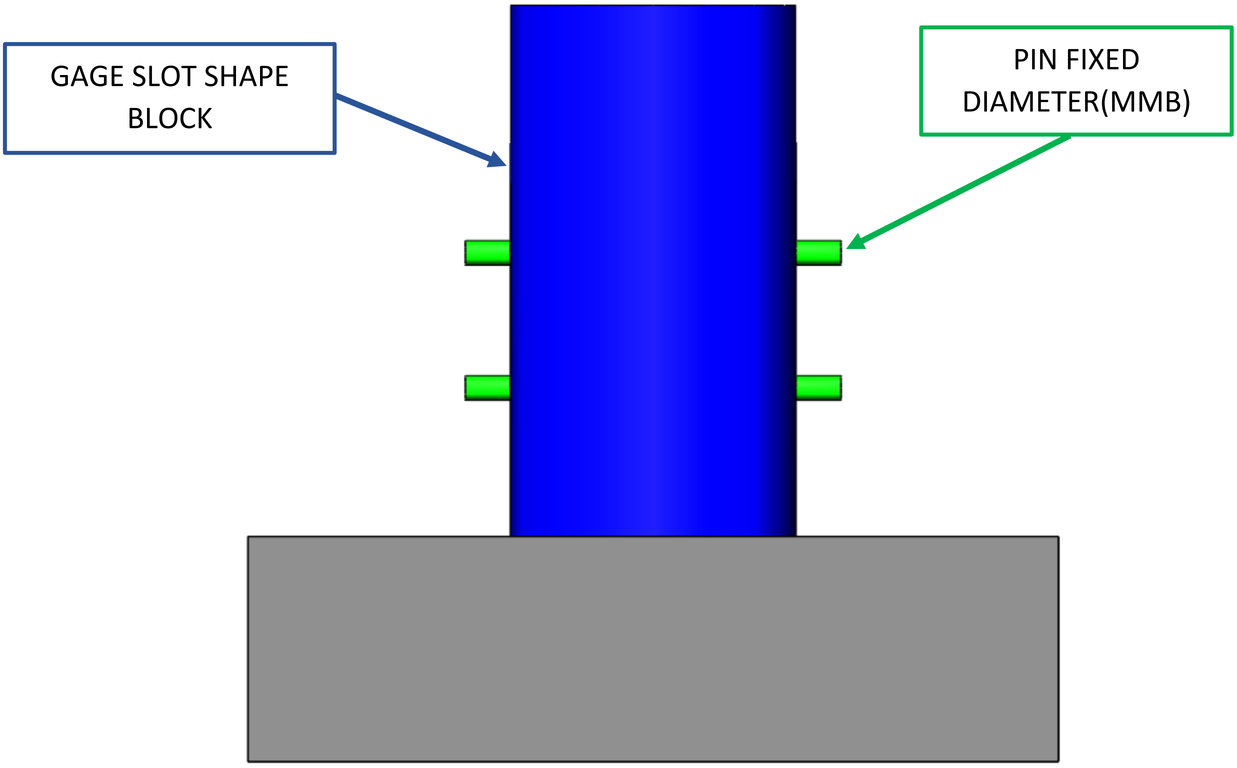


Figure 7.4

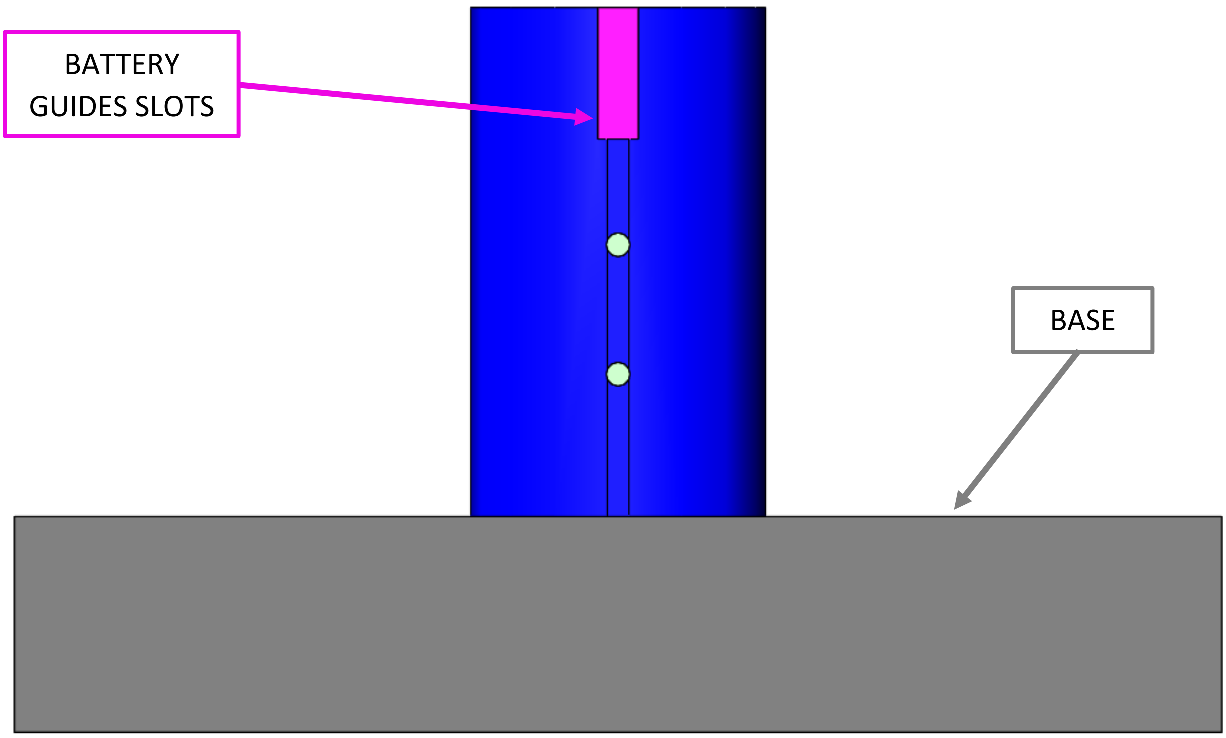


Figure 7.5

7.2 Upper support fixing sequence

The procedure to secure the upper support involves three actions (figure 7.6):

1. The block is fixed on the basement.
2. The Upper support is correctly mated to the block.
3. Pins are inserted, passing through the through-holes.

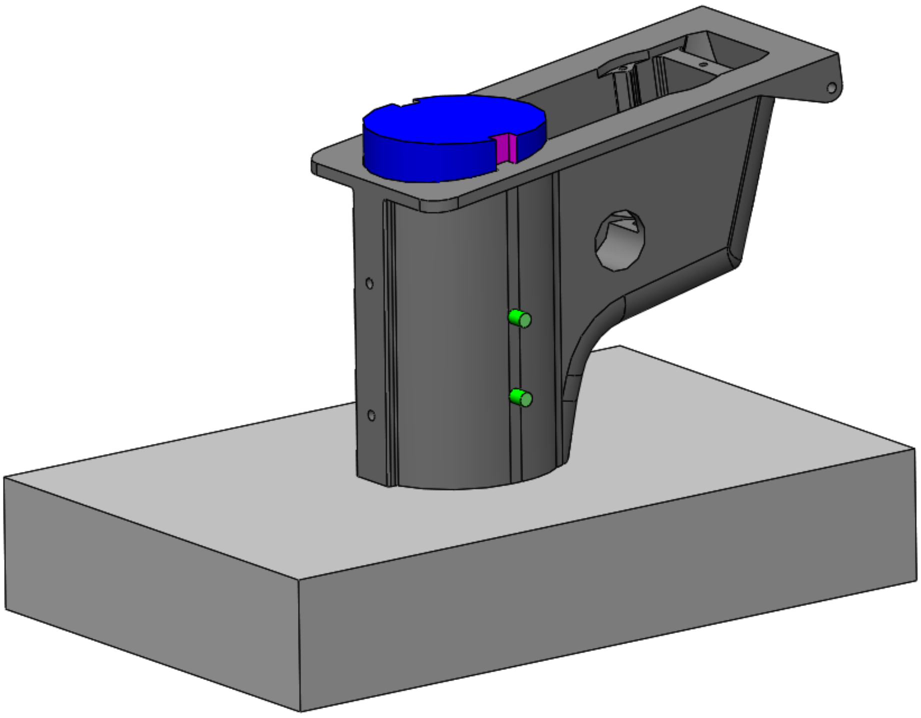


Figure 7.6

Once the component is set up, measures with the datum reference frame | AⓂ | BⓂ | can be inspected.

7.3 Handlebar holes control

The two holes have to ensure the correct assembly of the handlebar.

The functional requirement is not to inspect the alignment between the hole axis and the handlebar axis, but only to assure that the pin could fit inside the hole. Virtual condition boundaries must not be violated. The boundary is centered in axis true position and size at MMC-tolerance value. The maximum material virtual conditions are calculated subtracting, at the nominal diameter size, the value of the dimensional tolerance and of the location tolerance (bonus).

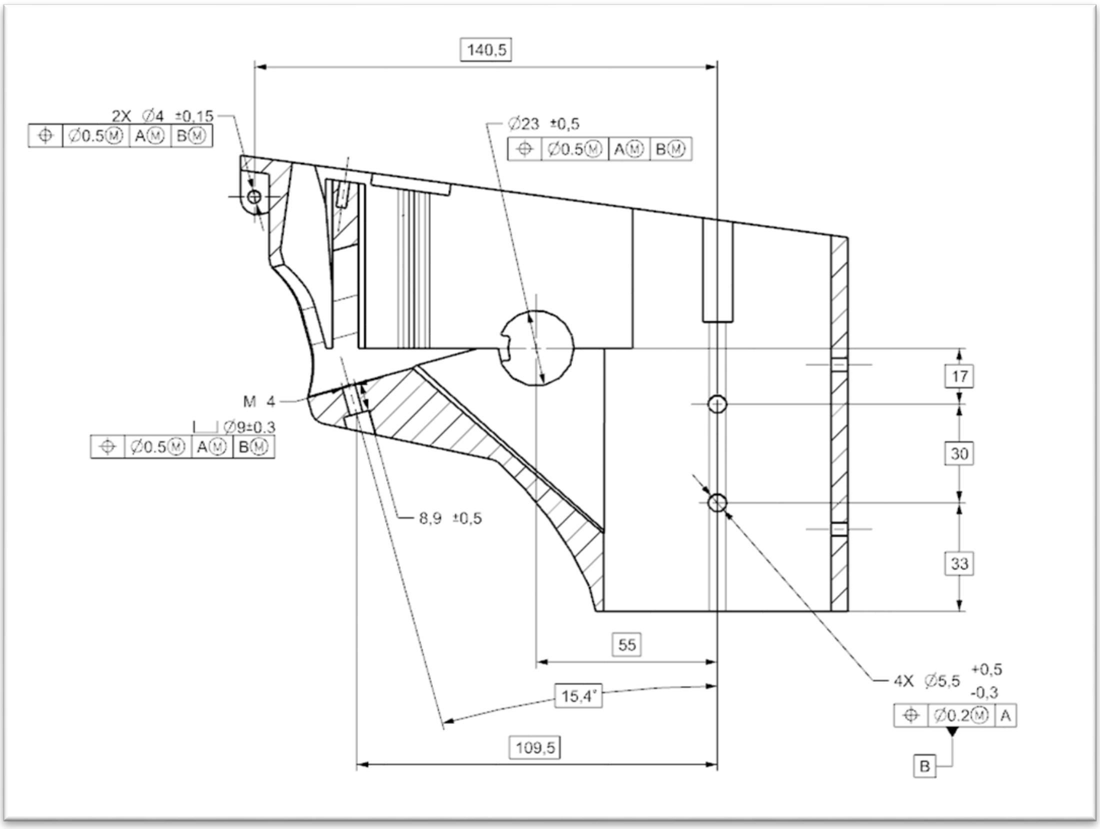


Figure 7.7

V.C HOLES = 23-0,5-0,5 = 22mm

The inspection of these holes has been carried out using a checking gage that permits the easy, repeatable and reproducible verification of the features over the time.

The checking gages are also called go/no gages. Their name is derived from two tests: the check involves the workpiece having to pass one test (go) and fail the other (no-go). In other words, it controls the dimension, the size of a features. This test is carried out inserting the checking gages by hands.

Another test can be done by considering only the go gage. In this case, the go gage dimensions are usually determined by considering the virtual dimensions. Unlike the previous test, turrets support the go gages and allow their correct positioning thanks to the basic dimensions.

The position of the handlebar holes has been controlled by a go gage (green) that has been made at the hole virtual condition, i.e. at a diameter of 22mm.

The presence of a small "tooth" has been also taken into account: it prevents the possible rotation of the handlebar. The tooth thickness as well as its concentric face has been controlled by using two position tolerances (figure 7.8). A housing, at the tooth virtual condition, has been realized on the go gage.

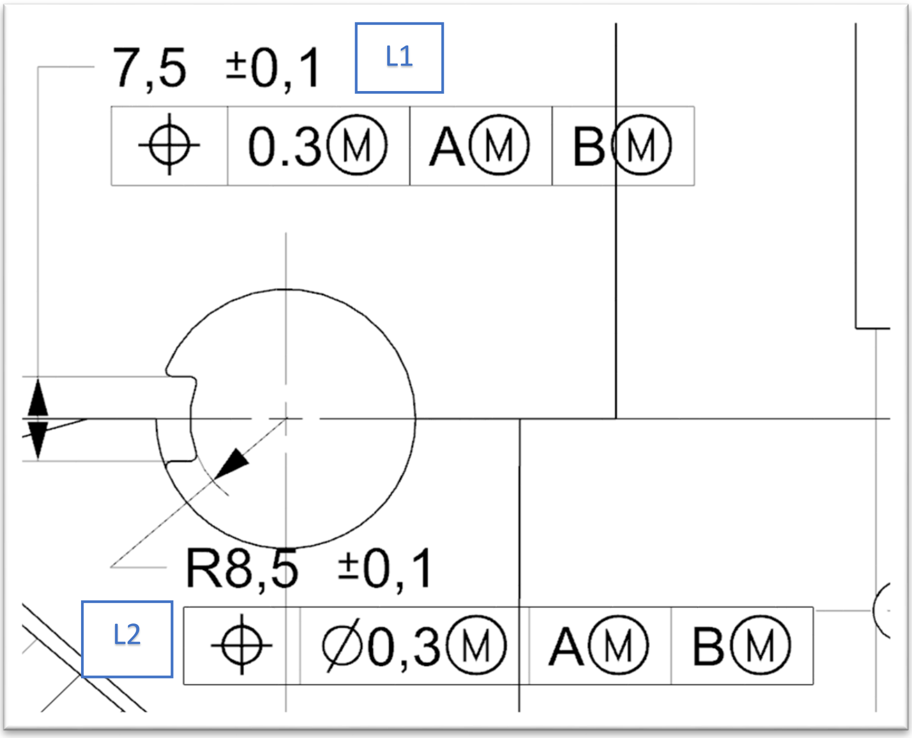


Figure 7.8

L1= 7,5+0,1+0,3 = 7,9mm

L2= 8,5-0,1-0,3 = 8,1mm

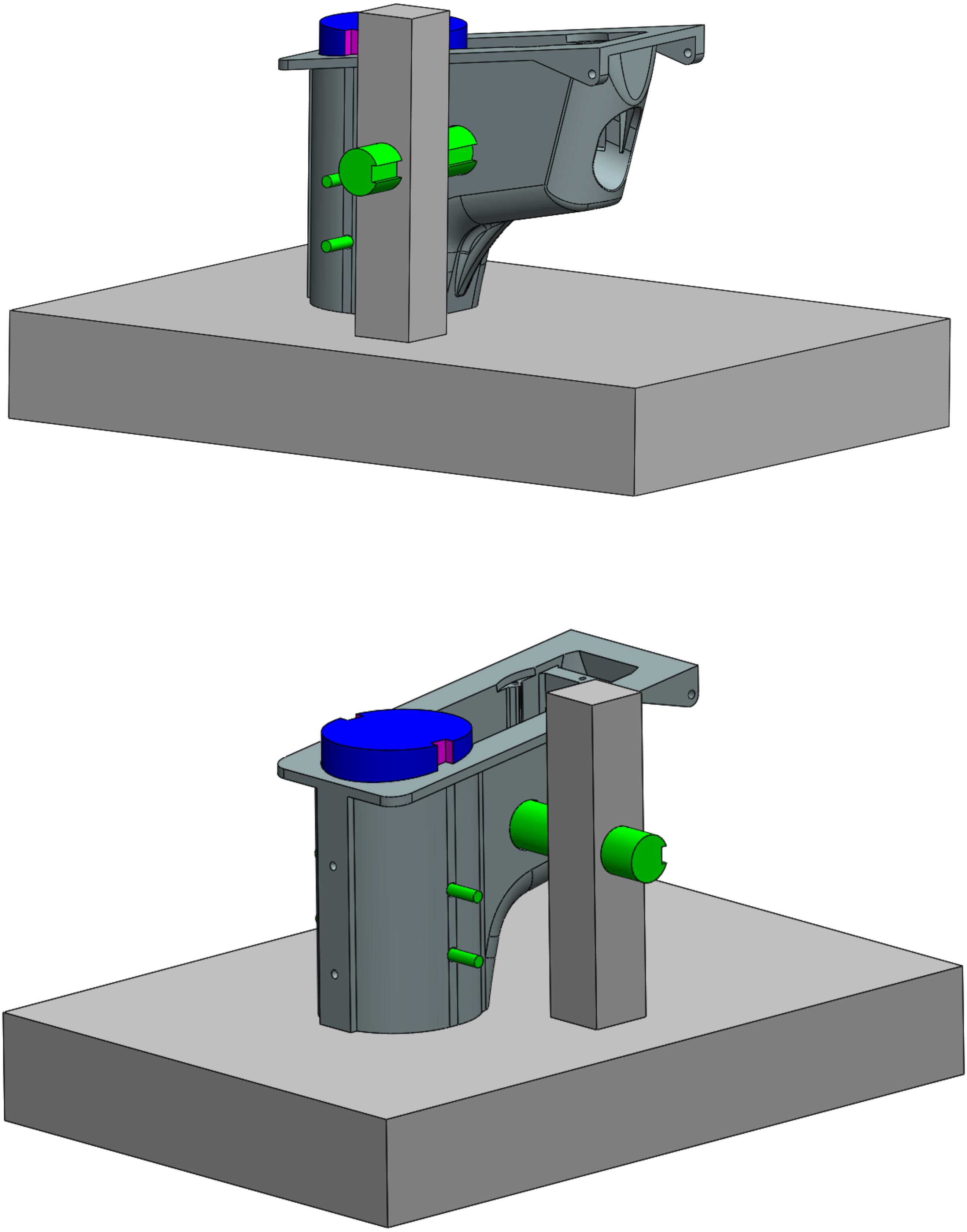


Figure 7.9

7.4 Headlight led control

An inspection of the led headlight slot hole has been made. The slot position tolerance has been controlled by a go gage at the dimensions of the slot virtual condition, previously calculated.

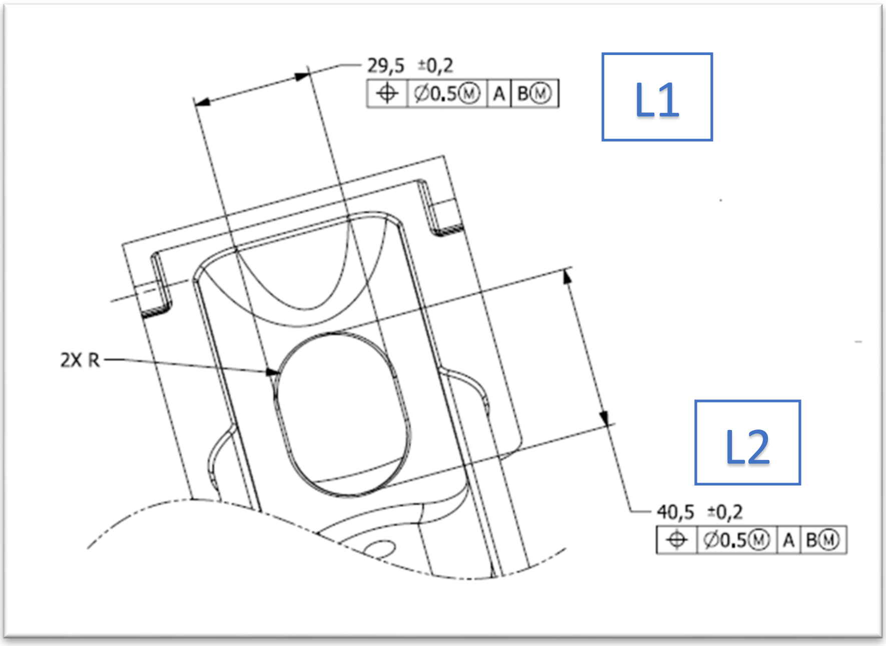


Figure 7.10

V.C L1 = 29,5-0,2-0,5 = 28,8 mm

V.C L2 = 40,5-0,2-0,5 = 39,8 mm

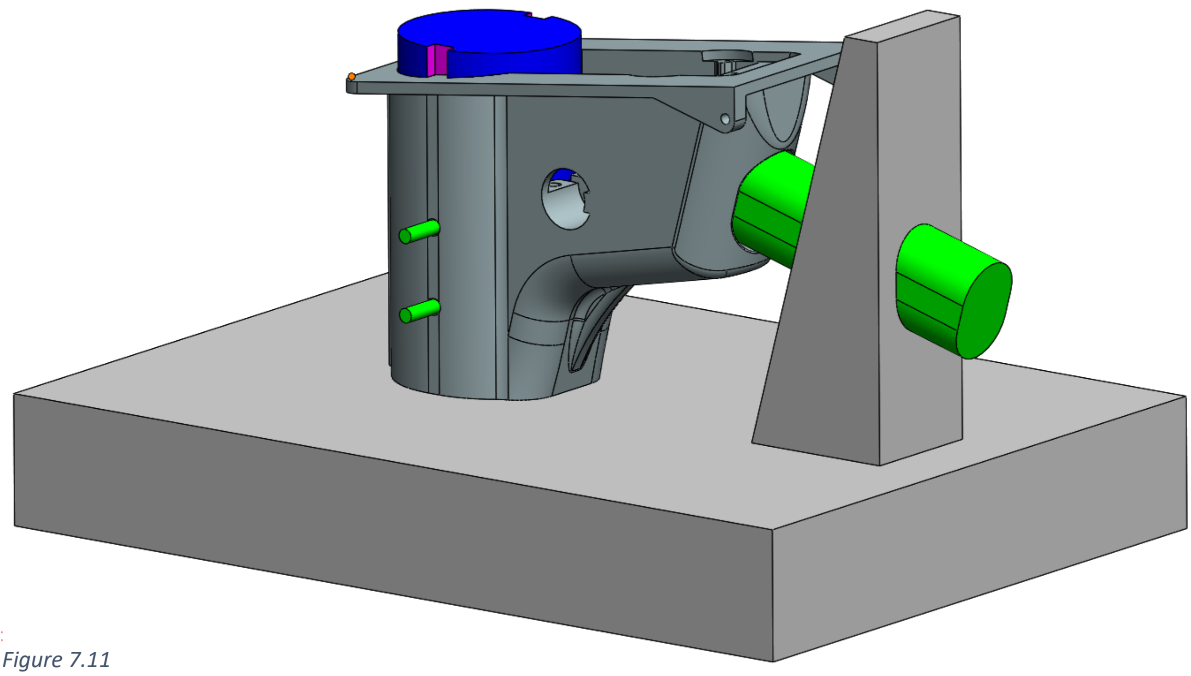


Figure 7.11

7.5 Connecting cover holes control

The pattern of two holes, which allow the connection of the cover on the upper support, has been controlled using the go gage test. A checking gage has been made at the hole virtual condition and placed at the correct position thanks to a turret and the basic dimensions.

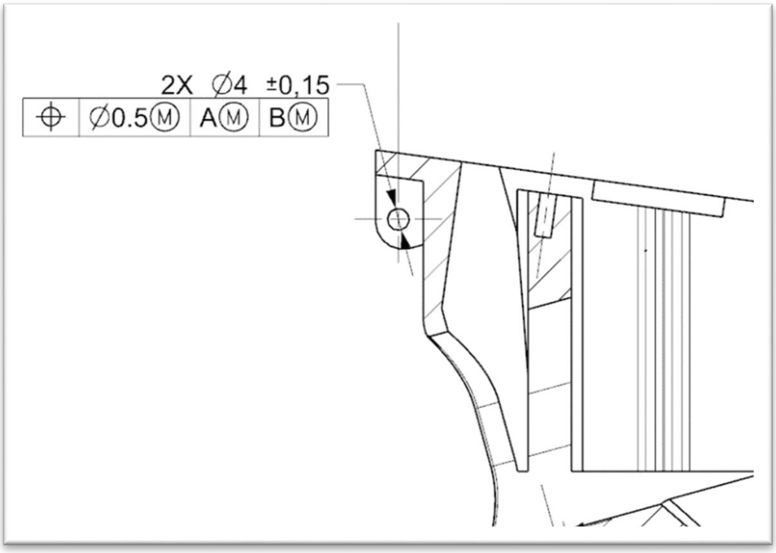


Figure 7.12

V.C HOLES = 4-0,15-0,5 = 3,35mm

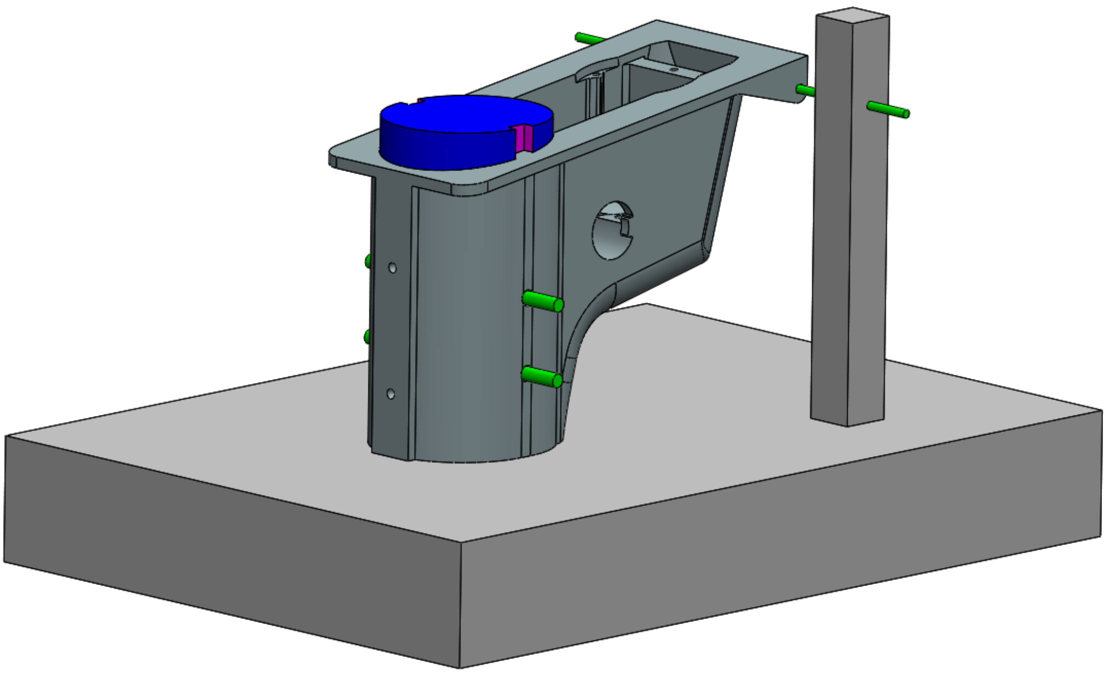


Figure 7.13

7.6 Fixing dashboard holes control

The control of the three display holes has been conducted differently. The presence of the datum C has to be taken into account.

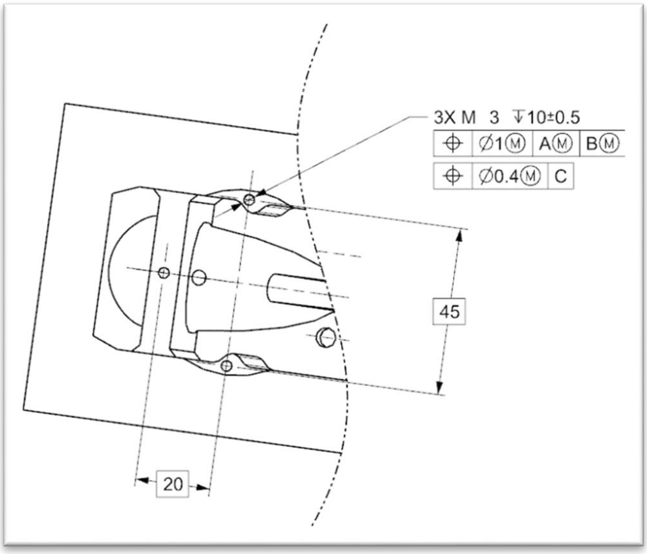


Figure 7.14

Two plates have been realized:

- A first plate with three thin cylinders has been used to control the location tolerance, with respect to the coordinate system AB.

  The cylinders represent the go gages made at the hole virtual condition, i.e. at a diameter of 2 mm (figure 7.15)

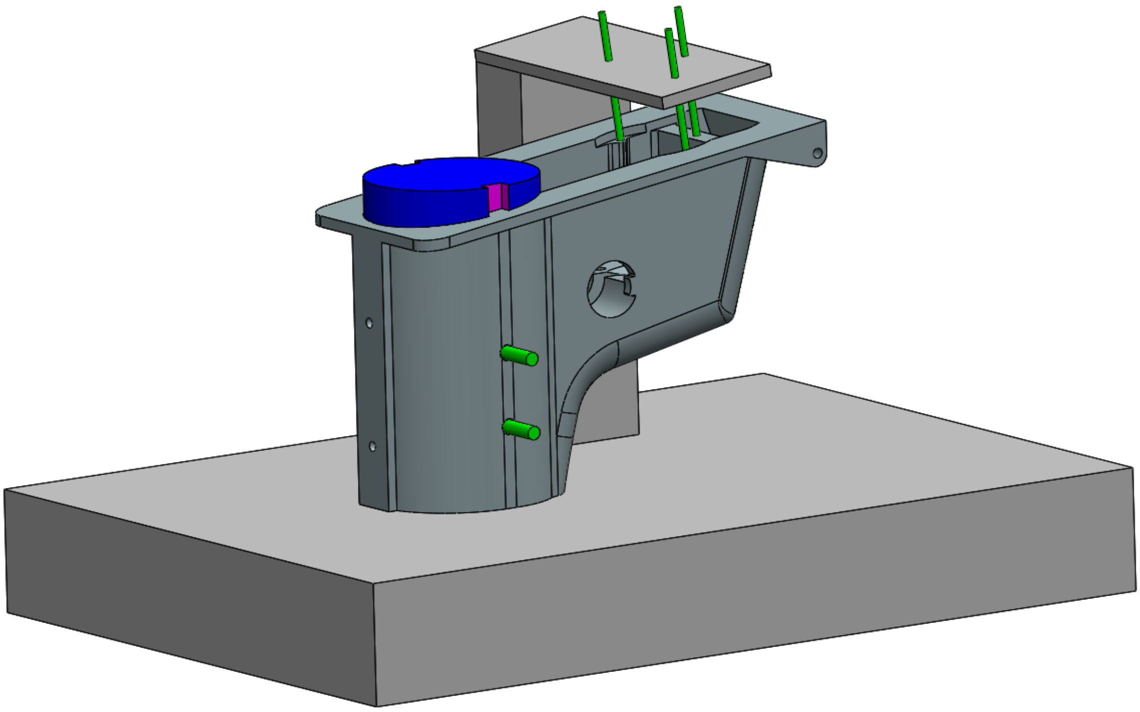


Figure 7.15

- A second plate has been placed, by hands, in order to encounter the inclined surface (figure 7.16). This operation has allowed the simulation of the datum C. Three cylinder have been realized: they control the interaxis between the holes. Because of the smaller tolerance, these cylinders have a bigger diameter than the cylinders of the first plate.
  The go gage has been made at the hole virtual condition, i.e. at a diameter of 2,6 mm.

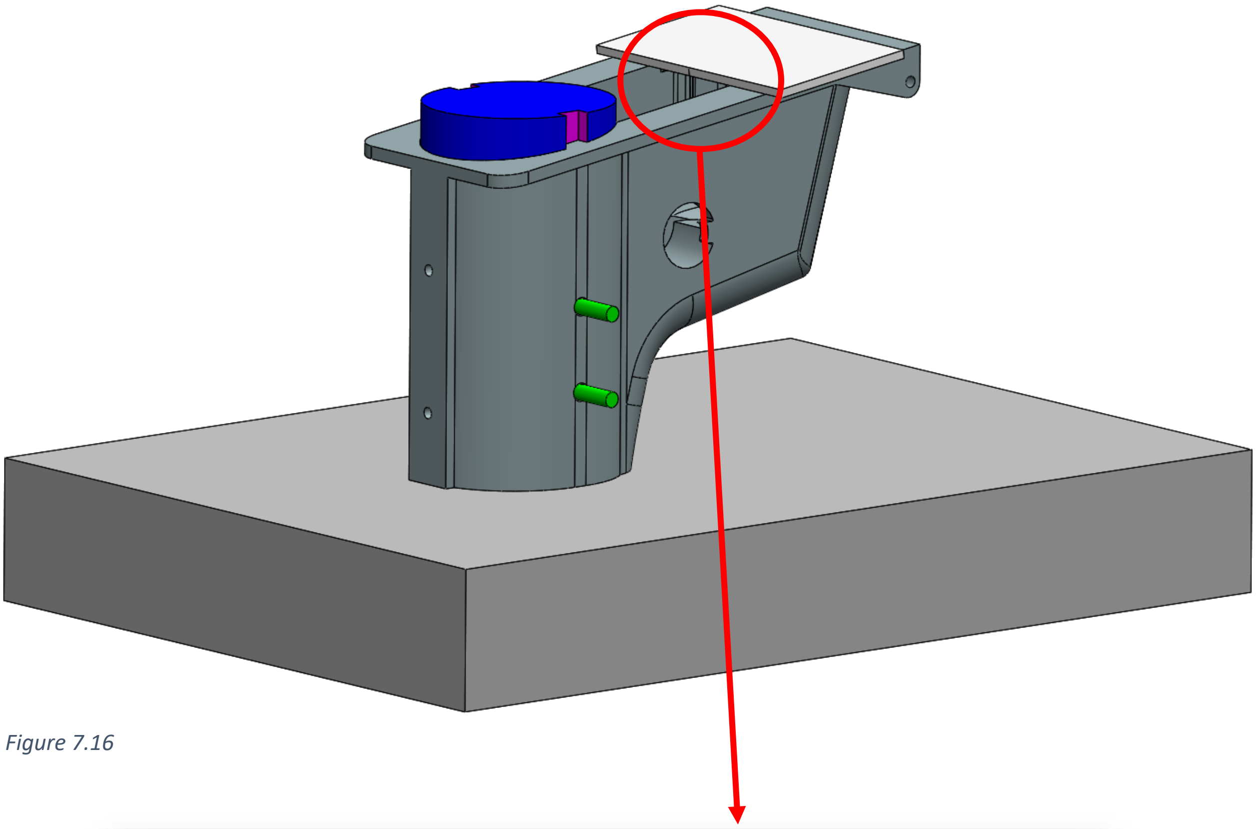


Figure 7.16

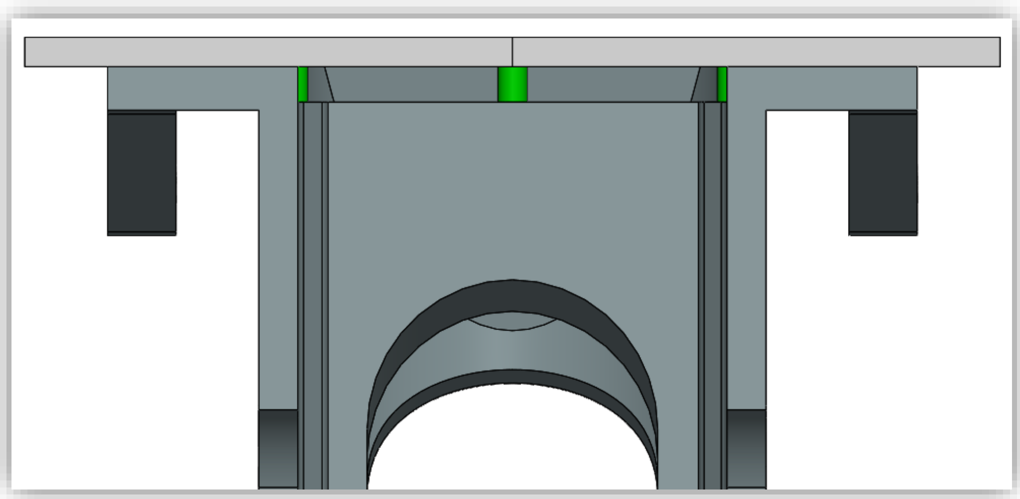


Figure 7.17

A control of the profile tolerance, applied to the inclined surface (the datum feature C), has been also carried out. It has been placed, on a face of a turret, a red strip as thick as the profile tolerance value, i.e. of 0,8mm. The strip is inclined as the surface concerned and is centered at its nominal position. Looking the component, from a lateral perspective, it is possible to understand if the tolerance is respected or not: if the inclined surface profile covers the strip, it means that the tolerance is violated (figure 7.19).

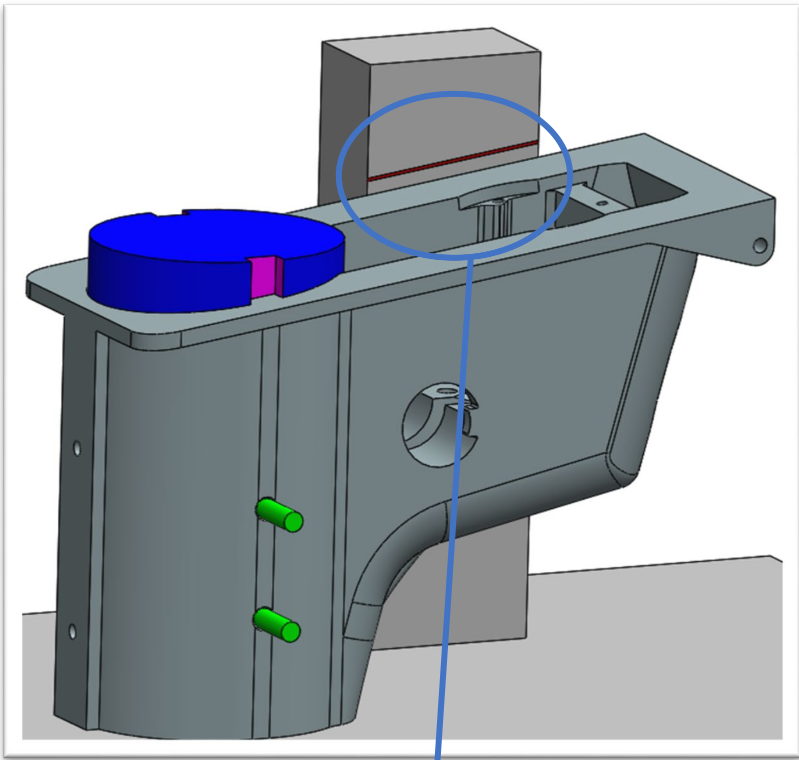


Figure 7.19

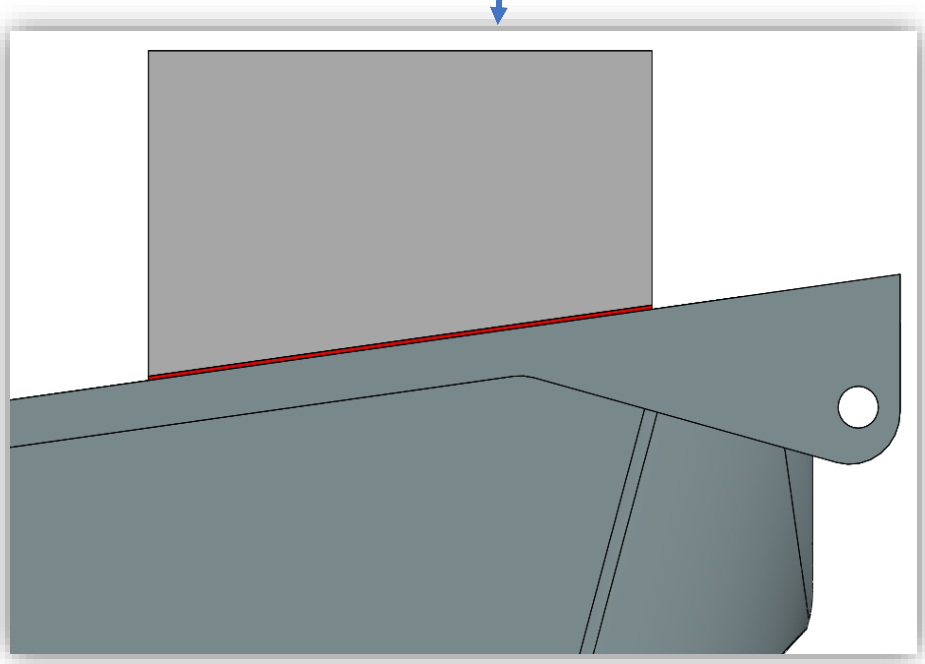


Figure 7.18

7.7 Final gage fixture

The final gage fixture includes the basement, the gage slot shape block and the turrets, that support the checking gages. The upper support can be now placed in its nominal position and all the control described can be carried out (figure 7.20).

The gage fixture can be realized in additive manufacturing, for an approximative check of the upper support features or when pieces present wide tolerances. The manufacture in series of the gage fixture and consequently the verification of numerous pieces requires, instead, the usage of specific material in order to minimize the errors. The size of the caliber must be at least one order of magnitude smaller than the smallest tolerance present, guaranteeing minimal tolerance errors. For these reasons almost every caliber has the basement made of aluminum, turrets made of epoxy or aluminum and the checking gage made of aluminum or steel.

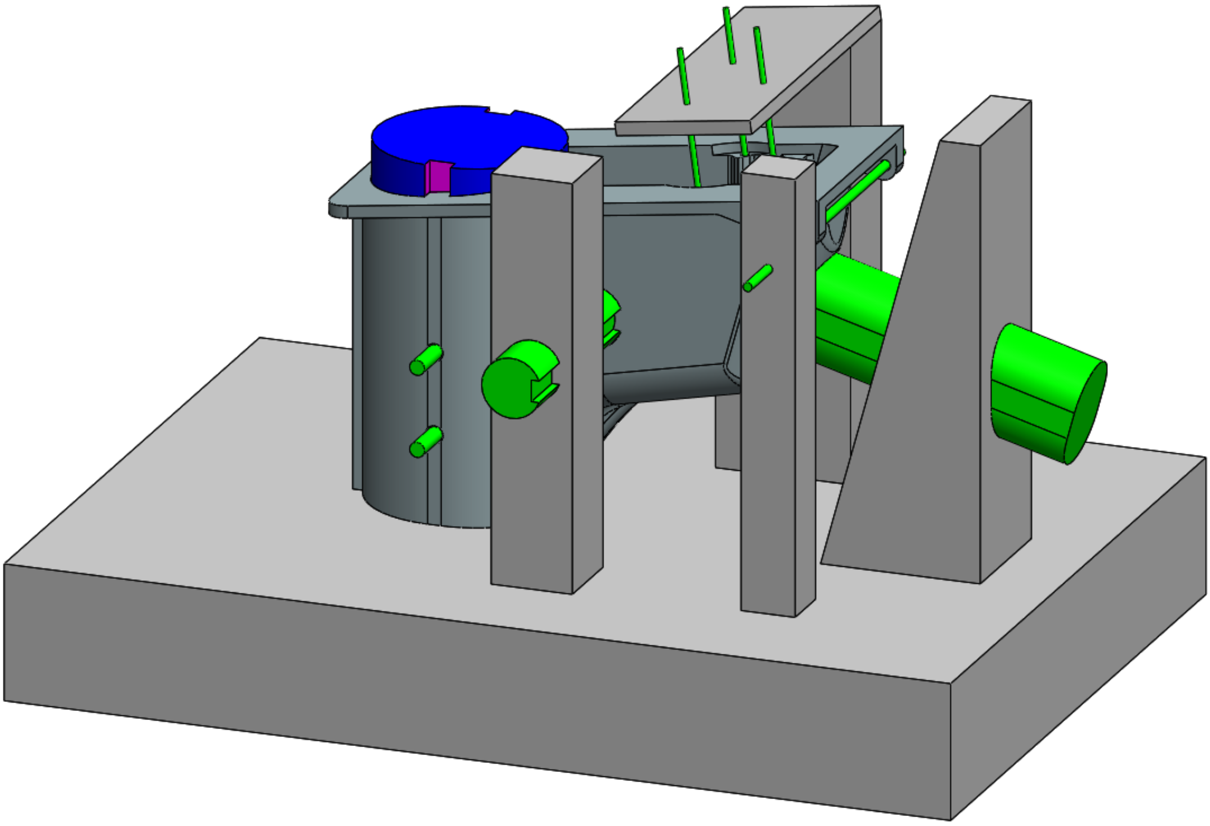


Figure 7.20

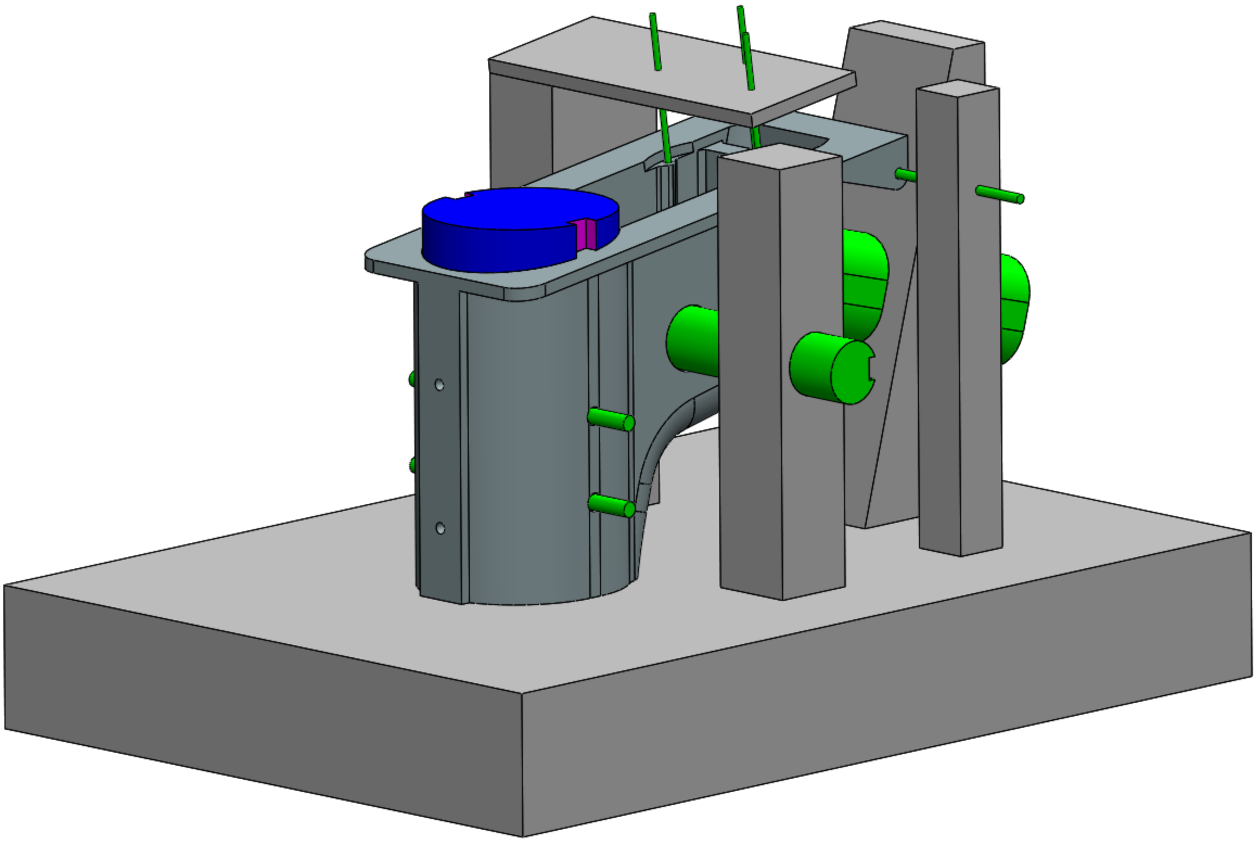


Figure 7.21

8 Conclusion

The thesis has displayed all the activities that have been carried out with the start-up TO.TEM and the contribution made in order to fulfill the objectives required.

The thesis has managed to advance an ongoing design activity for the e-scooter Lynx handlebar frame. All the steps, from the concept phase to the production one, have been analyzed and completed. A great amount of time has been spent on the design changes: unlike what usually happens on a university environment, where tasks or activities assigned are guided and present a precise result, the requests and the objectives given by the company were constantly changing. Internal dynamics were the main reasons, like the interactions with the commercial side or with the team members belonging to other branch of the engineering, like the electrical and the material or the mechanical production ones.

The kinematic analysis has shown the difficulty of having a commercial component that has to be adapted to a specific design. It has also demonstrated that sometimes the usage of custom components is required in order to allow the proper functionality of the e-scooter.

The work done has also exhibit the importance of the drafting and the correct use of the geometric tolerances to guarantee the correct assembly and functionality, to indicate the manufacturing objectives, to reduce the production costs and to transform the inspection in a reliable process with determined steps to follow.

The final task has been the creation of the gage fixture as a tool, already set to be given in the hands of the suppliers, in order to control and verify the component.