D4.1.

A SET OF DESIGN FOR MANUFACTURING & ASSEMBLY GUIDELINES

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EXECUTIVE SUMMARY

Nowadays, it is a common practice that consumer products are designed such that assembly and manufacturing are facilitated by deploying Design for Manufacture and Assembly (DFMA), principles. Such an approach typically results in several benefits, including:

- Minimising the total number of parts and tools used during production
- Designing parts that are easy to align and combine
- Reducing costly fastening operations
- Reducing defects incurred due to scrap, rejects, rework and correction
- Minimising overproduction by correctly estimating total number of parts required
- Reducing the number of part drawings that need to be designed and approved
- Reducing the waiting period of people and material due to less parts
- Reducing the cost of inventory

The cumulative effects of these advantages can lead to up to 50% reduction in number of parts, leading to 37% cost reduction and 50% improvement in time-to-market [1]. The most important guideline that the designers should follow to achieve the highest benefit is to reduce the number of parts inside an artefact as much as possible. This can be accomplished by combining two or more functions in a single component. Other guidelines include [2]:

- Make use of standardised components.
- Simplify the design.
- Make components symmetrical to eliminate reorientation. If symmetry cannot be achieved, exaggerate asymmetry features to facilitate orientating the parts.
- Design a base component to reduce the need for additional jigs and fixtures to hold the assembly.
- Design parts to be self-aligning and self-locating.
- Introduce guides and tapers to facilitate assembly.
- Avoid component features that induce tangling or nesting.
- Remove sharp corners from components so that they are guided into their correct position during assembly.
- Avoid expensive and time-consuming fastening operations.
- Design a vertically stacked product in order to achieve simpler top-down assemblies.
- Minimise tolerance and surface finish demands on components so that production costs are reduced.
- Design product for ease of packing.
- Ensure disassembly is equally practicable as assembly.
- Develop the design to contain as many identical components as possible.

It is recommended that the designer becomes familiar with these principles early in the design process in order to explore solutions that ultimately will be easier to develop. In order to illustrate the practical applicability of the DFMA guidelines in the context of the PRIME-VR2

project, three state-of-the-art VR controllers, the HTC Vive, Oculus Touch and PlayStation Move controllers, were opened and analysed. This analysis is accompanied with information on the technology that the controllers use, X-Ray images to show how the internal components reside in the closed controllers, and a product breakdown structure showing a top-down tree of how each component or sub-assembly is related to the end-products.

Using these DFMA guidelines as criteria to compare the three VR controllers, the PlayStation Move controller resulted to be the simplest controller. Sony, the Original Equipment Manufacturer (OEM) of this device, managed to keep production costs down which is reflected in the retail price of the controller. It is concluded that the greater the extend of applying these DFMA guidelines, the higher is the probability of designing a device consisting of the minimum number of parts with the most efficient assembly sequence.

BACKGROUND

The PRIME-VR2 design team needs to get familiar with the best practices in the field of product development. This document reviews a set of DFMA (*Design for Manufacture and Assembly*) guidelines that are used in this field. By specifically reviewing current state of the art Virtual Reality (VR) controllers, this document provides a sound background of how DFMA principles can be actually applied. This document should be used to support the work being carried out in Work Packages 3 and 5 such that the output from these work packages will eventually result in better designs.

Once a number of concept designs are available, including all the internal components that will be used, the team should combine efforts to iteratively review the functional requirements and analyse the required parts based on their function. The team should aim to have a number of standard parts and make use of the least number of parts. Following these steps, the design should be analysed in terms of quality (mistake proofing), handling (grasp and orientation) and insertion (locate and secure) opportunities in the design. The best concept should be selected and iteratively repeat the analysis until no further improvements can be done. Ultimately this will result in the detailed designs of the devices that have an optimal assembly sequence and features that permit the production at minimum cost.

1 INTRODUCTION

End-user products are typically composed of smaller modules or components, all assembled together to form a product that has one or more functions. Each sub-component should be important for the correct operation. The form of a product is determined by many factors, including the purpose, material and the manufacturing process. The DFMA philosophy which stands for Design for Manufacturing and Assembly, urges designers to think not just about the form, material, function and the manufacturing method but also in the assembly process, either manually or automatically, required to gradually build the end product.

In the field of product development, DFMA should be embraced by designers because it guides them to simplify the structure of components and their assembly procedure, reduce the number of components and control related costs. Product development can be broadly divided into a three-step process which starts from the design (blueprints) and progresses to the assembly of the manufactured parts, as shown in Figure 1. Design is the stage where the materials, shapes, and tolerances of the individual parts of a product are defined. It is a process where simple sketches are transformed into detailed technical part drawings, usually in 3D CAD (Computer-Aided Design) models. If DFMA aspects are not taken into consideration during the design stage, the manufacturing and assembly stage will eventually get delayed due to design optimization iterations. Decisions taken late in the design process come at higher costs. It is widely known that careful considerations of manufacturing and assembly early in the design process can reduce the total costs by over 70% [3].

Figure 1: Process of Product Development

1.1. Main objective and goal

The objectives of this document are to highlight DFMA guidelines which have been developed in the field of product development throughout the years. Where possible, these guidelines will be analysed with respect to three current state-of-the-art VR controllers, which are the HTC Vive controller, Oculus Touch controller and PlayStation Move controller.

The goal is to learn how DfMA guidelines have been adopted into these successful controllers and see how they can be adapted into the controllers that will be developed in the PRIME-VR2 project. This document is meant to be read by technical people familiar to the field of product design.

1.2. Methodology

The methodology adopted in this report is shown in Figure 2. The first step was to establish relevant guidelines related to the development of a product by researching literature that concerns DFMA. The pioneers in the field of DfMA, Boothroyd et. al (2011) have been working on this topic for over four decades and they have written books and developed software to help designers produce better products [3]. Therefore, most of knowledge has been generated by these authors.

Figure 2: Methodology adopted to analyse DFMA principles in existing controllers

In the second step, three VR controllers were torn down and in the third step the design of these VR controllers was analysed with respect to the DFMA guidelines to further grasp the meaning of the guidelines.

1.3. Terminology

Table 1 contains a list of frequently used terms and their description.

Table 1: Terminology

Term	***Description***
2K Moulding	An injection moulding process that injects two materials in one mould.
Boss	A boss is a cylindrical design feature that is used as a mounting fixture, location point, reinforcement feature or spacer.
Datum	A datum is a reference point, surface, or axis on an object against which measurements are made
DFA	Design For Assembly - a systematic procedure to maximise the use of components in the design of a product.
DFM	Design For Manufacture - a systematic procedure to maximise the use of manufacturing processes in the design of parts.
DFMA	Design For Manufacture and Assembly - a systematic procedure for analysing a design from the perspective of assembly processes.

Table 1: Terminology

Term	Description
Fillet	A fillet is a corner on the outside that has been rounded.
Knurled Insert	Knurled insert or threaded insert or threaded bushing, is a fastener element that is inserted into an object to add a threaded hole.
Lip/groove	A lip or a groove is a design feature in plastics that guide two parts to be assembled together, providing some degree of sealing.
Overmoulding	An injection moulding process that forces a thermoplastic/elastomer onto a secondary material (metal) to form a bond.
PCBA	Printed Circuit Board Assembly
Rib	Ribs are thin extensions that run perpendicular from a wall or plane. These are used to increase the strength of a part.
Tolerance	A tolerance is the stated permissible variation in the size of a dimension and is the difference between the upper and lower acceptable limits.

2 DESIGN FOR MANUFACTURING AND ASSEMBLY

2.1. What is DFMA?

The term ‘to manufacture’ refers to the manufacturing of each distinct component making up a product whereas the term ‘to assemble’ concerns the joining of parts to form the complete product. Boothroyd et al. explain that “design for manufacture (or DFM) means the design for the ease of manufacture of the collection of parts that form the product after assembly and design for assembly (or DFA) means the design of the product for the ease of assembly. Design for manufacture and assembly (DFMA) is a combination of DFA and DFM” [3]. Therefore, the aim of DFMA is to simplify the product structure in order to minimise manufacturing and assembly cost.

Having appropriate knowledge about manufacturing processes is crucial because the design should reflect the strengths and limitations of the process to be used. The aim of DFM is to maximise the use of manufacturing processes in the design of a component such that to reduce the overall cost of production. For example, if a mould tool requires to have an undercut for a feature, it is better to include it rather than employing another (post) process to achieve the required form. On the other hand, having a clear understanding of the role of each component in a product is as important because there are several costs related to them. The aim of DFA is to maximise the use of sub-components and to minimise the part count and assembly cost.

The combined consideration of DFM and DFA results in more efficient and effective solutions. This is done by maximising the use of the manufacturing process whilst reducing the number of components needed to be assembled together.

2.2. Benefits of DFMA

The highest benefits can be obtained if the DFMA principles are implemented at the beginning of the design process. Consumers always look for the most reliable product at the right price. Since the market is highly competitive, manufacturers try to find ways in reducing manufacturing costs without compromising on the quality and user experience of the product. The DFMA philosophy aims in producing simpler and more reliable products which are less expensive to manufacture and assemble [4]. By adopting the DFMA methodology, organisations tend to reduce materials, overheads, and labour related costs, reporting "up to 50% reduction in the number of parts, leading to 37% cost reduction and 50% improvement in time-to-market" [1]. However, the drawback of such an approach is that sometimes, in order to reduce the number of components and assembly steps, one results in more complex, non-modular and non-standard parts [4].

Antos (2016) lists the following advantages when applying the DFMA philosophy when designing for new products [1]:

- Be able to compare multiple designs of potential solutions
- Estimate the expenses and difficulties of a particular choice
- Minimize the total number of parts and tools used during production
- Design parts that are easy to align and combine
- Reduce costly fastening operations
- Reduce defects incurred due to scrap, rejects, rework and correction
- Minimize overproduction by correctly estimating total number of parts required
- Reduce the number of part drawings that need to be designed and approved
- Reduce the waiting period of people and material due to less parts
- Reduce the cost of inventory
- Shorten the development cycles
- Minimize excess processing
- Possibly, reducing number of suppliers

For this reason, designers need to become familiar with the guidelines mentioned in Section 3 and understand how these translate into real design practices. Section 4 provides ample examples of these design practices.

2.3. The process of DFMA

Figure 3 shows the typical steps of DFMA. The first step is to conduct DFA which will lead to the realisation of a simpler product structure and an economic material and processes selection by optimising **initial designs** for part count and assembly. DFA can start when a model/drawing/prototype of the end product together with a tentative assembly sequence are available. The DFA process should ideally go through a number of iterations to simplify the design as much as possible. Then, the best design is analysed for DFM in order to minimize the manufacturing costs. This step is performed on the **final design** and is driven by cost reduction by optimising the design for production readiness. The methodology can be utilised on new products or for the improvement of old designs.

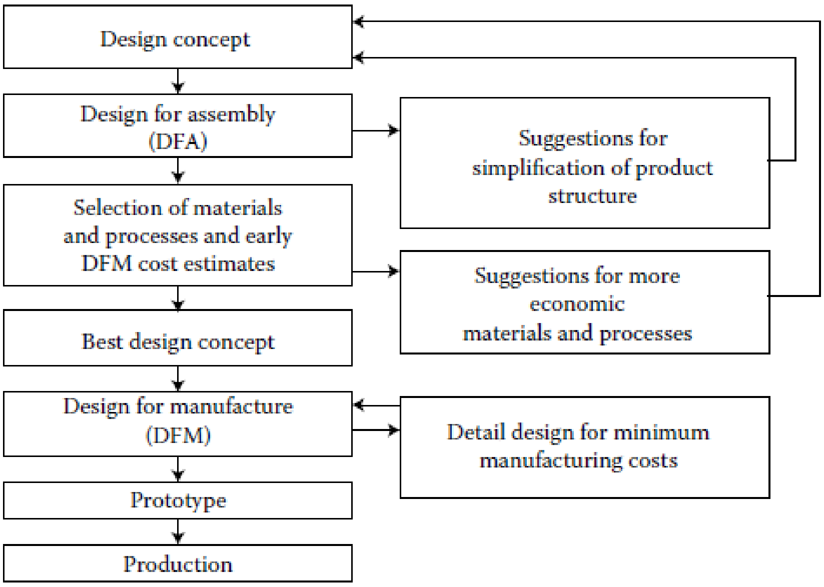


Figure 3: Typical Steps taken in the DFMA methodology. [3]

Edwards (2002) write that the DFMA procedure is heavily supported by the knowledge and experience that a designer, or company as a whole, has, "in fact, some DFMA is done purely through experience, with little or no support from a systematic procedure or formal guidelines" [4]. Boothroyd et al. have also developed software that performed DFMA analysis [3]. This software is able to assess the cost of a design using cost indices. For a detailed DFMA process and cost metrics calculation the reader is referred to *Product Design for Manufacture and Assembly* [3].

3 DESIGN FOR ASSEMBLY – RULES AND GUIDELINES

As the name implies, DFMA guidelines are statements in the form of general rules of thumb, a set of principles, or tips that have been derived from past knowledge and experience, that provide good design practice.

Various guidelines obtained from literature are detailed in the next sections [1-4], [6]. These have been selected with a priori knowledge that the current VR controllers, similar to many consumer products are made from plastics. These sections are divided based on the steps of the DFMA methodology. One can note that some guidelines are repeated because they apply for both assembly and manufacturing.

Table 2 details a list of guidelines that relate to the design of parts in relation to the assembly process. The first six guidelines are general guidelines which a designer needs to keep in mind during conceptualization. The subsequent guidelines can be used for the design improvement after an initial concept design with the relative components and assembly sequence are available. These encourage the designer to determine whether any of the sub-components are relevant to its function and how assembly can be facilitated by the analysis of handling and insertion tasks with respect to mistake proofing.

Table 2: Design guidelines for Assembly

Code	Guideline
DFAG_01	Review your design, redesign and iterate as necessary to simply assembly.
DFAG_02	Design for the most suitable production process with economic assembly as a goal.
DFAG_03	Plan the design with the intent of production.
DFAG_04	Where possible, avoid manual processing of parts and components at the design stage.
DFAG_05	Where possible, avoid manual processing of parts and components post manufacturing.
DFAG_06	Where possible, plan for automatic assembly since parts that can be automatically assembled are easier to handle and assemble manually. This may also result in a cheaper assembly cost, but one expects larger costs to repair.
DFAG_07	Where possible, make use of standardised components.
DFAG_08	Reduce the number of parts by combining two or more functions (multi-functional) in a single component. A reduction in part count keeps the number of assemblies to a minimum whilst reducing assembly costs.
DFAG_09	Simplify the design and aim for an economy of construction such as interchangeable components.
DFAG_10	Where possible, make components symmetrical about the axis of insertion to eliminate reorientation and make assembly easier. If not, exaggerate asymmetry features, as the component in Figure 4 (b), to facilitate orientating the parts. The component shown in Figure 4 (a) is more difficult to position.

(a) *(b)*

Figure 4: (a) Slightly asymmetrical (b) Pronounced asymmetrical [3].

DFAG_11 Design a base component to reduce the need for additional jigs and fixtures to hold the assembly (Figure 5).

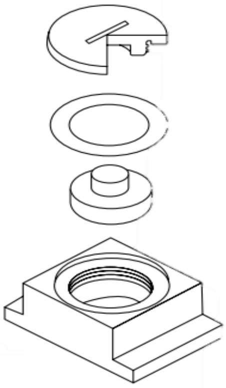
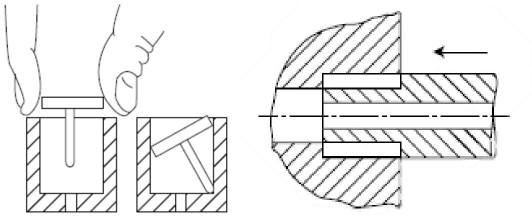
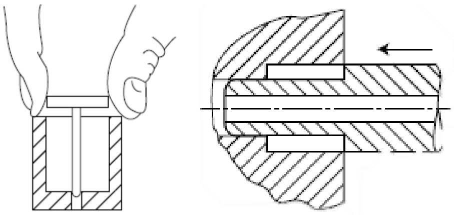


Figure 5: A base housing on which other components are assembled [3].

DFAG_12 Design parts to be self-aligning and self-locating. Figure 6 (a) is showing two examples of how difficult it is to insert parts due to short pins/shafts while Figure 6 (b) shows the improved design of the parts to facilitate insertion.



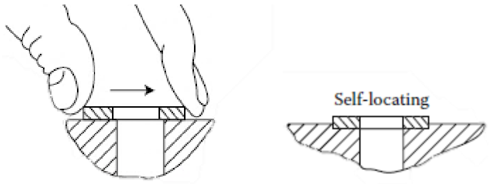
(a)



(b)

Figure 6: Inserting parts [3].

The provision of self-locating features such as pins and slots can avoid holding down the component for alignment, as shown in Figure 7.



(a) *(b)*

Figure 7: (a) Part with no self-locating feature (b) Part with self-locating feature [3].

DFAG_13 Introduce guides and tapers to facilitate assembly

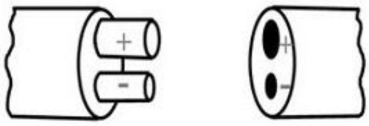


Figure 8: Pins acting as guide

DFAG_14 Avoid component features that induce tangling or nesting. Figure 9 illustrates various examples.

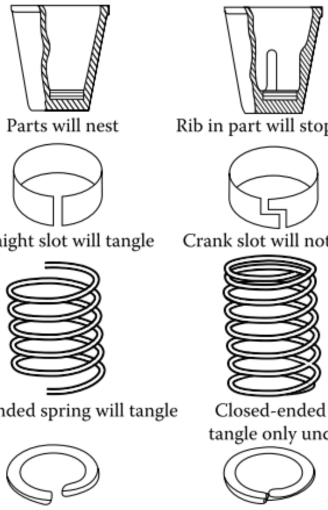


Figure 9: Examples of how nesting and tangling can be avoided by simple design changes [3].

DFAG_15 Remove sharp corners from components so that they are guided into their correct position during assembly, as shown in Figure 10.

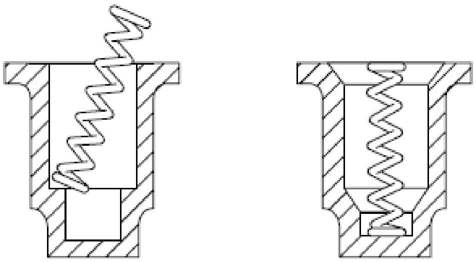


Figure 10: Provision of chamfers to allow easy insertion [3].

DFAG_16 Avoid expensive and time-consuming fastening operations. Self-fastening operations such as snap fitting is better than plastic bending, which is better than riveting, which is better than screwing. If you cannot eliminate fasteners, standardise them but minimize the number of different sizes and types of bolts used. This reduces inventory and eliminates confusion during assembly.

Screws used in the automatic assembly should have their end tapered in order to self-centre in a hole. As shown in Figure 11, cone point and oval point screws have the best self-centring performance. These two types of screws along with dog point type are suggested to be the only screws used in automatic assembly [3].

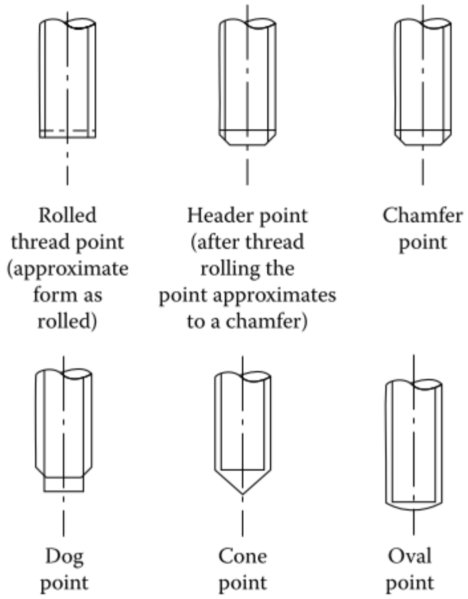


Figure 11: Various forms of screw points [3].

DFAG_17 Design a vertically stacked product in order to achieve simpler top-down assemblies, as illustrated in Figure 12.

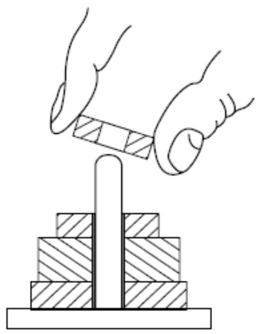


Figure 12: Vertical assembly [3].

Furthermore, a vertical assembly also helps during the movement (indexing) of the table of an automatic assembly line. This means that while the table is turning (indexing), parts and subassemblies will remain in their cavities (work carrier) due to the force of gravity. Tapered dowels can guide and secure base parts on the work carrier whilst a flat horizontal surface positioned at the centre of gravity of a rounded part can stabilise a base part in a work carrier.

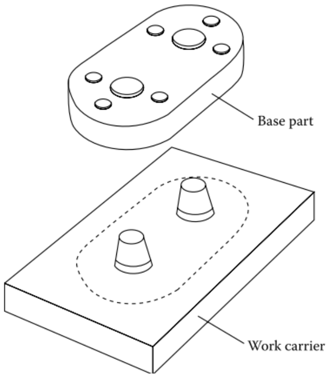


Figure 13: A base part on top of work carrier [3].

DFAG_18 Simplify handling of components. Avoid parts that are very small, thin, heavy, fragile, flexible, sharp, slippery and sticky. Furthermore, eliminate the necessity for using more than one hand, optical magnification or mechanical assistance. Figure 14 illustrates examples of parts with bad handling properties.

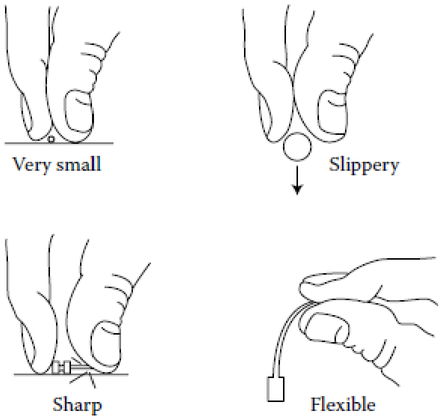


Figure 14: Examples of parts affecting part handling [3].

DFAG_19 Minimising tolerance and surface finish demand on components so that production costs are reduced. Do not specify high precision fits or tolerances tighter than essential for correct functioning. High tolerances are more demanding in the manufacturing process. Figure 15 shows an example of a part with high tolerances. Minimal changes to the manufacturing parameters might cause the part's dimensions to exceed its upper limits and as illustrated in Figure 15 (a), parts can get jammed due to high tolerances. By relaxing the tolerances a bit, one might still achieve the same function as shown in Figure 15 (b)

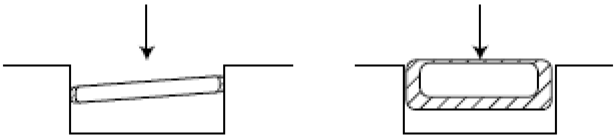


Figure 15: Tight tolerance [3].

DFAG_20	Designs should be made for ease of packing.
DFAG_21	Make sure disassembly is equally practicable as assembly.
DFAG_22	Develop the design to contain as many identical components as possible.
DFAG_23	Introduce datum systems whenever a high degree of accuracy is necessary in the location of interchangeable components.

3.1. Design guidelines concerning materials

Table 3 tabulates guidelines related to the choice of material and the expertise that a designer has. In this research project, since auxetic structures will be produced through Additive Manufacturing technology, one will require experimentation both with different materials, design and manufacturing parameters to understand the best specifications. Therefore, these guidelines might not be relevant during the design process.

Table 3: Design guidelines on Materials

Code	**Guideline**
DGfM_01	Make use of the cheapest materials and methods of fabrication that are suitable for the design.
DGfM_02	Do not specify materials that are hard to obtain unless there are no alternative.
DGfM_03	Consider the use of well tried and tested components and materials, rather than new and uncertain ones in order to achieve a high level of reliability.
DGfM_04	Consider using economical order quantities.
DGfM_05	Consider the use of stock items when you need only a small quantity of components.

4 DESIGN FOR ASSEMBLY – STATE-OF-THE-ART VIRTUAL REALITY CONTROLLERS

4.1. HTC VIVE VR Controller

The HTC Vive tracking technology works thanks to two light emitting boxes, called Lighthouses, installed above the player's height, inclined down and opposite to each other in a 4.5mx4.5m play area. Rather than using a camera, these Lighthouses contain an array of LEDs which flash synchronously at a rate of 60 pulses per second [5]. This light is sensed by the infrared (IR) sensors in the Headset and controllers and a stopwatch is triggered in them. Then the Lighthouses fire two consecutive IR laser beams which sweep (scan) the play area horizontally and vertically. These laser sweeps are detected by each IR sensor at different times due to their pattern of position in the devices and because of the speed of the angular motion of the laser swipe. By comparing the timing of when each sensor in the headset and controller is triggered, positions and orientation of the hands and head are calculated with high accuracy and low latency [8].

4.1.1. Terminology

Figure 16 shows some of the terminology used in the Product Breakdown Structure of the HTC Vive controller.

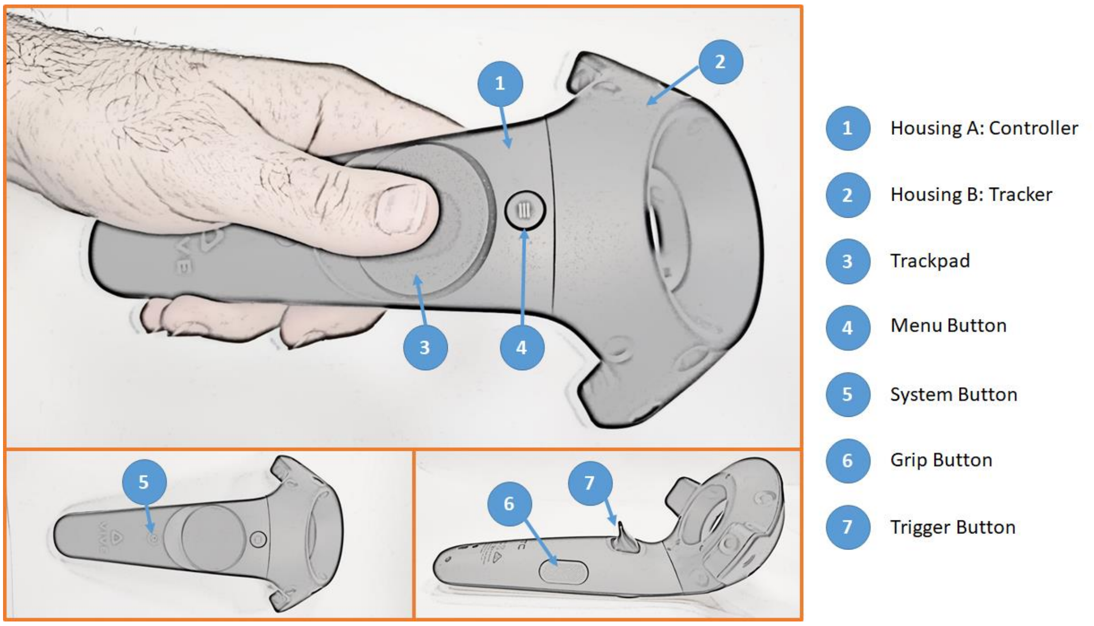
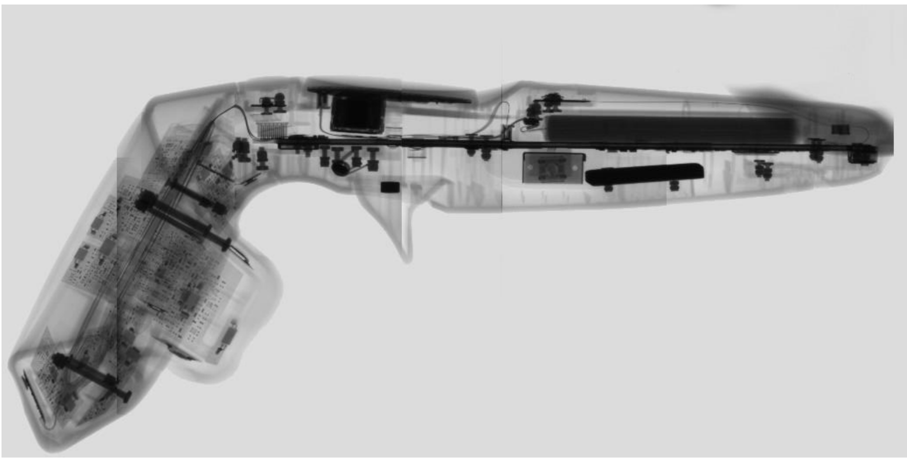


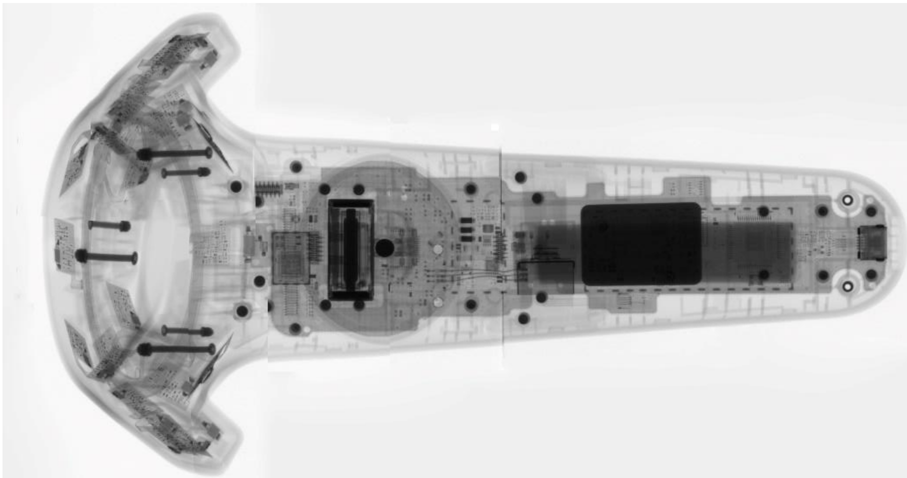
Figure 16: HTC Vive Controller terminology

4.1.2. X-Ray Images

Figure 17 shows X-Ray images of the HTC Vive controller from a side and plan elevation. Metal components are shown in black whilst plastics can be seen in various shades of gray. The housing, electronics and fasteners of the Vive can be clearly distinguished. Note that each elevation is made up of several merged images.



(a)



(b)

Figure 17: X-Ray images of the HTC Vive (a) Side elevation (b) Plan elevation

4.1.3. Product Breakdown Structure

The HTC Vive controller was disassembled in order to understand the components inside it and the assembly design features it has. The Product Breakdown Structure is shown in Figure 18. Each part was assigned a name related to its function.

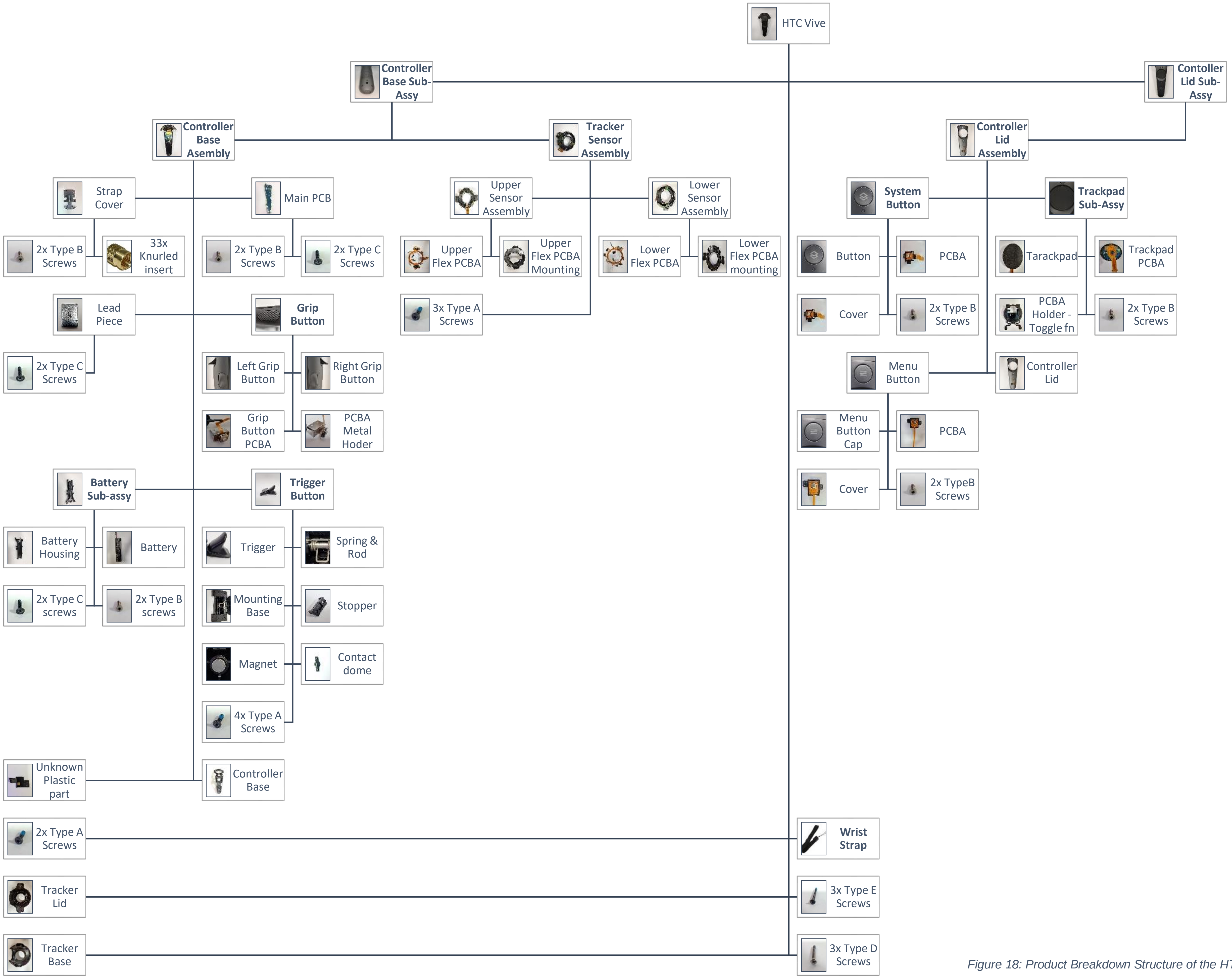


Figure 18: Product Breakdown Structure of the HTC Vive Controller

4.1.4. DFMA guidelines review based on the HTC Vive Controller

General comments

There are at least 40 different parts on the HTC Vive Controller, including screws, buttons, and various flexible PCBAs. If the wrist strap is further decomposed into other parts, the total number of parts increases to 44. This part count does not include all the electronic components assembled on the PCBs. Each PCBA and Flex PCBA is considered as one component.

VR systems in the market require two controllers, one in each hand. Like the PlayStation Move controller, the Vive controller is ambidextrous, meaning that the left and right controllers are identical.

Further to the parts highlighted in the Product Breakdown Structure, the Vive controller uses double-sided bonding tape, namely, to attach the IR-Sensor circuits on the upper and lower flex PCBAs Mountings, and some components on the PCBs. In total, there are 24 infrared sensors in each controller, including, 33 screws, various daughterboards (with flexible PCBAs), PCBAs holders and buttons.

Figure 19: Teardown of the PS Move VR controller

The Vive controller has one of the most reliable tracking system, with an ergonomic design and minimal amount of input buttons thanks to the multi-function trackpad and dual-stage trigger. It is quite large as a VR controller and this is mainly because the tracking system is in front of the controller. This creates some bending moments which are countered by a piece of metal positioned towards the bottom part of the controller as can be seen by the black block on the X-Ray image in Figure 17. The controller makes use of expensive technology and a single controller costs around €218 [source: BestWare].

Material & Manufacturing Process

The controller has been designed to be produced in high volumes. The rigid plastic parts are produced through Injection Moulding since all the features of the parts are in the direction in which the mould moves. Each plastic part's material is marked on the plastic. Almost all plastic parts have the letters "PC" embossed on them, which means that their material is Polycarbonate as can be seen in Figure 20. The inner Tracker parts, that is, the Upper and Lower IR Sensor Mounting Frames are made from ABS since their marking is ABS. Furthermore, the cavity number of the mould in which they were produced is also shown adjacent to the Material marking, as shown in Figure 20. It is presumed that all plastic parts were produced in 4-cavity moulds since the largest cavity number marking found was "#4".

Figure 20: Material and Cavity number marking on a plastic part

The wall thickness of the controller 2mm and several ribs are used to strengthen the parts along wide areas as can be seen in Figure 21.

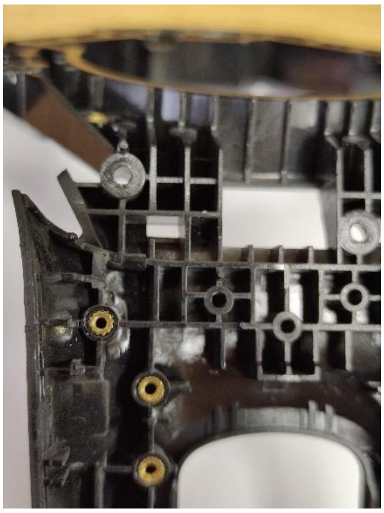


Figure 21: Ribs and bosses on the Base housing of the HTC Vive Controller

Like the Oculus Touch Controller Base housing, the Base housing of the Vive controller is quite complicated. Since the Base is practically the backbone for the Tracker module as shown in Figure 22, the tool has two parting lines: one for the controller part and one for the tracker part.

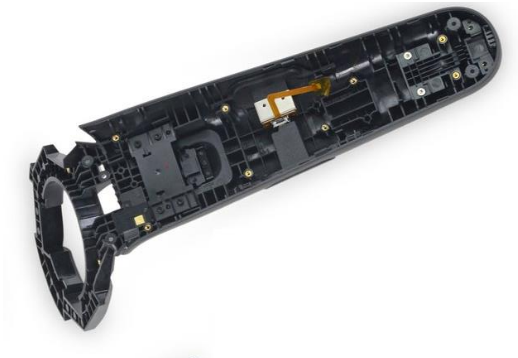


Figure 22: Base housing

It is important to note that both the Bases and Lids housings of the controller and tracker modules are insert moulded with knurled inserts. Figure 21 shows three such knurled inserts, brass inserts that provide a thread for bolts, embedded in the plastic. Furthermore, the controllers Base housing is overmoulded with a thin layer of a rubber-like material that gives a comfortable grip of the controller (Figure 23).

Figure 23: Base housing overmoulded with a rubber-like material

It was also noticed that parts with an 'A-surface', that is parts that are visible to the end user have a different finish that the surfaces which are hidden inside the switch. For instance, the Trigger button shown in Figure 24 has a matte finish A-surface and an normal surface on the inside. Most probably, the mould's cavity (tool) was surface treated to produce a different finish.

(a) (b)

Figure 24: Trigger button sub-assembly (a) inside surface (b) A-surface

The Tracker Base and Lid housings contain infrared sensing cavities (filters) which guide incoming light towards the inner sensors. The filters are shown in and are attached after moulding and painting.

Figure 25: The Tracker's Base and Lid housings. IR filters show purple against light.

It can also be noted that ejector pins locations have been carefully distributed all over the parts, some of which were integrated with the ribs. Figure 26 (a) shows ribs with circular sections around the perimeter of the tracker have been used as features on which ejector pins can push the Base housing (Tracker area) out from the moulding tool.

(a) *(b)*

Figure 26: (a) Circular ribs to support ejection (b) underside of the circular ribs

These circular ribs are similar to bosses but without holes. Figure 26 (b) shows the underside of the same part where there are circular grooves underneath the circular ribs. These were either purposely designed on the part to avoid sinking due to thick material or actual sink marks. Figure 27. shows how a sink mark is created due to a bad DFM [7].

Buttons and light diffusers are assembled on the controller's Lid housing using spherical heat staking. This is a process by which protruding positioning pins are melted over another part to secure it in place and prevent them from dislodging as shown in Figure 27 (a), a rubber button, and in Figure 27 (b), a light diffusion panel. Guidelines for Ultrasonic (Heat) Staking can be found in section 2 of Chapter 5 of *Designing Plastic Parts for Assembly* [7].

(a) *(b)*

Figure 27: Heat staking on a (a) rubber button and (b) a light diffusion panel.

Note that all buttons apart from the Trackpad button are 2K moulded, where a plastic base is covered with-rubber to improve the haptics of the button**.** For instance, Figure 28 is showing the Grip button where the A-surface and the little flaps on the side are rubber and the base on which the tact switch is attached is hard plastic.

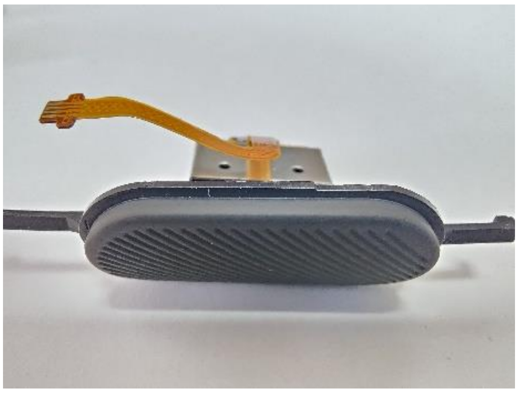


Figure 28: Right Grip button (with tact switch)

DFA Guideline	**Examples from the HTC Vive Controller**
DFAG_07: Make use of standardised components whenever possible.	All parts are designed purposely for the controller except for the several bolts and knurled inserts used to fasten different assemblies. These are discussed in DFAG_16.
DFAG_08: Reduce the number of parts by combining two or more functions in one component (multi-functional).	Figure 29 depicts an example of a part with combined purposes. As the name given to the part, the Trackpad PCBA holder, holds the PCBA under the Trackpad button. Instead of designing separate parts to achieve 8 directional movements, small wedges around the part and two wiggly arms manage to achieve the actuation mechanism.

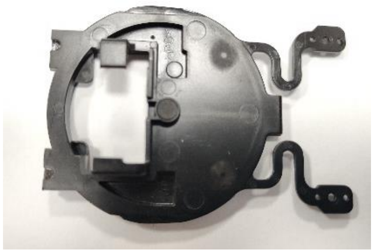


Figure 29: Trackpad PCBA Holder

In the example below, slots in the ribs of the housing (Figure 30) were designed to provide the assembly feature for the Grip Button (Figure 28). Here, the slots were designed to create an interference fit between the ribs (plastic) and the button wings (rubber). Figure 31 shows how the button is secured between the ribs.

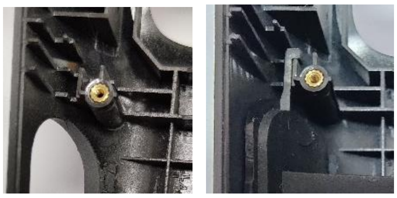


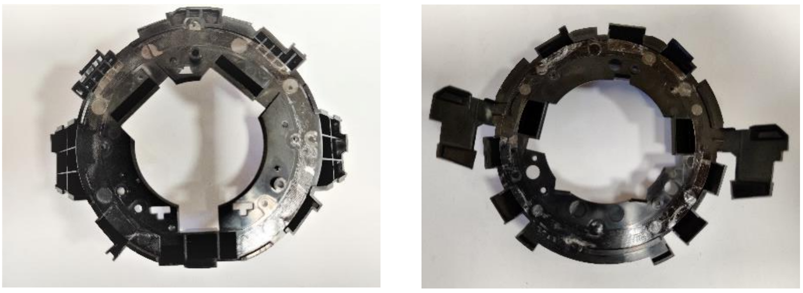
Figure 30: Close-up of the ribs that are acting as slots for assembly

Figure 31: Assembly of Grip button through slots in ribs

DFAG_09: Simplify the design and aim	As stated in the beginning, the tracker section makes the design of the controller complex. The upper and lower PCBA mountings, shown in Figure 32 have several planes on which the IR sensors are mounted to

for economy of construction such as inter-changeable components.

achieve accurate tracking of the user’s hands. This is an example where functionality was more important than the simplification of the design and economy of construction.



(a) (b)

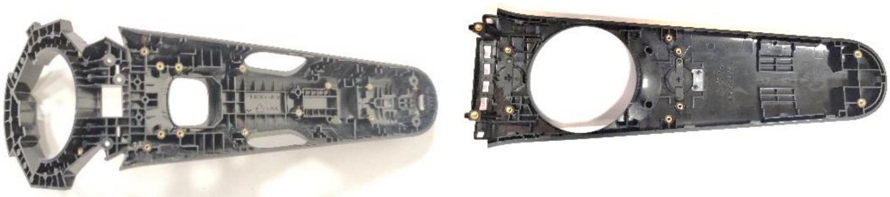
Figure 32: (a) Upper and (b) Lower Flex PCBA Mountings

DFAG_10: Where possible, make components symmetrical to eliminate reorientation and make assembly easier. If not, exaggerate asymmetry features to facilitate orientating the parts.

The Trackpad button is a circular part where the PCBA can be assembled on it in any orientation as can be seen in Figure 33.

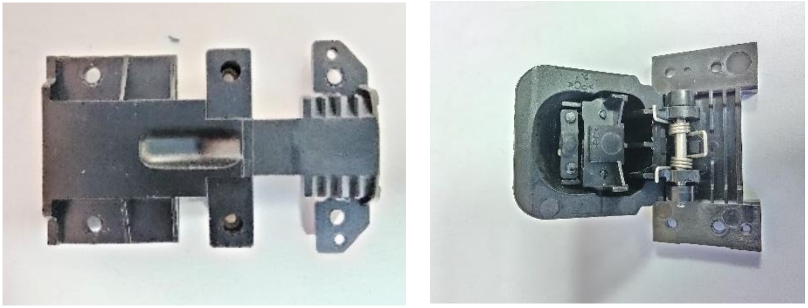
Figure 33: Trackpad Cover

There are plenty of other parts that are symmetrical in one direction. Among these, there are the housings of the controller (Figure 34), the housing of the tracker (Figure 25), and other small parts such as the Wrist Strap Holder (Figure 35 (a)) and all the parts in the Trigger Button sub-assembly (Figure 35 (b)), including the double torsion spring.



(a) (b)

Figure 34: HTC Vive Housing (a) Base (b) Lid



(a) (b)

Figure 35: (a) Wrist Strap Holder (b) Trigger button sub-assembly

DFAG_11: Design a base component to reduce the need for additional jigs and fixtures to hold the assembly.

Figure 34 shows the lower two housings of the controller. These two parts can be held on fixtures and the related components assembled on them. When all the components are assembled on these parts, the controller can be closed as can be seen in Figure 36.

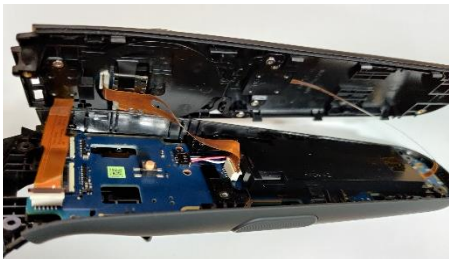


Figure 36: Closing the controller

However, sub-assemblies such as the Trigger button sub-assembly (Figure 24) and the Tracker Flex PCBA Mounting sub-assembly (Figure 37) need to be assembled in dedicated stations before they go to the main controller.

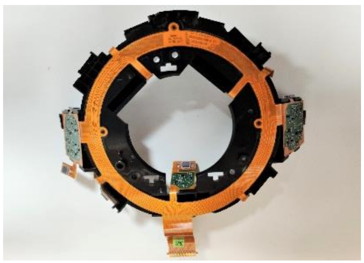
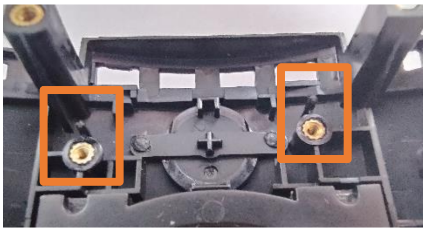
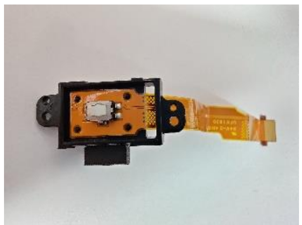


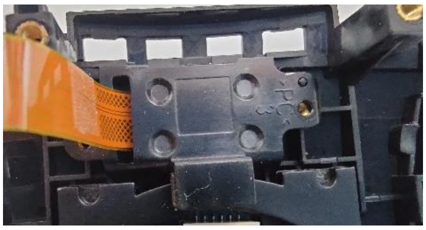
Figure 37: Tracker Mounting sub-assembly

DFAG_12: Design parts to be self-aligning and self-locating.

Self-locating features for parts with poka-yoke mechanisms and/or pronounced asymmetry have been added to the housing sub-assembly to avoid assembly mistakes and to stabilise parts for subsequent operations such as screw fastening. These features, often in the form of pins, have been integrated with reinforcement ribs. Figure 38 (a) shows two locating pins that are slightly offset by design, thus preventing the possibility for incorrect assembly. Figure 38 (b) shows the mating part with corresponding holes and Figure 38 (c) shows the assembled parts.

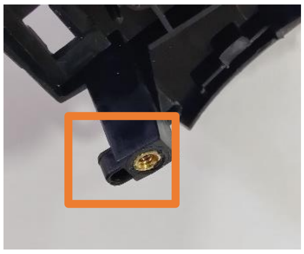
(a) (b)



(c)

Figure 38: (a) Self-locating pins on Controller Lid for System button sub-assembly (b) System button sub-assembly (c) System button sub-assembly located in place

Figure 39 (a) shows two pins located in the middle section of the Base housing which guide the assembly of the lid with the corresponding holes shown in Figure 39 (b). Figure 40 shows how this feature facilitates the assembly by first achieving correct alignment.

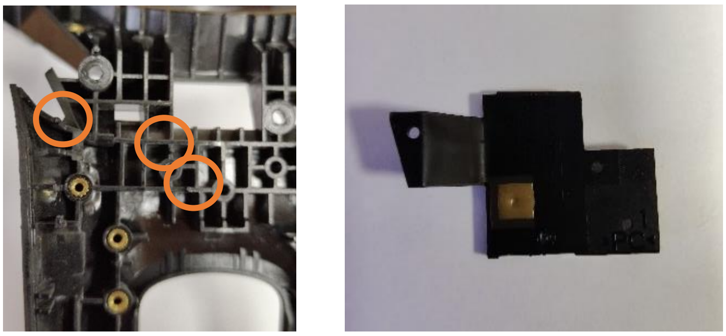
 

(a) (b)

Figure 39: Guiding pin on Base of housing Hole in Lid of housing

Figure 40: Lid-Base assembly

Three other positioning pins in the housing are found just below the previous locating pins. These pins, shown in Figure 41 (a), apart from aligning the two parts together, provide an interference fit (Figure 42).



(a) *(b)*

Figure 41: (a) Positioning pins (b) corresponding positioning holes on a part

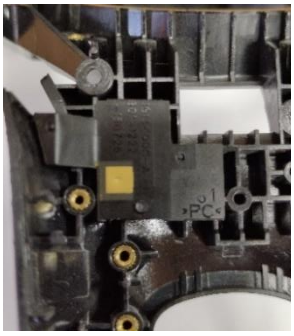


Figure 42: Positioning/alignment of parts by using guiding pins

Other purposely designed pins in the Base housing, guide the PCBA (motherboard of the controller) to sit on the reinforcing ribs as shown in Figure 43.

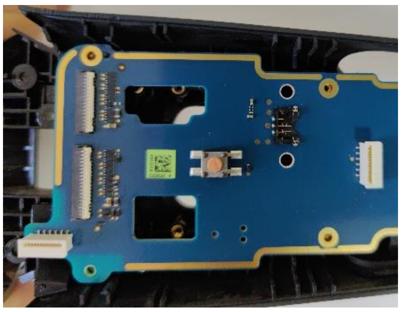
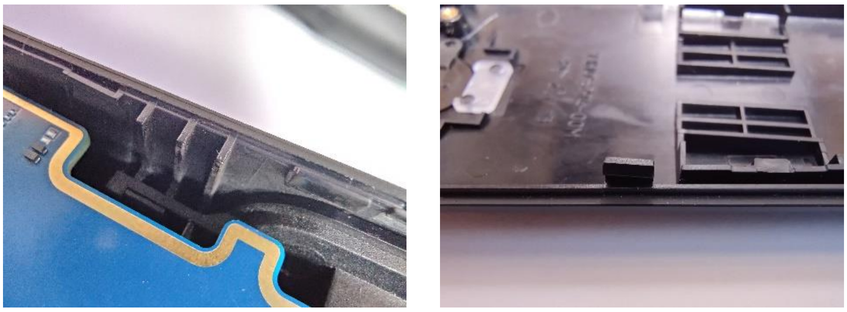


Figure 43: Ribs guiding assembly of PCBA onto housing

DFAG_13: Introduce guides and tapers to facilitate assembly

A lip or a groove is a design feature in plastics that guide two parts to be assembled together at the parting line along the walls. All the controllers and product manufacturers use this feature because it aligns assembly parts before they are finally fastened together. A lip and groove feature provide a small degree of sealing but mainly it guides and aligns the assembly of two parts.

Figure 44 (a) shows a lip feature on the outer wall of the plastic part (Base housing). Figure 44 (b) shows a groove feature on the corresponding mating part (Lid housing). A rule of thumb to use is to make a lip about 50-60% of the wall thickness (Keane, 2017).



(a) *(b)*

Figure 44: (a) Lip Feature on the Base part (b) Groove feature on the Lid part

DFAG_14: Avoid component features that induce tangling or nesting.

All plastic components are rigid, except for the ribbon cables/flex PCBAs. On an assembly line, such flexible PCBAs and normal PCBAs are stored in purposely designed anti-static trays but will impose some degree of nesting when being assembled due to their supple nature.

Figure 45 shows the intricacy in assembling the ribbon cable containing the IR sensors in the tracker.

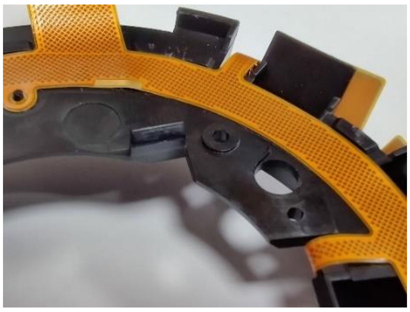


Figure 45: Assembly of the IR Sensors Ribbon Cable

All the plastic parts contain ribs or other form features that prevent them from sticking, nest or tangle when they are in boxes for assembly such as the Wrist Strap Holder shown in Figure 46.

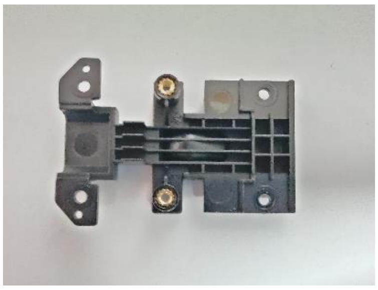


Figure 46: Wrist Strap Holder

In fact, a considerable number of ribs are used in the HTC Vive controller. Ribs replace solid structures with hollow ones. Thus, reducing component material/weight and improving manufacturability (e.g. reduce production times) and the performance of the part.

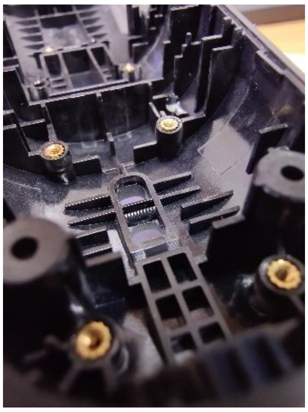


Figure 47: Ribs inside the Vive controller

Rubber buttons have been over-moulded with hard plastic to provide rigidness such as the ones shown in Figure 28 and Figure 48.

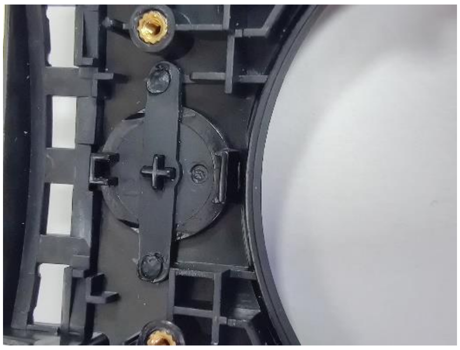


Figure 48: Menu Button - hard plastic and rubber materials

DFAG_15: Remove sharp corners from components so that they positioned correctly during assembly

Although ribs are not chamfered or filleted to guide the assembly, the combination of locating pins and adequate rib design have contributed to align parts during assembly.

DFAG_16: Avoid time-consuming and expensive fastening operations.

On the controller and tracker housings, there are several snap fit clips which are used to close the controller. Typical examples are provided in Figure 49 and Figure 50. The controller uses 8 cantilever beam type of snap fits in total: the Base has the groove feature whilst the lid part contains the hook part of the clip. These clips are designed to close the controller housing and to take most of the workload during its lifecycle such as impact, vibratory, and other operational loads.

(a) *(b)*

Figure 49: (a) Snap-fit clip on the Lid housing and (b) a clipping window on the Base housing

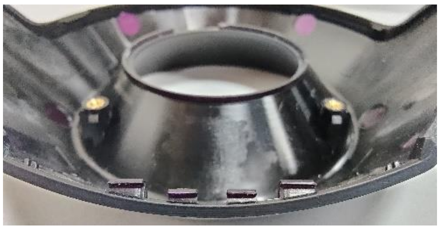


Figure 50: Tracker Lid has both snap-fit clips and knurled inserts

However, bolt fasteners have been added to avoid the possibility that the switch opens if it is accidentally dropped or internal parts start to rattle during the controller's life use. Vibrational noises that are usually experienced when the vibration motor provides haptic feedback, affect negatively the user experiences of a product.

The Vive controller uses five different types of bolts as can be seen from Figure 51:

a) **Type A:** 5.2mm T5 Torx Black bolts, quantity: 9
b) **Type B:** 4.2mm T5 Torx Silver bolts, quantity: 12
c) **Type C:** Phillips 00 5.8mm Black bolts, quantity: 6
d) **Type D:** Phillips 00 12.8mm Silver bolts, quantity: 3
e) **Type E:** 21mm T5 Torx Black bolts, quantity: 3

(a) *(b)* *(c)* *(d)* *(e)*

Figure 51: Bolts used in the HTC VIve Controller:
(a) Type A (b) Type B (c) Type C (d) Type D (e) Type E

It was noticed that the stainless-steel bolts were used for the bottom part of the controller whilst black, magnetic bolts were used in the upper part. It is believed that stainless steel bolts were used to avoid the bolts from getting rusted just in case sweat or other liquid falls in the controller. All bolts used are long enough to first engage with the thread before release. Figure 52 is an example of a long screw which is used to secure the housing. This also extends the concept of DFAG_13.

Figure 52: Type D Screw

As can be observed in the photos of the bolts, the bottom part of the thread is painted blue. This is not paint but an aerobic glue, also known as threadlocker, which exists in various adhesive strength. Between the threads of a bolt and nut there is less than 30% of metal engagement and threadlocker is used to fill the gaps, preventing threads from rusting and eliminate noises due to vibrations.

Apart from fasteners, transparent yellow tape, possibly polyimide film, is used over connections as shown in Figure 53. Figure 54 shows a clip-on connector and Figure 55 shows an insert-and-lock type of connector.

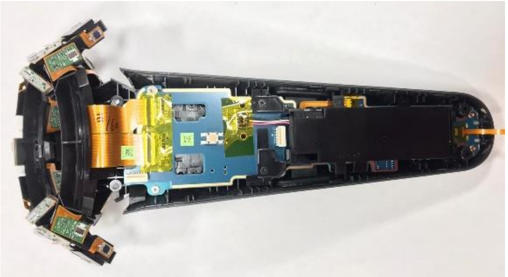


Figure 53: Base sub-assembly with polyimide tape on top of connectors

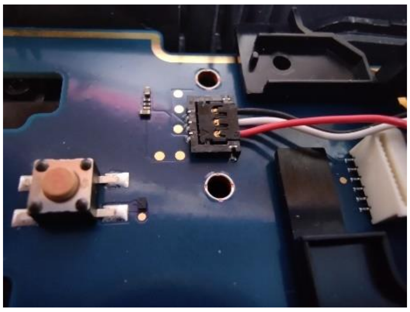


Figure 54: Battery Connector

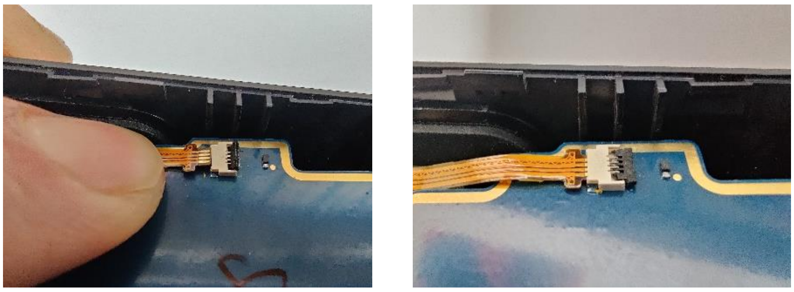


Figure 55: Clip-on connector

All IR Sensor PCBAs in the tracker are bonded to the mounting frames using double sided tape as shown in Figure 56.

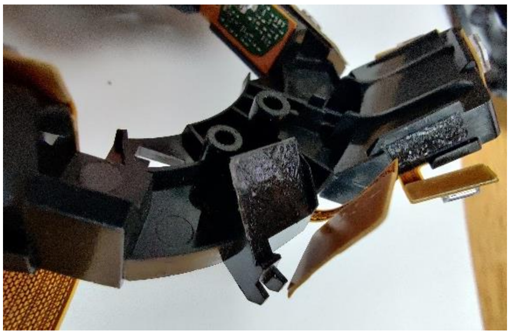


Figure 56: Adhesive under each IR sensor PCBA

Similarly, the Trackpad PCBA is bonded to the Trackpad button using tape. On the same PCBA, a large component, presumably a gyro meter, is attached to the PCBA using the same adhesive as shown in Figure 57.

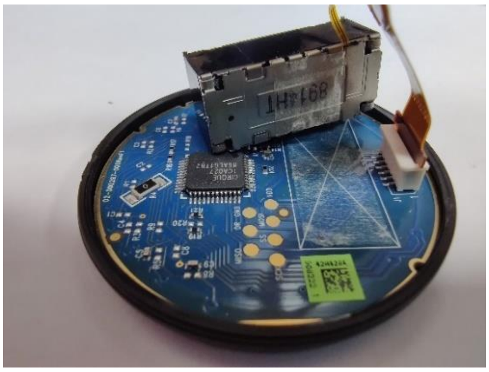


Figure 57: Trackpad PCBA

DFAG_17: Design a vertically stacked product in order to achieve simpler top-down assemblies.

As shown in Figure 58 and Figure 59, the switch has been designed in such a way that parts can be assembled from above (top-down assembly) and positively located into pins or slots or by clips or fasteners such that during assembly line indexing, sub-assemblies do not move.

Figure 58: Components assembled on Controller Base

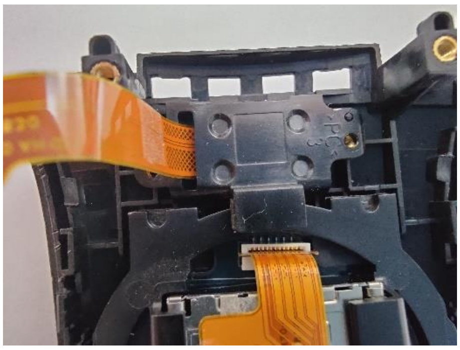


Figure 59: Stacked components

The Lid housing cannot be assembled directly to the Base housing. The Trackpad, Menu and System buttons sub-assemblies need to be assembled the Lid first. This means that a separate dedicated station is required for Lid sub-assembly. Having PCBAs on different sections, such as the example illustrated in Figure 60, makes the manual assembly of the flex PCBs to the connectors a bit difficult and tedious. However, this approach improves haptics and button stability since sub-assemblies are directly fastened to the Lid.

DFAG_18: Simplify handling of components.

Almost all parts are easy to handle. However, small parts such as the parts found in the Trigger button sub-assembly are a bit cumbersome to pick up and assemble them. It is believed that the assembly line for the HTC Vive controller is semi-automatic, meaning that certain stations provide automatic assembly while other stations require manual assembly by a trained operator.

The most difficult parts to handle are ribbon cables, especially the ones which connect the Lid with Base housings as shown in Figure 60. These are done manually.

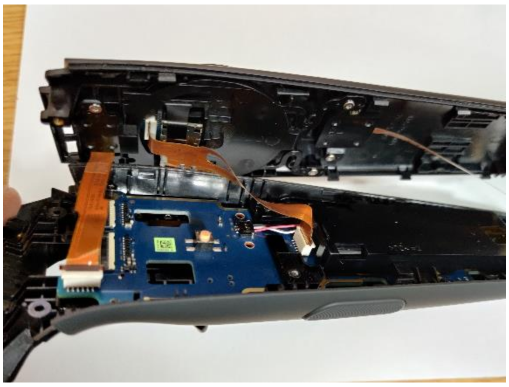


Figure 60: Assembly of ribbon cables prior the closure of the controller

DFAG_19: Minimise tolerance and surface finish demands on components so that production costs are reduced.

With regard to surface finish, HTC have heavily invested to have a pleasant controller during use. The appearance looks very sleek and of high quality. After parts are produced, they are painted and laser engraved. This is very common on all high-end consumer products which require a finish that does not look like raw plastic.

With regard to tolerances, these are certainly present in the switch given the amount of parts that are assembled or mated together. For instance, locating pins are required to have an appropriate fit with the respective parts. Ribs which are used as reference placement planes for other components are required to be within tolerances for every part to stack as per design. Similarly, clips and clipping edges/windows are required to be within tolerance for the snap fit feature to work.

DFAG_20: Designs should be made for ease of packing.

Figure 61 (a) and (b) show the packaging of the HTC's Vive VR system, which includes a pair of Vive controllers, while Figure 62 is showing the packaging of a single controller.

(a) *(b)*

Figure 61: (a) Exploded view of the HTC Vive Controller Packaging (source: NoobFeed), and (b) Actual packaging of the HTC Vive Controller

Figure 62: Singel controller Packaging of the HTC Vive controller (source: Stormy Studio)

These packaging pictures show a lot of wasted space and material in order to accommodate the organic shape of the controller.

DFAG_21: Make sure disassembly is equally practicable as assembly.

Unless the IR sensors Flex PCB does not need to be removed, disassembly is not very difficult. One must be careful in removing the ribbon cables and to unfasten a few of hidden bolts which need to be unfastened before trying to dislodge the lid and base housings. Other than that, disassembly is straight forward.

Furthermore, each sub-IR sensor PCBA is attached to the Upper and Lower Flex PCBA Mountings using double sided tape which makes these sub PCBAs very hard to detach.

DFAG_22: Develop the design to contain identical components.

No identical parts are used except for the bolts and the 24 IR sensors used in the Tracker. However, as stated in the beginning of the DFMA Analysis, one requires two controllers during normal use of the VR system. Thus, each component is utilised twice per each VR system.

DFAG_23: Introduce datum systems whenever a high degree of accuracy is necessary.

The main datums lie in the plane where the controller's housings come together and another at an angle where the Tracker housings are closed. However, other internal datums are present given the number of parts that are assembled.

Other Observations

DFAG_06: Where possible, plan for

The assembly line for this controller is semi-automatic, meaning that there are areas where parts could be automatically feeded and assembled, and there are areas in which an operator is required for

automatic assembly since parts that can be automatically assembled are easier to handle and assemble manually.	manual assembly. The way the tracker is at an angle to the rest of the controller, one requires orienting the parts, especially for the assembly of the Upper and Lower IR sensor Flex PCBAs. Most probably, in the assembly line, a fixture has been designed such that the tracker parts can be assembled easily and securely.

4.2. Oculus Touch Controller

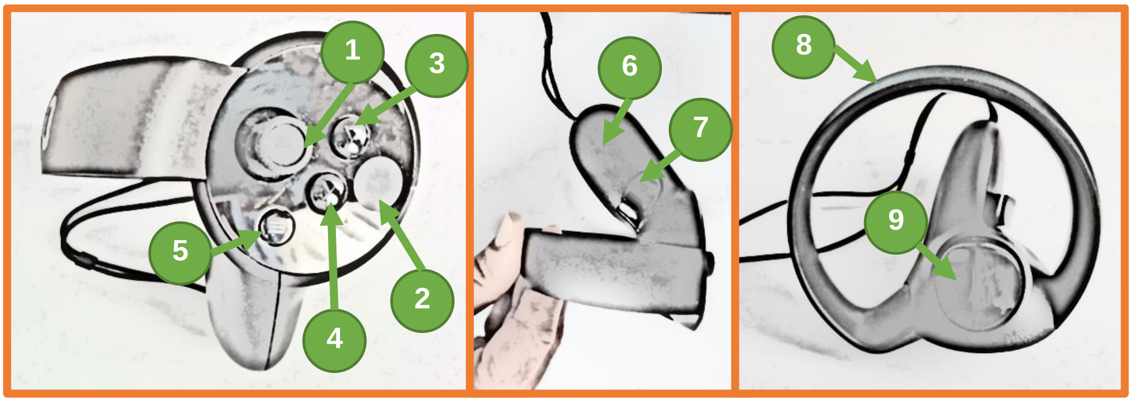
Like the Oculus Rift headset, the Touch controllers use a set infrared LEDs laid out in a distinct pattern of the elliptical ring of each controller as shown in Figure 63.

Figure 63: Infrared photo while the Oculus Touch controllers are being used (source: iFixIt)

These infrared LEDs' position can be accurately tracked in 3D space by the two infrared sensors positioned in front of the end-user, and subsequently represented in the virtual environment. The choice of having two separate controllers (which basically are mirror images of each other) was dependent on the tracking technology used. This enables the system to recognise which is the left or right controller even if the arms are crossed.

4.2.1. Terminology

Figure 64 illustrates some of the component's terminology used in the Product Breakdown Structure of the Oculus Touch controller.

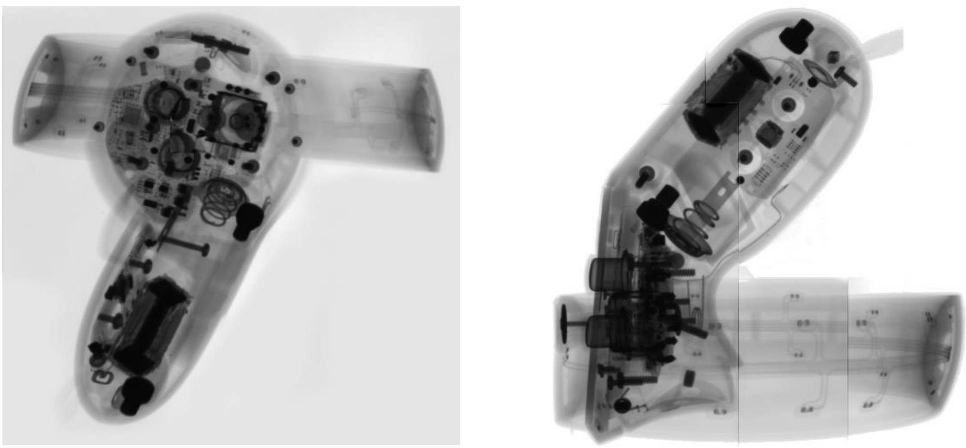


1 Joystick	2 Touch sensor button	3 Y button
4 X button	5 Options button	6 Knob
7 Grip Trigger button	8 Tracker Cover	9 Trigger button

Figure 64: Oculus Touch Controller Terminology

4.2.2. X-Ray Images

Figure 65 shows the X-Ray images of the Oculus Touch Left controller from various elevations. Note that each elevation is made up of several merged images.



(a) *(b)*

(c)

Figure 65: X-Ray images of the Oculus Rift (RHS) controller (a) Plan elevation (b)Front elevation (c) Side elevation

4.2.3. Product Breakdown Structure

The Oculus Touch controller (OTC) was disassembled in order to understand the components inside it and the assembly design features it has. The Product Breakdown Structure is shown in Figure 66.

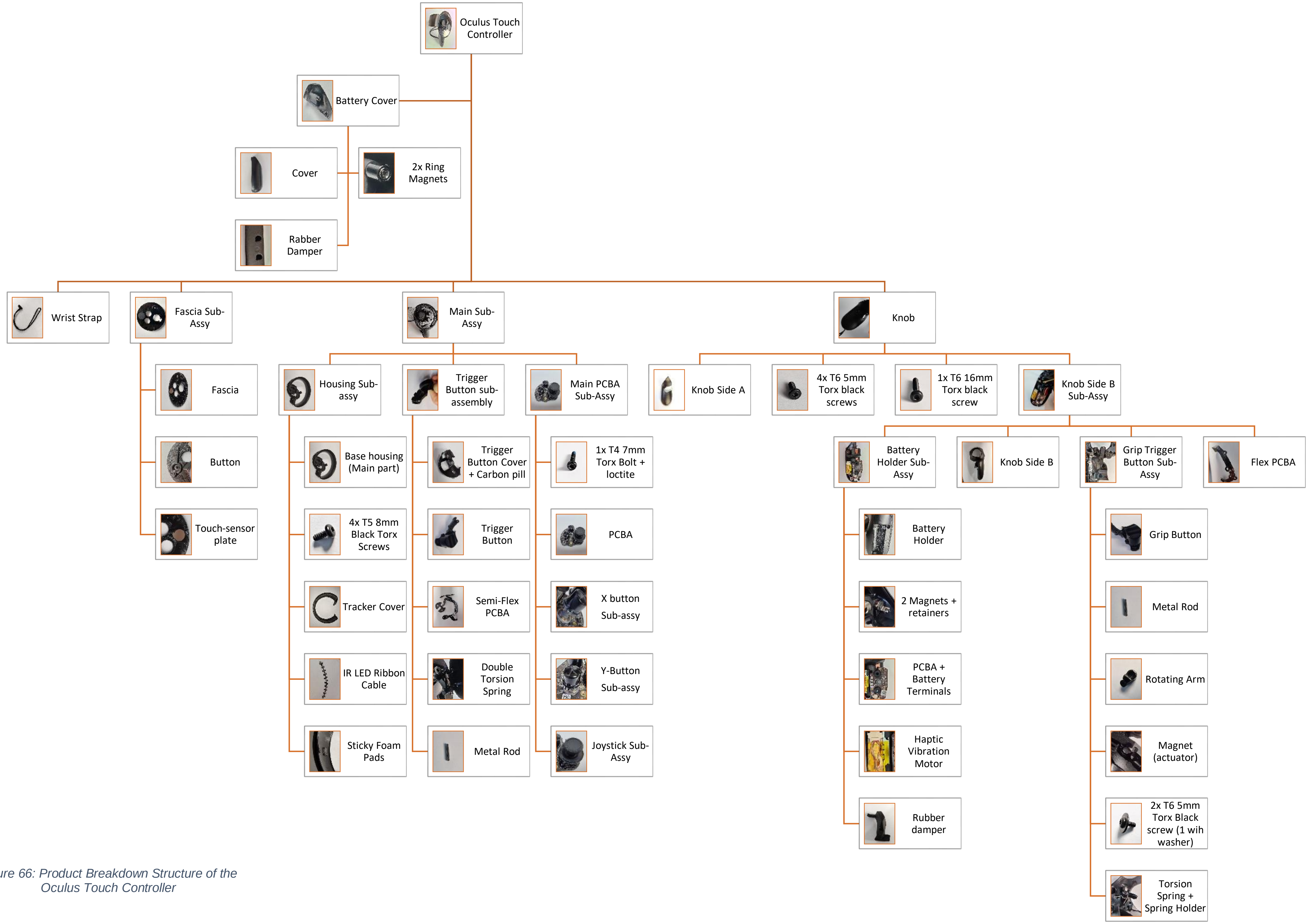


Figure 66: Product Breakdown Structure of the Oculus Touch Controller

4.2.4. DFMA guidelines review based on the OTC

General comments There are at least 40 different parts on the Oculus Touch controller (OTC), including magnets in the battery cover, foam pads in the Tracker Ring cover, rubber dampers and several screws. If the wrist strap is further decomposed into other parts, the total number of parts increases to 42. Unlike the HTC Vive and PlayStation Move controllers, the Oculus Touch controllers are not ambidextrous. This means the actual number of parts per set is almost double.

Further to the parts highlighted in the Product Breakdown Structure, the Oculus Touch controller makes several uses of double sided bonding tape, namely to attach the IR-LEDs Flex PCBA which contains 22 infrared LEDs, rubber dampers to the housing, various daughterboards with flexible PCBAs, the foam pads, magnets and the main Fascia. The latter is not fastened or retained using clips but secured using high adhesion tape.

Figure 67: Teardown of the OTC controller

The Touch controller has the most ergonomic, lightest and smallest design. Its design is very complex because all the components are densely packed into a compact controller. The original retail price for a pair of Oculus Touch controllers was $199 at launch but now each controller can be bought separately for €70 (source: Oculus).

Material & Manufacturing Process Although the material of the plastic components is not revealed by the markings on the inside of the parts nor specified on the specifications, it is presumed that the main material used is either polycarbonate or ABS or a mixture of both. Per each controller, there is a total of 14 plastic parts. These include three very small parts which are used in the Grip Trigger button sub-assembly, two glossy trigger buttons, two buttons and a fascia which have an acrylic-like base material (glossy and transparent), four parts that form the knob (in which the battery resides), a large Base housing and a Tracker cover. The latter two parts have a brushed matte finish except for the Oculus logo and other markings. All parts are injection moulded.

The Base (main part) consists of a large complex plastic part, injection moulded as a single part. It features thick wall thicknesses of 4-5mm.

Figure 68: Base housing

There are three major rubber parts: one acting as a stopper for the wrist strap (Figure 69 (a)), one acting as a damper when closing the battery cover in the knob (Figure 69 (b)), and another rubber part that dampens the actuation of the trigger button (Figure 69 (c)). There is a total of 18 foam pads (Figure 69 (d)) in the Tracker cover which cushion its assembly to the Base housing while protecting the IR LEDs. Another two, lager but thinner, foam pads are used on a part that forms the knob. This plastic part is in contact with the haptic motor of the controller and so these foam pads are used to eliminate vibrations.

(a) *(b)* *(c)* *(d)*

Figure 69: Rubber dampers and foam pads

Figure 70: Heat staked button assembly

DFA Guidelines	**Examples from the Oculus Touch Controller (OTC)**
DFAG_07: Make use of standardised components whenever possible.	As in the other controllers, most parts are custom made for the specific controller. However, fasteners used are quite standard and readily available in large quantities. The OTC uses five different types of screws as can be seen from Figure 71: (a) 1x T6 16mm Torx black screw, (b) 4x T5 8mm Torx black screws (c) 5x T6 5mm Torx black screws, (d) 1x T4 7mm Torx Bolt + blue thread-lock and (e) 1x T6 5mm Washer Screw.

(a) *(b)* *(c)*

(d) *(e)*

Figure 71: Different screws used in the Oculus Touch controller

The OTC makes use of two standard ring magnets (Figure 72(a)) and two corresponding 6mm diameter pill magnets. Both the Trigger and Grip Trigger buttons utilise a standard 2mm stainless steel pin (Figure 72(b)) for the rotation of buttons.

(a) *(b)*

Figure 72: Ring magnet and stainless-steel pin

On the main PCBA (Figure 73), standard parts such as resistors, diodes, etc are mounted. Moreover, the controller uses two single rubber domes with tact switches and a joystick which are probably outsourced from the same suppliers.

Figure 73: Main PCBA

DFAG_08: Reduce the number of parts by combining two or more functions (multi-functional) in a single component.

As already described, the Base housing shown in Figure 68 has been designed as the backbone of the controller such that almost all the other parts are assembled to it. As highlighted (red) in Figure 74, the Base houses 8 bosses-like features on which the Tracker cover and the various Knob parts are fastened using the self-threading screws mentioned in DFAG_07. Another boss-like feature is shown in yellow which supports the T4 Torx bolt for the fastening of the main PCBA with the Base housing. The Fascia of the OTC is also mounted to the Base housing using an adhesive bonding as shown in Figure 75.

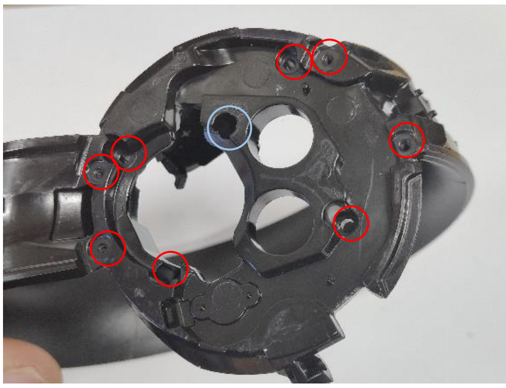


Figure 74: Top part of the Base Housing

Figure 75: Mounting of the Fascia using double-sided bonding tape

The IR-LEDs Flex PCBA is also mounted on the Base housing as shown in Figure 76. One end of this part is fixed to another flex PCBA using clip-on connectors, then, through double sided adhesive, the IR-LEDs Flex PCBA is attached to the Base housing, thereby ensuring it is aligned with two sets of locating pins.

Figure 76: Mounting of the IR-LEDs Flex PCBA onto the Base housing

DFAG_09: Simplify the design.	At first glance, the OTC looks very simple - Figure 77. However, to make an ergonomically and such an aesthetically pleasing and lightweight controller, the designers had to design complex parts which manage to come together in a compact controller.

Figure 77: The Oculus Touch Left Controller

DFAG_10: Where possible, make parts symmetrical to assembly easier.	No symmetrical parts are present, and all parts are highly asymmetrical.
DFAG_11: Design a base component to reduce the need for additional jigs.	This rule does not apply since the Base housing needs to be reoriented several times for the assembly of the controller.

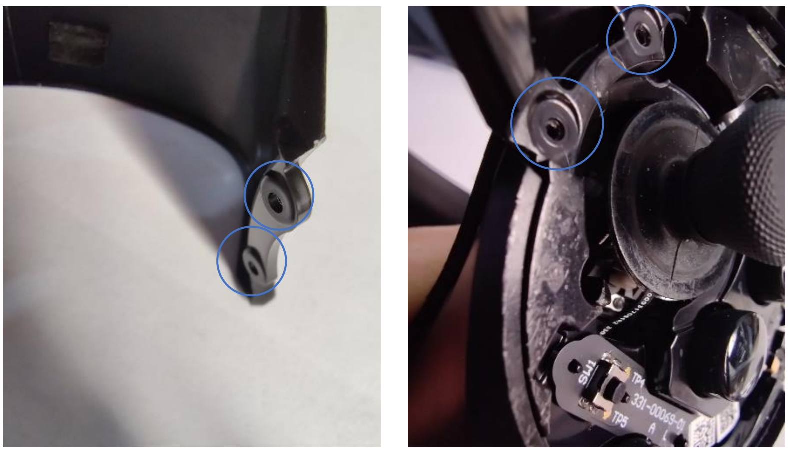
DFAG_12: Design parts to be self-aligning and self-locating.

Figure 78 (a) shows the Battery cover of the OTC whereas Figure 78 (b) is showing the corresponding Battery Holder. As can be seen in coloured circles, three protruded features are present to guide the insertion of the battery cover into the holder.

(a) *(b)*

Figure 78: (a) Battery Cover and (b) Battery holder

The Tracker cover shown in Figure 79 (a) has two tapered, embossed bosses at each end that when assembled over the Base housing, the two parts clip together. This makes the screw fastening operation an easier task.



(a) *(b)*

Figure 79: (a) Tapered bosses that self-locate in (b) the corresponding grooves of the housing

It was also noted that to fasten the washer screw shown in Figure 71 (e) into the Rotating arm of the Trigger button mechanism shown in Figure 80 requires the use of two hands.

Figure 80: Rotating arm of the Trigger button actuation mechanism

DFAG_13: Introduce guides and tapers to facilitate assembly

Figure 80 illustrates an example of how tapered bosses align with taped groves in the mating part shown in Figure 81. These counter-featured parts allow the Tracker cover to mount the base and fit together, prior fastening the screws.

Figure 81: Tapered groove for the assembly of the Tracker cover

Figure 82: Alignment pins for Ribbon Cables

DFAG_14: Avoid component features that induce tangling or nesting.

The most components prone to tangling are the springs used under the X and Y buttons (Figure 83). Most probably these are installed on the assembly line together with the buttons. Since the springs' ends are hidden, it is impossible to see whether the springs are close ended. Attempting to dissemble them would damage the spring.

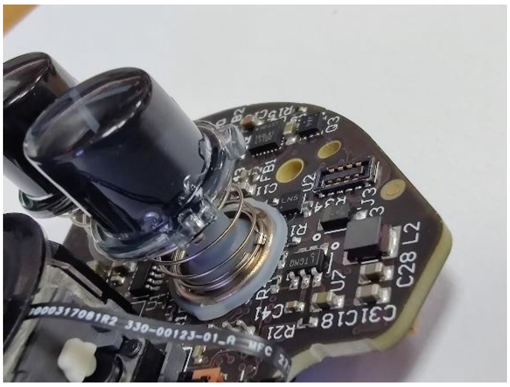


Figure 83: Springs used in the X and Y Buttons of the OTC

The OTC makes use of flexible PCBAs (or PCBAs with ribbon cables) as shown in Figure 84. Such components are normally stored in anti-static trays separated from each other. However, the assembly of flexible PCBAs require the operator to orient the part multiple times which in progress might cause tangling with the other controller sub-components.

Figure 84: Different ribbon cable used in the OTC

Like the Vive controller, the OTC uses small bolts. The assembly and fastening operations of such components might require the operator to use both hands.

DFAG_15: Remove sharp corners from components so that they are guided into their correct position during assembly

As can be seen from Figure 85 and the previous images, all parts are free from sharp corners. In this case, the Trigger button sub-assembly components are smooth such that when the Trigger button is pressed, the Rotating arm is able to move as smoothly as possible.

Figure 85: Trigger button actuation mechanism

Figure 86 depicts the Base house turned upside-down, where the IR LEDs flex PCBA is mounted. In this photo, one can observe the smoothness of the features and the lack of sharp corners. This is reflected in the other components of the controller.

Figure 86: The Base housing, upside-down

DFAG_16: Avoid expensive and time-consuming fastening operations.

Only screws and adhesives are used in the switch assembly as detailed in the previous examples. However, the battery compartment, since the controller uses a standard AA battery and is accessible to the end-user for battery replacement, closes with magnets as shown in Figure 87. Apart from being a very professional feature, this makes it very easy for the end user to replace the battery.

(a) *(b)*

Figure 87: (a) Battery cover (b) Battery Holder

DFAG_17: Design a vertically stacked product in order to achieve simpler top-down assemblies.

Only the Main PCBA and the Fascia are assembled vertically downwards, the rest of the parts require orienting the parts accordingly.

DFAG_18: Simplify handling of components.

The smallest parts are found in the Trigger button actuation mechanism shown in Figure 85. It is believed that this sub-assembly is facilitated through an automatic assembly station.

DFAG_19: Minimise tolerance and surface finish demands on components so that production costs are reduced..

Tolerances in the Ring area of the Tracker are quite tight in order to obtain a seamless assembly as can be seen in Figure 88 (a). On the other hand, as shown in Figure 88 (b), less tolerances were specified in the knob area which is composed of three components assembled together and less visible while the controller is in use.

(a) *(b)*

Figure 88: Parting lines between different parts in the (a) Knob and (b) elliptical Tracker

Inside the switch, one can find high tolerances where there are stamped parts involved such as the battery terminals which are to be assembled on the Battery Holder as shown in Figure 89. To ensure a tight fit, the holes punched in the battery terminal must be within tolerance of the battery holder which is injection moulded. On the other hand, the PCBA mounted on the battery holder has wider tolerances because ultimately it is held in place by soldering of the terminals.

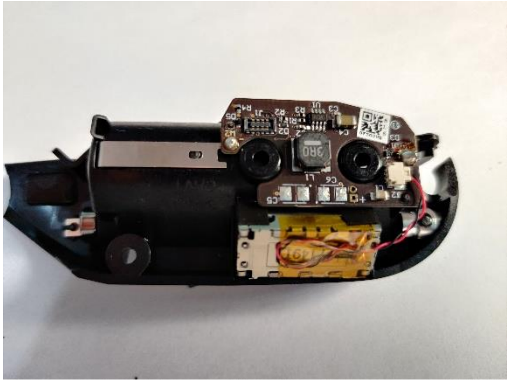


Figure 89:The backside of the Battery Holder

Mechanism such as the actuation of the Trigger Button (Figure 90) may also have stricter tolerances in order for the actuation to function correctly.

Figure 90: The mechanism of the Trigger Button

Conversely, the tolerances for the place area of the ribbon cables is quite loose as shown in Figure 90 and Figure 91. However, locating pins and corresponding holes in the ribbon cables need to have tighter tolerances to have an interference fit.

Figure 91: IR-LEDs Ribbon cable

DFAG_20: Designs should be made for ease of packing.

As can be seen from Figure 92 and Figure 93, due to the controllers' design there is a lot of empty space in the packaging. This does not make the packaging sustainable since there is a lot of extra material used.

Figure 92: Packaging of an Oculus system, including headset, controllers, hardware and IR sensors (source: RoadToVR)

Figure 93: Controllers set packaging (source: RoadToVR)

DFAG_21: Make sure disassembly is equally practicable as assembly.

It is not easy to disassemble the controller, especially due to the hidden screws and adhesive bonding which is heavily used throughout the switch. Furthermore, since no threaded inserts are used but threads are formed through the self-threading screws, the threads can get damaged during disassembly.

DFAG_22: Develop the design to contain as many identical components as possible.

As can be seen from Figure 94, the left and right controllers are symmetrical. This means that each plastic part has a different design and unfortunately no parts can be used on the other controller except for some electrical components such as the components mounted on the Main PCBA (resistors, tact switches, rubber domes, joystick, battery terminals, etc.), and the screws, magnets and pins.

Figure 94: Oculus Touch Left and Right controllers (source: Evan-Amos)

DFAG_23: Introduce datum systems whenever a high degree of accuracy is necessary in the location of interchangeable components.	It is conjectured that several datums are used in the switch because to close the switch, parts are assembled from different axes. For instance, the knob is composed of three parts as shown in Figure 88 (b) whilst the elliptical tracker has an elliptical datum Figure 88 (a).
DFAG_06: Where possible, plan for automatic assembly since parts that can be automatically assembled are easier to handle and assemble manually.	It is difficult to state whether the assembly line for the OTC is completely manual but there are certain assembly steps which are required to be done with the assistance of machines, such as the insertion of the Trigger button pins, and the application of the double sided tape. The assembly of ribbon cables/flexible PCBAs demand orientating the sub-assemblies several times. Manual assembly is probably assisted by several jigs and fixtures that hold the sub-assemblies in place to ease the operation.

4.3. PlayStation Move Controller

The PlayStation (PS) Move controller consists of a big glowing orb which is tracked by the PS Eye, an intelligent camera. Inside the orb there is an RGB LED which can light up to any colour, allowing the camera to track multiple Move controllers simultaneously. Apart from tracking the location and size of the glowing orb to locate the location of the controller, the controller sends gyroscope data via Bluetooth to the console to track twists, turns, and other movements.

4.3.1. Terminology

Figure 95 illustrates some of the component's terminology used in the Product Breakdown Structure of the PlayStation Move controller.

4.3.2. X-Ray Images

Figure 96 shows X-Ray images of the PlayStation Move controller from a plan and side elevation. Metal components are shown in black whilst plastics can be seen in various shades of gray. The housing, electronics and fasteners of the controller can be clearly distinguished. Note that each elevation is made up of several merged images.

4.3.3. Product Breakdown Structure

The PlayStation Move controller was torn down in order to understand the components inside it and the assembly design features it has. The Product Breakdown Structure is shown in Figure 97.

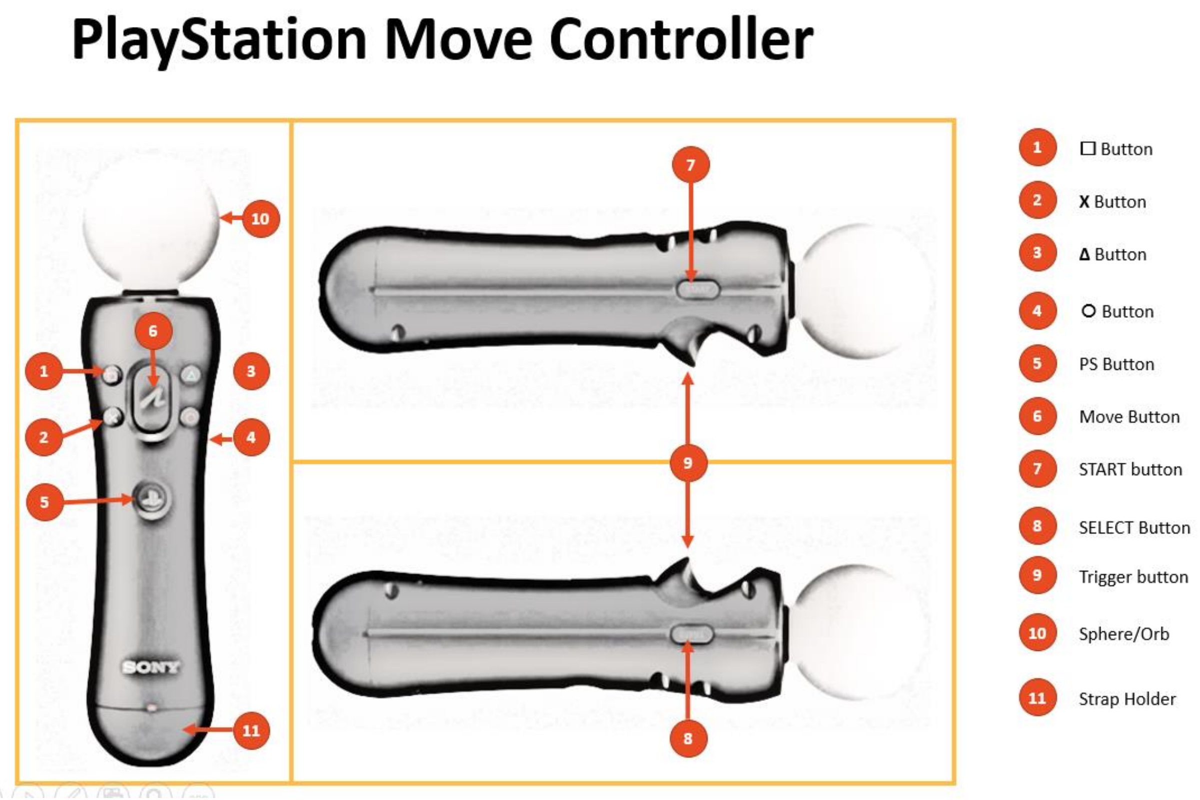
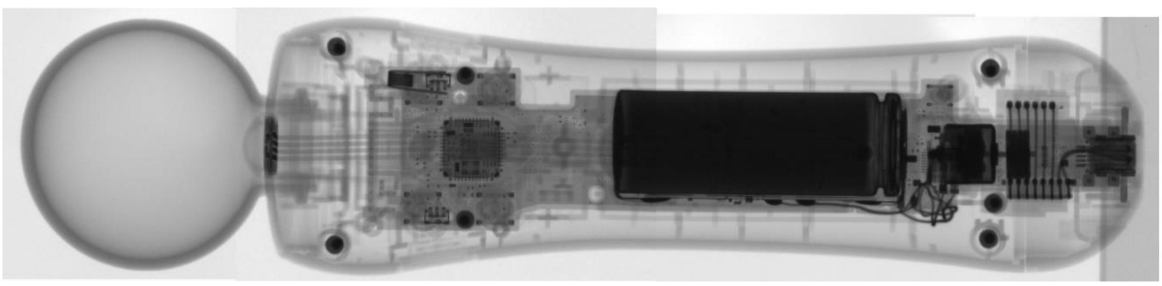


Figure 95:PS Move Controller Terminology



(a)

(b)

Figure 96: X-Ray Image of the PlayStation Move VR Controller (a) Plan elevation (b) Side elevation

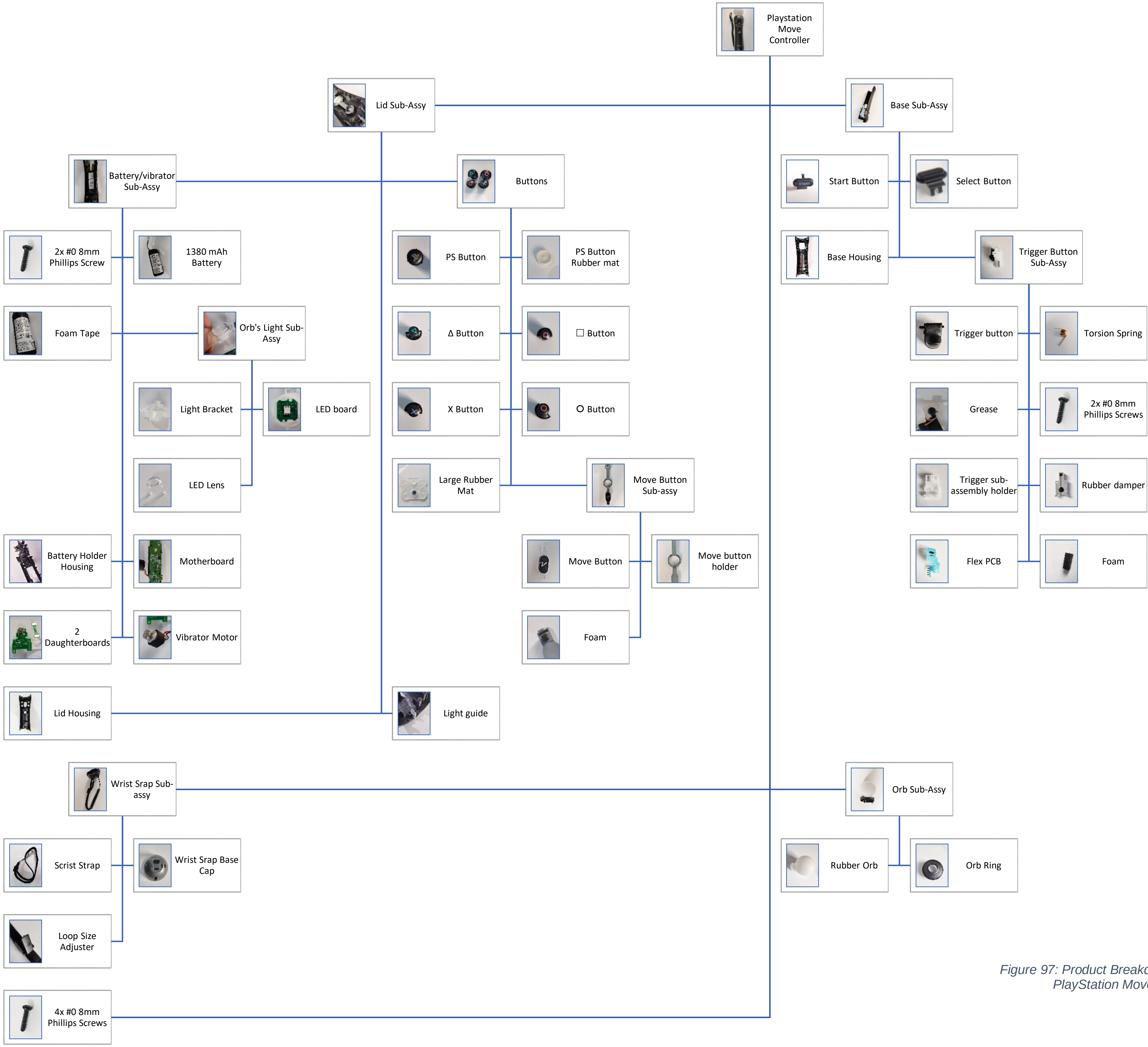


Figure 97: Product Breakdown Structure of the PlayStation Move Controller

4.3.4. DFMA guidelines review based on the PS Move Controller

General comments There are 37 different parts on the PS Move Controller, including grease (lubricant), a piece of tape around the battery used for shimming and a piece of foam for light contact pressure on electrical contacts. If the wrist strap was to be considered in more detail, the total number of parts increases to 41.

Figure 98: Teardown of the PS Move VR controller

This controller shows a simple design with less part numbers and much easier assembly procedure than the other controllers (DFMG_01). Another big difference from the other controllers is that it does not make use of a single adhesive tape or Loctite in any location. Furthermore, only identical screws are used throughout the controller, making inventory smaller whilst facilitating the assembly procedure. The simplicity in the design is reflected in the price. The cost of a twin-pack (2 PS Move controllers) ranges between €80-€100.

Material & Manufacturing Process Most components of the PlayStation Move controller are made out of Acrylonitrile Butadiene Styrene (ABS) as can be seen in the material markings of Figure 99. This material is cheap (DGfM_01 & DFMG_03), easy to obtain (DGfM_02) in bulk (DGfM_04), and since it is used in multiple parts it means that the designer/manufacturer has experience in using it (DGfM_03).

Figure 99: Material markings on the components

ABS can be easily processed through Injection Moulding, has glossy properties, is very durable and offers great wear resistance and good heat deflection temperature. In terms of durability, Polycarbonate, the material used in the HTC's Vive controller, is somewhat stronger due to higher impact resistance, is lighter and has also good manufacturing properties.

The controller has three light guides (Figure 100). These lightguides or lenses are made of transparent material that could either be Polycarbonate or acrylic, the latter being a better option for light transmission. One light guide is located at the base of the controller and acts as the controller status indicator - Figure 100 (a). A lens type of light guide (Figure 100 (b)) is used to magnify and disperse light in the Orb of the controller. The Move button, shown in Figure 100 (c) light to be transmitted through the 'V' logo. This effect is achieved by spraying the underside of the button black.

Figure 100: Light guides (a) Status indicator (b) LED Lens (c) Move button

Furthermore, the controller has elastomer parts, including rubber mats/domes with carbon pills and a large rubber Orb - see Figure 101.

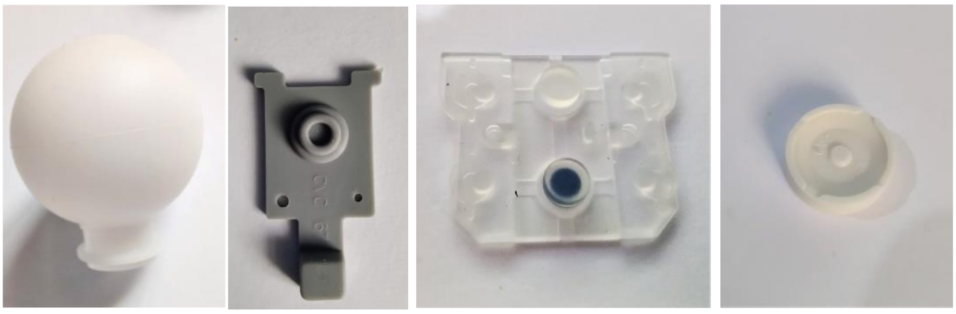


Figure 101: Rubber parts in the PS Move controller

The symbol buttons (Δ, O, ☐ and X) are 2K moulded as can be seen in Figure 102.

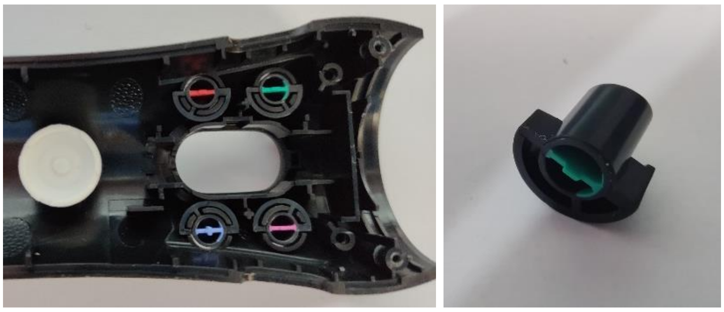


Figure 102: 2K Injection Moulded symbol buttons

DFA Guidelines	**Examples in the PlayStation Move Controller**
DFAG_07: Make use of standardised components.	The only standard part that could be identified in this controller is the 8mm #0 Phillips self-threading screw, shown in Figure 103.

Figure 103: 8mm #0 Philips self-threading screw

Another probable standard or bought-in ‘component’ used is the grease/lubricant that is applied to the Trigger button (Figure 104) to improve the travel and reduce wear between the two plastics.

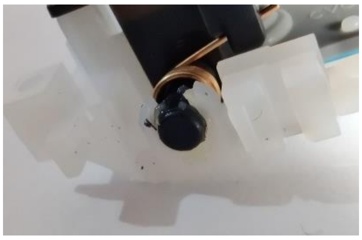


Figure 104: Grease in the rotating area of the trigger button

DFAG_08: Reduce the number of parts by combining two or more functions (multi-functional) in a single component.

The Trigger button Sub-Assy holder (Figure 105) is a very good example for this guideline because it has multiple functions.

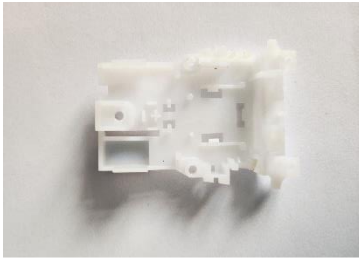
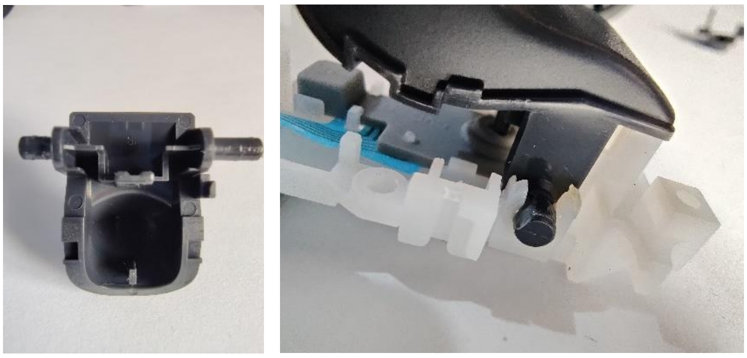


Figure 105: Trigger-button Sub-Assy Holder

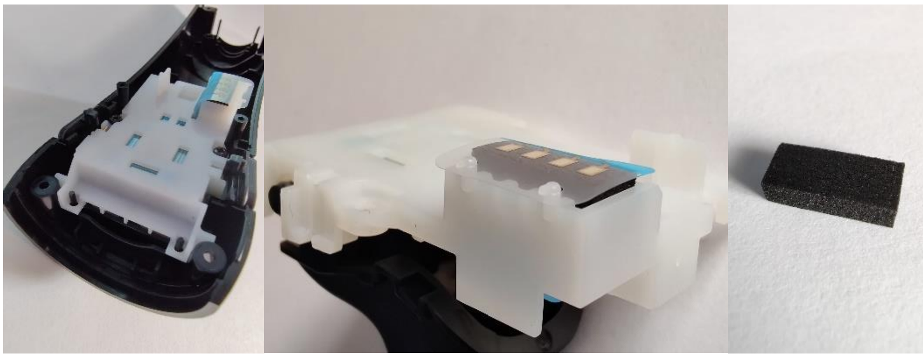
Compared to the other controllers, the trigger button mechanism (Figure 106) omits the metal rod on which the button rotates. Instead the trigger button has been designed with a thick pin such that it rotates on a circular snap fit on the holder.



(a) *(b)*

Figure 106: (a) Trigger button (bottom side) (b)Circular snap fit

The holder, houses the electrical circuitry of the Trigger button as shown in Figure 107 (a). Figure 107 (b) shows the retaining pins that secure the Flex PCB in place. These perpendicular pins facilitate the assembly of the flex by holding this end in place whilst rotating and inserting the other end of the flex PCB on the other side of the holder. This feature comes at a cost - an undercut (DFMG_06).



(a) (b) (c)

Figure 107: (a) Trigger button Sub-Assy on the Base housing (b) Retaining features for the flexible PCB (c) Foam pad

By securing the holder to the Base housing (Figure 107 (a)) using the screws, since the Trigger button is attached to the holder, there is no need to secure the Trigger button using clips or fasteners.

Furthermore, the area shown in Figure 108 (a) houses a small piece of foam Figure 107 (c) which is used to provide contact (through interference) between the contacts on the flex PCB and the highlighted (red) contacts on the motherboard Figure 108 (b). The holder acts as a spacer between the Lid sub-assembly and the Base housing.

(a) (b)

Figure 108: (a) Foam pocket (b) Contacts on the Motherboard

DFAG_09: Simplify the design and aim for economy of construction such as interchangeable components.

The PlayStation Move VR Controller is a twin controller. As can be seen in Figure 109, the left and right VR controllers are identical. It is assumed that both controllers are identical since externally, they look aesthetically the same.

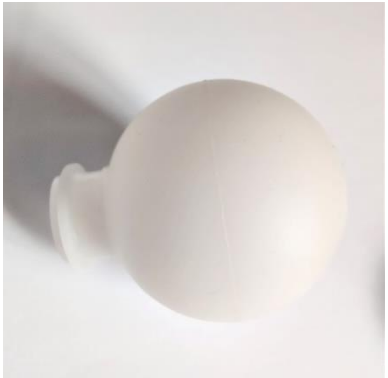
Figure 109: PlayStation Move VR Left and Right Controllers

The PS Move design borrows from an earlier version of the PlayStation Move Navigator controller which is shown in Figure 110.

Figure 110: PlayStation Move Navigation controller (Source: Evan-Amos)

DFAG_10: Where possible, make components symmetrical to eliminate reorientation and make assembly easier. If not, exaggerate asymmetry features to facilitate orientating the parts.	All parts of the PS Move controller are not symmetrical except for the Orb Ring Figure 111 (a) and the Orb itself Figure 111 (b). As can be seen from Figure 112, the Orb can be inserted into the Orb Ring at any angle as this will not affect the assembly of the other components.

(a)



(b)

Figure 111: (a) Orb Ring (b) Rubber Orb

Figure 112: Orb sub-assembly

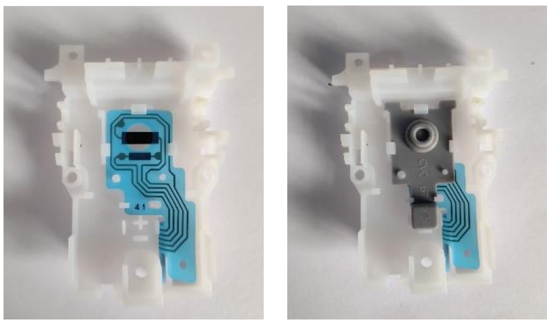
DFAG_11: Design a base component to reduce the need for additional jigs and fixtures to hold the assembly.

Similar to the HTC Vive controller, this controller is composed of two halves as shown in Figure 113. Furthermore, it has a few sub-assemblies which require individual assembly stations. These sub-assemblys and other components are top-down assembled in the respective housings.

Figure 113: An opened PlayStation VR Controller

DFAG_12: Design parts to be self-aligning and self-locating.

Figure 114 shows the differently sized locating pins on the Trigger button Holder which allow for the correct assembly of the rubber mat and Flex PCB. The thick and thin pins act as poke yoke during assembly, allowing for the former parts to be correctly positioned and oriented.



(a) *(b)*

Figure 114: Assembly of the (a) flex PCB and the (b) Trigger button rubber mat

Figure 115 shows how the Holder of the Trigger button is self-located onto the Base housing. Note that the pins are long enough to provide guiding (during automatic/manual assembly). However, they are short enough to avoid incorrect assembly by aligning the Holder upside down.

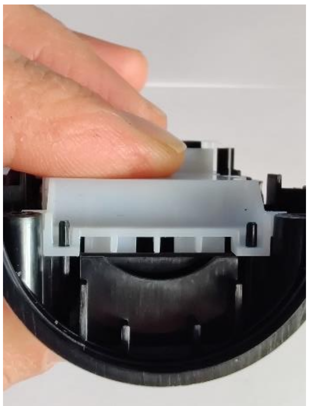


Figure 115: Alignment of the Trigger button Holder onto the Base housing

Figure 116 shows how the Light Bracket is positing on the Lid housing, Figure 116(a) shows how the guides and grooves are located in the Lid housing. Figure 116 (b) shows how the central wedge aligns the bracket to the Lid housing Figure 116 (c) is a plan elevation of how the bracket is aligned on top of the bosses that are used to fasten the housing together.

(a) *(b)* *(c)*

Figure 116: Assembly of the LED PCB holder in the Base housing

The four symbol buttons and the PS button (Figure 117) have been designed in such a way that no button can be inserted in the slot incorrectly (Figure 118). Appropriate guides in the buttons act as poke yoke to prevent incorrect assembly.

Figure 117: PlayStation Move Controller symbol buttons

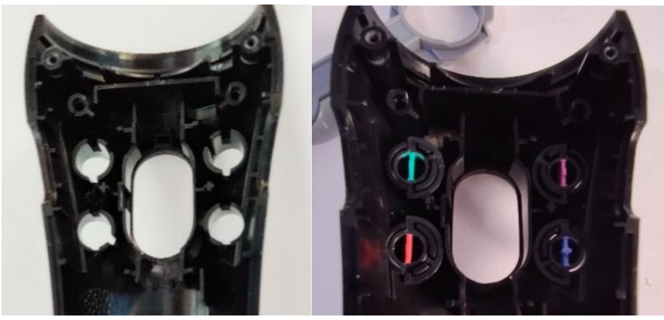


Figure 118: Base housings and symbol buttons assembly

Two alternating locating pins are used to align and position the motherboard on top of the Battery holder.

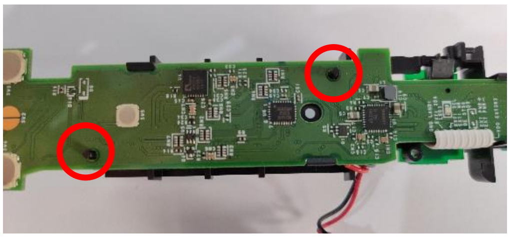


Figure 119: Locating Pins on the Battery holder to align the motherboard

As shown in Figure 120, a large locating pin on the Lid housing is present to align the assembly of the Base housing while closing the controller.

Figure 120: Locating pin on the Battery Holder to align the Base housing to the Lid housing

Similar to locating pins, lips allow two mating parts to be aligned together. Lips are present along the parting line of the hosing, specifically wherever two or more parts mate together. Figure 121 shows how the contour of the button is used as a lip that locates the button in the Base housing whilst acting as a stopper from moving outward from the preload of the torsion spring.

Figure 121: Trigger button

DFAG_13: Introduce guides and tapers to facilitate assembly	As can be seen in Figure 123, the side buttons (Figure 122) are assembled by inserting them into a slot, similar to the symbol buttons in Figure 118.

Figure 122: Plan elevation of the START button

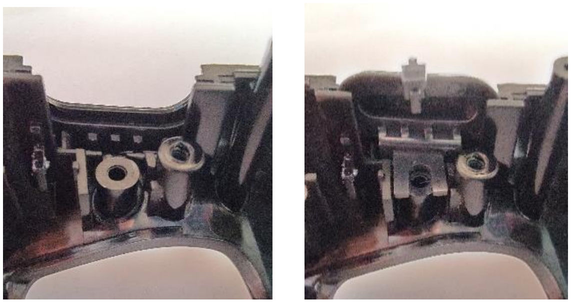


Figure 123: Start button inside respective guide

DFAG_14: Avoid component features that induce tangling or nesting.	The only component that can provide a degree of tangling is the torsion spring (Figure 124). Nesting is not possible since the length of the body is larger than the inner diameter. A vibratory bowl feeder will manage to untangle these torsion springs and lead them to appropriate gripper for assembly.

Figure 124: Torsion Spring

It can be generalised that only large parts are utilised in this switch apart from the torsion spring (Figure 124), the screws (Figure 103), foam pads (Figure 107 (c)) and the light guide at the bottom of the controller (Figure 100(a)). However, these are not considered very small and automatic assembly facilitates the feeding and positioning of parts.

DFAG_15: Remove sharp corners from components so that they are guided into their correct position during assembly

Ribs have been chamfered in order to remove sharp edges as shown in Figure 125.

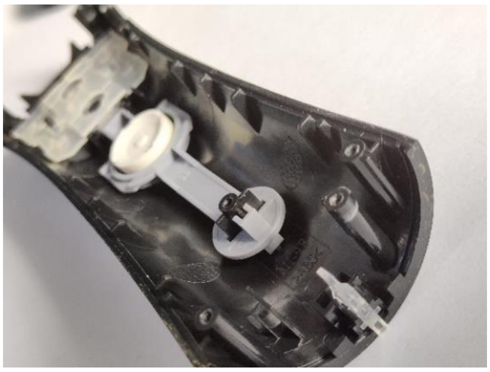


Figure 125: Chamfered ribs

DFAG_16: Avoid expensive and time-consuming fastening operations.

This controller utilises only 8 screws of the same type. These screws are driven into bosses without any knurled inserts. This means that the screws used are self-threading and a thread is automatically formed when tightening the screws for the first time. Furthermore, all screws are identical. This minimises inventory and number of different screwdrivers on the assembly line

Figure 126: A boss in the Lid housing

The use of clips and snap fits has been used extensively in the PS Move controller. Figure 127 shows three snap fit clips on the holder of the battery. The number of clips is limited to just three by alternating them. This makes assembly quicker whilst facilitating the design.

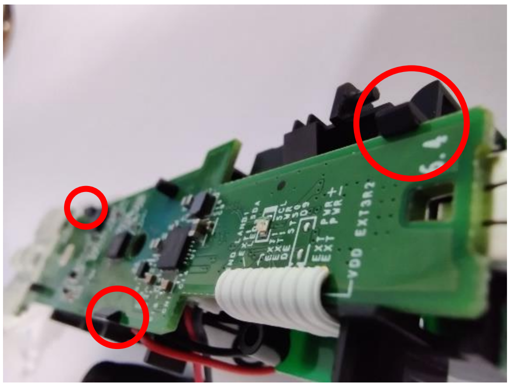


Figure 127: Three press-fit clips on alternating sides of the Battery Holder

The Lens is assembled to the Light bracket using snap fits. This fitting also secures the LED board in place as can be seen in Figure 128.

Figure 128:Light bracket sub-assembly

The Trigger button is assembled to the holder using a circular snap fit which allows the button to rotate, as shown in Figure 129. This design of circular snap fit will keep the button in place since the holder is fastened to the Base housing.

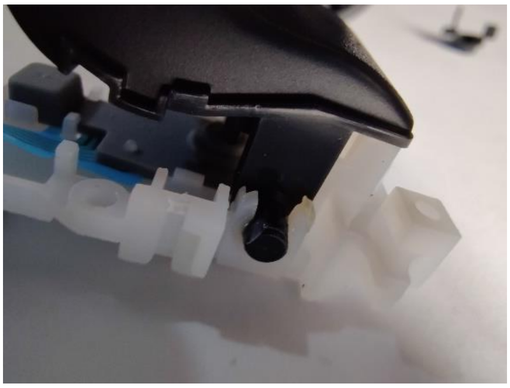


Figure 129: Circular snap fit in the Trigger button holder

DFAG_17: Design a vertically stacked product in order to achieve simpler top-down assemblies.

From the analysis carried out on the switch, it is conjectured that the assembly of the controller starts with the START and SELECT buttons where these are placed on the Base housing as shown in Figure 123.

Figure 107 illustrates how the Trigger button sub-assembly is then assembled on top of the Base housing followed by two screws which tightens the components together whilst holding the START and SELECT buttons in place. It is important to highlight that to complete the trigger button sub-assembly, one requires to rotate the Trigger button sub-assembly holder to assemble all the subcomponents, especially for the flex PCB.

Similar examples are shown in Figure 118 where the symbol buttons are vertically assembled, and Figure 125 depicts how the rubber mats and the Move button sub-assembly are stacked upon the symbol buttons.

Following the assembly of the buttons, the Light bracket is vertically installed in the Lid housing as shown in Figure 130 which is followed by the Battery / Vibration Motor sub-assembly which contains the main motherboard, the battery holder, the daughter boards, the vibration motor and the LED board as shown in Figure 131.

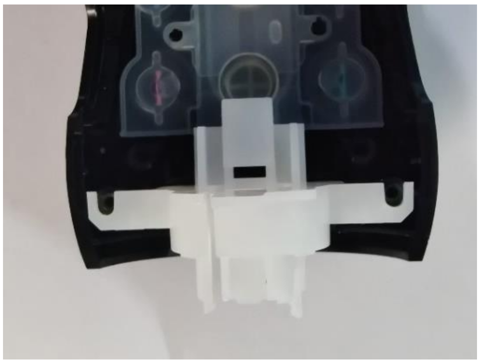


Figure 130: Light bracket bracket assembly on top of the Lid housing

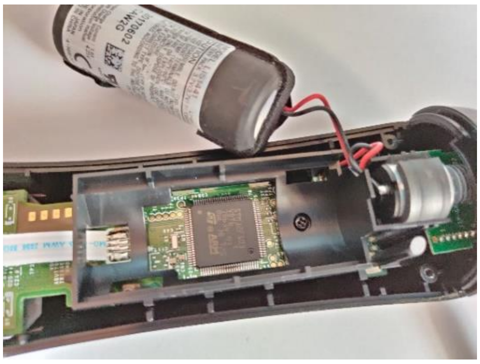


Figure 131: Assembly of the Battery-Vibration Motor sub-assembly on Lid housing

However, this design also contains some lateral assemblies. The ends of the controller needs to be assembled before the Base sub-assembly is placed on top of the Lid sub-assembly to close the controller. The ends of the controller are shown in Figure 132.

Once the lid sub-assembly is aligned on top of the base sub-assembly, the controller is closed using 4 screws. These are screwed vertically.

(a) *(b)*

Figure 132: (a) Orb-end of controller (b) Wrist strap-end of the controller

DFAG_18: Simplify handling of components.

PlayStation's Move VR controller makes use of a single flexible PCB (Figure 133) which resides in the Trigger Button Sub-Assy.

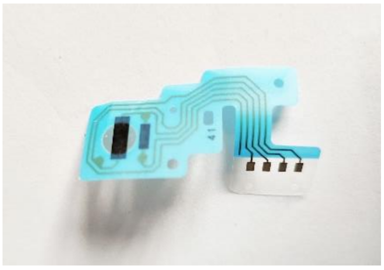


Figure 133: Flex PCB

Another Small part is a lightguide which is automatically assembled in the Lid housing.

Figure 134: Light guide

Also, two small daughterboards are used as shown in Figure 135. Since they are already soldered to a thick wire harness, assembly of these boards to the Battery Holder is not difficult and very manoeuvrable.

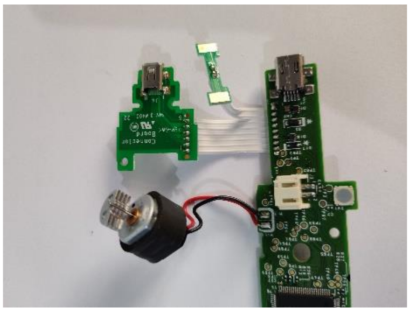


Figure 135: Two daughterboards and Vibration motor assembled to the motherboard

Another small daughterboard contains the LED of the controller's Orb as shown in Figure 136. However, since this board contains a long ribbon cable, the assembly of the board is very easy.

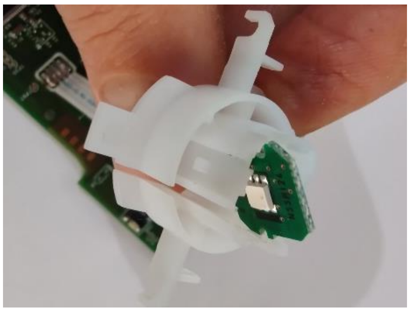


Figure 136: Assembly of the LED daughterboard

DFAG_19: Minimise tolerance and surface finish demands on components so that production costs are reduced.

As can be seen in Figure 137 the torsion spring is resting on the stopper of the Trigger button very loosely. The designer has allowed the torsion spring to move in a gap without imposing tight tolerances.

Figure 137: Torsion spring assembled in Trigger button

Both ends of the Torsion spring are not hindered by the sub-assembly but reside in specifically designed gaps (Figure 138) with enough tolerances to maintain good haptics of the Trigger button.

Figure 138: Torsion spring assembly in Trigger button -sub-assembly

DFAG_20: Designs should be made for ease of packing.

The PS Move controller is normally sold in pairs and given that the controllers are very compact and linear, the packaging is very economical as can be seen in Figure 139. Two controllers are fitted in a box measuring approximately 105mm x 226mm x 74mm (l/h/w).

(a) *(b)*

Figure 139: (a) Outer packaging (b) Internal packaging of the PS Move Controller (source: GamesQ8)

DFAG_21: Make sure disassembly is equally practicable as assembly.

The switch has been disassembled and re-assembled during the teardown analysis. There are a number of components (vibration motor, two daughter boards, and LED board) that are soldered directly to the PCB. Since the battery might get replaced during the use life phase of the controller, instead of soldering the battery to the board like the other components, a connector is used as shown in Figure 140.

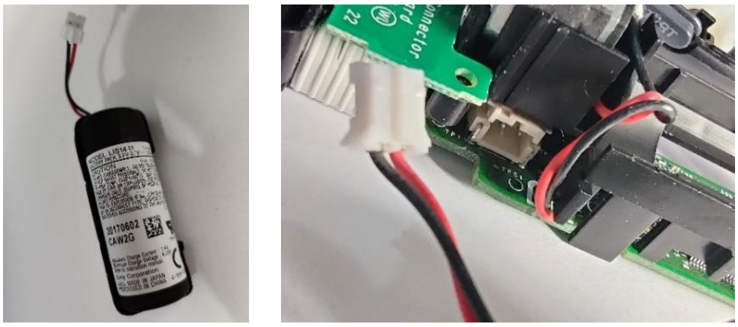


Figure 140: Battery assembly using a connector

It must be noted that the use of threading screws may limit the number of times of disassembling the controller since the plastic thread that is formed may get deteriorated over multiple disassembles.

DFAG_22: Develop the design to contain as many identical components as possible.

No identical parts are used except for the screws. However, as stated in DFAG_20, the controllers are sold in pairs. Therefore, for every VR System, twice the parts are needed.

DFAG_23: Introduce datum systems whenever a high degree of accuracy is necessary in the location of interchangeable components.

The datum is probably the middle of the housing between the Lid and Base housings as shown in Figure 141. This datum splits the switch in two main sub-assemblies.

Figure 141: Side elevation of the PS Move controller

Other Observations

DFAG_06: Where possible, plan for automatic assembly since parts that can be automatically assembled are easier to handle and assemble manually.

From the way the components are assembled, the Trigger button sub-assembly and Battery Holder sub-assembly require manual intervention. This is because both holders need to be oriented at least one time in order to place all sub-components. Although this is not a difficult task for a machine, the flexible PCB and the daughter boards need to be twisted in order to be placed in the correct position. Similarly, the LED board needs to be passed through the light bracket as shown in Figure 136.

5 DISCUSSION

In Section 4, the DFMA guidelines were reviewed and their application to the VR controllers was analysed. It could be seen that all controllers, intentionally or not, applied DFMA guidelines for the assembly of the controllers. Section 5.1 compares the three controllers based on critical aspects that are DFMA related, and section 13 discusses the applicability of these principles to auxetic structures, which is a key element in the PRIME-VR2 controllers.

5.1. VR controller comparison based on the DFA principles

Technology & number of parts

It was observed that the technology being used to track the motion of the controller heavily impacts the complexity of the controller. In terms of number of components, almost the same number of parts could be observed, with the PS Move having 37 different parts, the HTC Vive has 40 parts and the OTC contains 41 different parts. Due to the tracking technology used in the OTC, the controller is not ambidextrous, resulting in mirror image parts. This means that the number of components per a pair of controllers is double for the OTC.

The HTC Vive and the OTC use IR technology, where the former uses IR sensors and the latter one uses IR LEDs in the controllers, making them work in any light condition. On the other hand, the PS Move uses an RGB LED and it requires a dim lit environment for the camera to accurately track the glowing orb. By reducing the number of parts, as discussed in section 2.2, design associated costs, parts costs, manufacturing costs, assembly costs and other overheads are also reduced. Although all controllers show that an effort was done to reduce the number of parts, the PS Move design is deemed as the best example. One clear case where the PS Move implemented principle DFAG_08 better than the other controllers is in the trigger button. Both the Touch and Vive controllers make use of a metal pin on which the trigger button rotates, whilst the trigger button of the Move controller has an integrated shaft. The same applies for the Trigger button holder where the one of the PS Move is multifunctional. The Vive controller could have removed a part, 2 knurled inserts and 2 bolts if the wrist strap attachment feature has been integrated to the housing or adopted a simple stopper feature as was done in the OTC.

Dimension & product cost

Apart from the technology used, the size and ergonomics of the controller also affect the price. In terms of ergonomics, all controllers are grabbed similarly, making thorough use of the thumb due its range of movement and the forefinger. The Vive and the Touch controllers utilise the ability of grasping of the hand to actuate another button. The PS Move controller, which has a wand-like on the outside design, looks much simpler than the other controllers. This has contributed to having cheaper manufacturing costs. The OTC has the most compact design of all but is not the most expensive controller, whilst the HTC Vive is the most expensive and largest controller. Bigger parts imply bigger tools and more material used. However, it is deemed that a considerable portion of the overall cost is attributed to the 24 IR sensors residing in the tracker part of the controller. The tracker increases the weight and the dimensions of the controller but it is believed that HTC opted for this design to have a modular design for the stand-alone Vive Tracker, shown in Figure 142, which can be attached to other accessories.

Figure 142: Vive Tracker

All the parts of the three controllers are Injection Moulded. The Vive controller uses Overmoulding in almost all the buttons, On the other hand, 2K Moulding is used in the symbol buttons of the Move controller. The parts of the Touch controller are produced through normal injection moulding. With respect to the OTC, different surface finishes were included to introduce a contrast between the body and the trigger buttons. The use of injection moulding reflects the high volumes with which these controllers sell. The entertainment industry is quite large when compared to medical rehabilitation and thus it is a more competitive market.

Although they all use different technologies, the PS Move embraces the DFMA philosophy more than the other controllers. This is reflected in the simplicity of the parts and layout of the controller as will be discussed in the next sections.

Fastening operations

It is clear that the best examples in this category is the Move controller. It uses just 8 screws throughout the whole switch, compared to the Touch controller which uses 12 screws and the Vive controller that uses 33 bolts. Furthermore, the Move controller uses just 1 type of screw, whilst the Touch and the Vive use 5 types of screws and bolts respectively. Having just one type of fastener, the Move controller design team managed to drastically reduce inventory on the assembly line and possible assembly mistakes and number of suppliers. On the other hand, the Vive and Touch controllers require different screwdriver bits in order to fasten every bolt/screw.

The Touch and the Move controllers make use of self-threading screws while the HTC Vive uses bolts and knurled inserts to fasten parts together. Therefore, apart from having 33 bolts, the Vive utilise 33 corresponding knurled inserts. Furthermore, in the Vive controller, a drop of threadlocker is used on every bolt present. Although the size of the screws inside the OTC and the size of the bolts inside the Vive is not very different, screws have a large thread and potentially have a bigger surface overlap to plastic than bolts to threads. In case of the Move controller, the screws are much larger, meaning that the thread is even larger than that of the other controllers. The disadvantage of using screws compared to bolts is that unfastening the screws several times will damage the self-generated thread.

The use of bolts follows the Design for Disassembly (DFD) philosophy where the designer is encouraged to make a design that disassembly is as easy as assembly. In electronic consumer products, a very common problem that everyone experience is that the battery life deteriorates in time. The team of the OTC designed the controller to use a standard AA battery which can be easily replaced by opening a cover that secures with magnets. However, with respect to repair, the OTC is very difficult to disassemble since the top Fascia is attached using an adhesive.

From the teardown analysis it was concluded that the use of screws/bolts is inevitable in a handheld controller. The housing of the Vive controller can be closed using snap fits only but since the probability of falling to the floor is high, the controllers require strong, ‘permanent’ fasteners.

Snap fits have been used to assemble sub-assemblies, such as a PCBA with a housing, in order to support the final assembly of the switch. The OTC does not have any snap fit features, thus saving mould costs on undercuts, but makes use of magnets and double-sided tape. The latter provided very strong bonds between plastic/rubber and electronic components as it was very hard to detach the components.

Asymmetrical parts and mistake proofing

Through this review, one can see only three parts that were designed symmetrical in the axis of insertion: (1) Trackpad cover in the OTC, (2) the rubber Orb and (3) the Orb ring of the PS Move controller. The benefit of symmetrical parts is that less time is taken to assemble them in the controllers as the task to orient the parts is eliminated. On the other hand, most of the other parts in the Vive and Move controllers were symmetric in another axis as detailed in the review.

It was noted that features in sub-components were specifically designed to aid assembly and avoid assembly errors. This was seen in various locating pins with different diameters or with an offset to eliminate symmetricity. No symmetrical parts were noticed on the OTC.

Top-down assembly and self-alignment

A total top-down assembly allows parts to be assembled one after another requiring less automatic assembly stations. However, none of the switches are designed to be entirely top-down assemblies. The Move controller is made of two major top-down assemblies: one for the Lid and one for the Base. The Vive controller also has a similar assembly procedure for the main body but the assembly of the tracker’s components require additional assembly steps. The OTC, due to its form, requires the switch to be oriented several times in order to install all the components. Interesting to note that all housings and holders have been designed such that all parts are aligned in place before performing a fastening operation. Locating pins facilitated the assembly of all components, including the most difficult parts, that is, the flex PCBAs. The assembly of the latter parts is not top down as could be seen in sections 4.1.4 and 4.2.4. Furthermore, the Move controller only used one flex PCBAs which did not make use of any adhesive, thanks to its simple design.

Tangling parts and manual assembly

This part of the discussion analyses components from a manual assembly point of view. The easiest parts to handle were those of the Move controller. For instance, the screw size used makes them adequate for manual assembly. However, the bolts used in the Vive controller and OTC are small for manual assembly. Nonetheless, all switches could be reassembled manually after the teardown.

Obviously, the biggest assembly task there is, is in the Vive controller. It makes use of two long ribbon cables with several branches that house 24 IR sensor PCBAs. To manually attach each IR sensor PCBA requires the part to be handled and oriented several times so that they are placed on the right plane, keeping in mind that for each sensor PCBA, one needs to unwrap the backing of the double sided tape. With so many parts and complicated design of the Mountings, tangling is unavoidable. In the OTC one can find a similar assembly situation. However, since all the IR LEDs are assembled on the same circular plane, the branches of the IR LEDs do not need to be twisted and attached. The OTC has also two other ribbon cables which go from the main PCBA to the electronics in the knob. These require difficult manoeuvres. The daughterboards in the Move controller also need to be twisted in order to put them in place. However, this is a trivial step compared to the assembly of the ribbon cables on the other controllers.

5.2. Applicability to Low-volume Products

Low-volume production is a generic term used for production of specific, personalised or special artefacts that are not meant to be adequate for all end-users. Personalised devices, especially ones that are based on anthropomorphic data or human condition, need to be produced through low-volume production means, unless parts of the same devices are designed to be modular. The overhead costs of low-volume production runs are normally much higher than high-volume production since tooling cost is split on a fewer number of parts which increases the part cost. In high-volume production, costs are even lower because of the faster rate of production.

The benefits of the DFMA philosophy can be easily overlooked if one assumes that DFMA principles are only useful for high-volume products. This frame of mind is inappropriate because cost savings can be done on any design which does not embrace these guidelines The DFMA methodology is driven by a single purpose, that of identifying areas where unnecessary costs can be reduced, eliminated or prevented. The DFMA philosophy aims to reduce costs in every element listed in the product cost equation shown below.

Irrespective of the volume quantities, the cost of a product can be reduce if one tries to find ways to:

- Reduce the number of parts. Apart from using less material due to a smaller number of parts, this will have an impact on the assembly costs and overheads since less parts mean less steps to assembly and less chances to make mistakes and waste material. In case that a dedicated machine is required to manufacture a part, the elimination of that part would result in huge cost savings. Similarly, an outsourced part involves a lot of overheads such as inspections and logistics.
- Simplify the assembly process. By considering guidelines DFAG_10 to DFAG_23 one can find a myriad of opportunities to reduce assembly costs, especially if one embraces DFAG_06, that is, designing parts for a fully automated assembly line since parts that

can be automatically assembled are easier to handle and assemble manually. Thus, reding assembly costs and overheads.

- Choose the most suitable production process. Additive manufacturing has a lot of benefits, including the fact that certain part designs cannot be produce by a different process or would require operations. AM allows the manufacturing of customised parts, eliminating the need of investing in expensive tools for different parts.
- Use standard parts. Standard parts cost far less than custom made parts which would also require huge investments.
- Choose an adequate material. The DfMGs listed in section 3.2 provide guidelines on how the material is chosen. One should use familiar and commonly found materials in order to keep material and overheads costs low.
- Understand the capabilities of the chosen manufacturing process. Do not overdesign a part which will lead to a more expensive fabrication process.
- Reduce tight tolerances and eliminate expensive post process operations. Both tight tolerances and extra operations heavily increase the cost of manufacturing and overheads.

Therefore, even though the PRIME-VR2 project concerns customised controllers, one should still design the parts as if one is going to produce them in large volumes whilst keeping in mind the manufacturing process

6 DESIGN FOR ADDITIVE MANUFACTURING - GENERAL DESIGN CONSIDERATIONS

There are a number of fundamental design aspects that should be considered during the initial design phase concerning parts and components fabricated through *Additive Manufacturing* (AM). In this section, the different fundamental elements which are relevant to 3D printing will be considered. These include: layer height, shrinkage and warping, support structures and fillets. Further on this will be considered in relevance to the different existing AM technologies, in particular with respect to *Fused Deposition Modelling* (FDM), *Stereolithography* (SLA), *Digital Light Synthesis* (DLS) and *Selective Laser Sintering* (SLS).

There are several considerations in relation to DFA the designer should keep in mind. From the previous sections one can note that existing controllers are not manufactured using AM techniques. For instance, injection moulded components in existing components does not necessarily always apply to 3D printed components. However this does not rule out that internal assembly procedures from DFA might apply in the manufacturing of several parts such as vibration motors, PCBA, screws, bolts and battery components.

6.1. Layer height

The underlying principle of all 3D printing technologies is the additive manufacturing of parts and components layer by layer. Many factors contribute to the surface finish and the quality of the final product, however, *layer height* (also known as *z-axis resolution*) is typically the most influential parameter given no postprocessing is done [9]. Different layer heights in FDM can be observed in Figure 143.

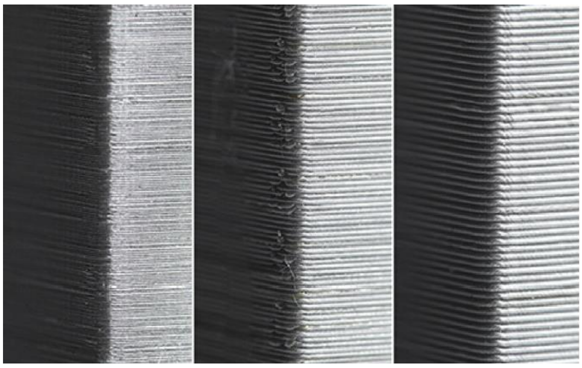


Figure 143: A macro view of three FDM prints with layer heights 50, 200 and 300 microns at the same scale [9]

A smaller layer height generally implies a smoother surface finish, a better accuracy and a greater ability to print finer details. A thicker layer will generally result in a faster print, however the respective layers may become visible once the product is printed. There exists a linear relationship between printing time and layer height such that a model with layer height of 50μm will take twice as long to print relative to the same model with a layer height of 100μm [9].

Most commercial 3D printers involve a default layer height setting consistent with the type of AM technology capability. Table 4 shows the common layer heights in relation to the type of AM technology in industry.

Table 4: Common layer heights in 3D printing [9].

Technology	**Common Layer Thickness** (*μm*)
FDM	50 – 400
SLA/DLS	24 – 100
SLS	100
Material Jetting	16 – 30
Binder Jetting	100
SLM	50

From Table 4, one can conclude that FDM will generally involve the roughest surface finish whilst material jetting offers the smoothest finish. The layer heights presented in Table 4 would generally fit different applications in industry, such as biomedical, automotive and aerospace applications. Layer heights can also be reduced to increase surface smoothness, however this may result in an increased printing time and cost.

6.2. Shrinkage and warping

Shrinkage and warping of 3D printed models is a common issue associated with 3D printing. Temperature and curing are two mechanisms which can typically cause such defects in the print [10], [11].

6.3. Temperature and Curing

Differential cooling and differences in temperature across the part during the 3D printing process can result in the development of residual stresses within the model which eventually cause warping and shrinkage. FDM, SLS and SLM (*powder bed fusion*) technologies all make use of elevated temperatures in order to print the desired geometries and thus the model is susceptible to heat-induced shrinkage and warping. This happens due to contraction of the material upon cooling which leads to material shrinkage [12], [13], [14]. This contraction will also affect the surrounding areas giving rise to internal residual stresses. In some cases, the model may warp and even form a number of cracks. SLA/DLS and Material Jetting processes do not essentially operate at elevated temperatures during the printing process. However, during the curing stage of the layers there might still be the development of shrunk and warped components. The models are usually exposed to a UV curing light source where, layer by layer, there is a solidification and shrinking process. Stress may develop between layers as one layer solidifies and shrinks but the subsequent layer does not [12], [15]. Therefore, during the curing process the model may still be subjected to internal stresses. This is also applicable during the post-curing process depending on the material characteristics, temperature and time of exposure to UV. Post-curing could lead to the relaxation of stresses, especially when the curing stage involves increased temperatures.

6.4. Minimising shrinkage and warping

The highest rates of differential cooling problems are typically associated with the thickest and largest portions of the printed part being connected together by means of thin features as explained further on. These thin features are typically subjected to warping due to faster cooling rates. Designers must take shrinkage and warping factors into consideration and keep a constant wall thickness throughout the part. This will ensure that warping and shrinkage are reduced. The aspect ratio can also impact shrinkage and warping. Reducing the difference between different sides of the geometry in terms of length, will also result in a reduction of shrinkage and warping.

Keeping a temperature-controlled printing environment through the use of industrial printers reduces the likelihood of shrinkage and warping. In particular, flat surfaces which are large in size are particularly prone to shrinkage and warping and should be kept to a minimum [12], [16], [15]. Ranges for these thicknesses are given later on in the document. If these cannot be avoided, designers should take into consideration multiple components to build and replace the same surface. Support material is crucial in order to anchor parts which are at a risk of warping, especially in SLM and SLA/DLS printing processes.

6.5. Support structures

Support structures are important in all 3D printing technologies, be it SLS, SLM, FDM or SLA [15]. Support structures are required for a successful and accurate print. Most of the times, support structures are required as a base platform such that layers can be printed upon this platform. A typical example of AM support is shown in Figure 144.

Figure 144: Printed component involving support structures build in SLA [17].

Upon choosing the type of 3D printing technology, designers must be careful what type of support structures will be integrated and in what way. Support structures generally require post-processing on the printed part for them to be removed. In turn this leads to poorer surface quality and decreased surface defects [11], [18]. Technologies such as FDM make use of dissolvable support structures so that material removal is facilitated. On the other hand, powder-based technologies do not require post-processing of any kind.

6.6. Fillets

Fillets are commonly included in the design as these help in the reduction of stress concentrations at the edges and at the corners of the part which facilitates printing. Some technologies create a *natural fillet* on each and every corner and edge upon 3D printing [15]. Technologies such as FDM produce an outer radius which is equal to the radius of the nozzle [19]. SLS printed parts generally have a minimum radius of about 0.4mm on sharp edges.

Designers should include fillets on printed parts wherever this is possible whilst the minimum radius should not exceed 2mm. Outer edges which are designed to be attached to the building plate may be substituted by a 45° chamfer since this does not require support material [20]. This is shown in Figure 145.

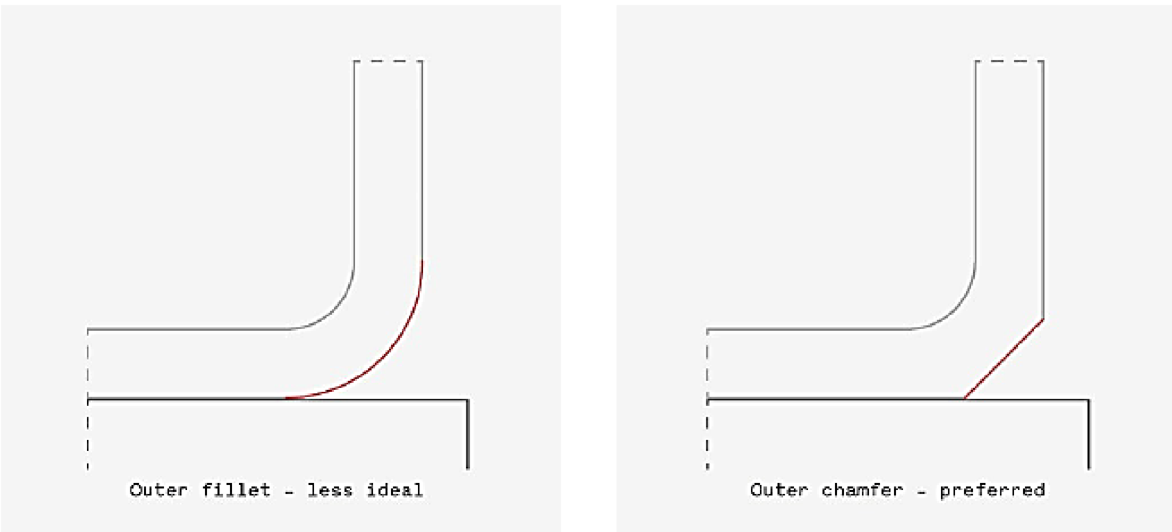
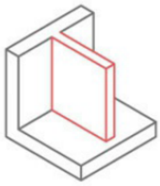
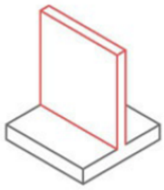
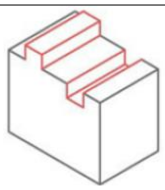


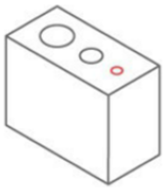
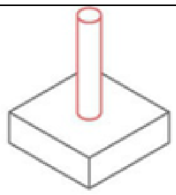
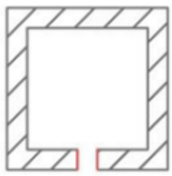
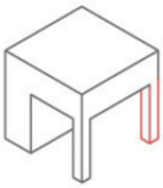
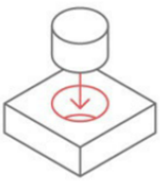
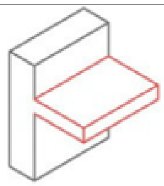
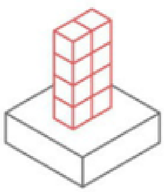
Figure 145: A fillet contacting the build edges as compared with a 45° chamfer [17].

7 DESIGN FEATURES IN ADDITIVE MANUFACTURING

In this section, a range of 3D printed design features which are commonly adopted in AM technologies will be provided. Table 5 presents a brief description of several design features which are applicable to all AM technologies.

Table 5: A represents a range of 3D printing design feature guidelines and their description [13], [14], [14], [18], [20]–[29].

Type	Feature	Guideline
Supported walls		*The minimum wall thickness for walls connected on two or more sides. These supported walls minimise the likelihood of warping.*
Unsupported walls		*The minimum wall thickness for walls connected to the remaining components of the printed part only on one side. The likelihood of warping of the printed part is higher.*
Overhangs		*The smallest angle for printed walls such that the wall may be manufactured without support structures. Walls printed at a lower angle may involve the use of support structures. This is also known as **self-supporting angle.***
Embossed & Engraved details		*The minimum height for print features and the minimum imprinted depth recessed on the part surface. These must not be too small as details may fuse together or with the rest of the part.*
Horizontal bridges		*The longest bridge length between any two points on the part which can be printed without the need of support structures.*

Holes		*The minimum diameter for successfully printing a circular hole. This varies from one technology to another.*
Pin diameter		*The minimum diameter for a printed pin which is the most reliable for the printer.*
Escape holes		*The minimum size for an escape hole which allows for post-processing material removal. Parts are usually printed hollow in order to save cost and weight. Escape holes are generally included to assist in the removal of build material following printing.*
Minimum feature		*The minimum thickness of 3D printed features in order to ensure the print is successful.*
Connecting & moving parts		*The clearance which is recommended based on the required component fit. When no fit is specified there is an assumption that the fit is an interlocking one. Clearance varies with the material chosen for the application.*
Unsupported Edges		*The maximum length of an overhang which is of a cantilever type.*
Aspect Ratio		*The maximum ratio corresponding to the vertical height of the print to the cross-section of the part. This will ensure a stable 3D printed part attached to the building plate.*

8 DESIGN GUIDELINES FOR FUSED DEPOSITION MODELLING (FDM)

FDM is typically considered as one of the simplest technologies in 3D printing. However, there are still a number of limitations worth considering within this technology. Primarily, FDM parts generally behave anisotropically [29]. Also, parts most of the time require the use of support structures. This section provides a description of FDM printing and the relevant applicable design features.

Overhangs are rather common features in FDM printing. As described in Table 5, an overhang exists whenever the topmost layer is only partially supported by the one below. Typical examples include curved surfaces or walls at an angle. In FDM, support material is generally required when the angle of an overhang is less than or equal to 45° relative to the horizontal [15], [17]. In this case, support material is required, as shown in Figure 146.

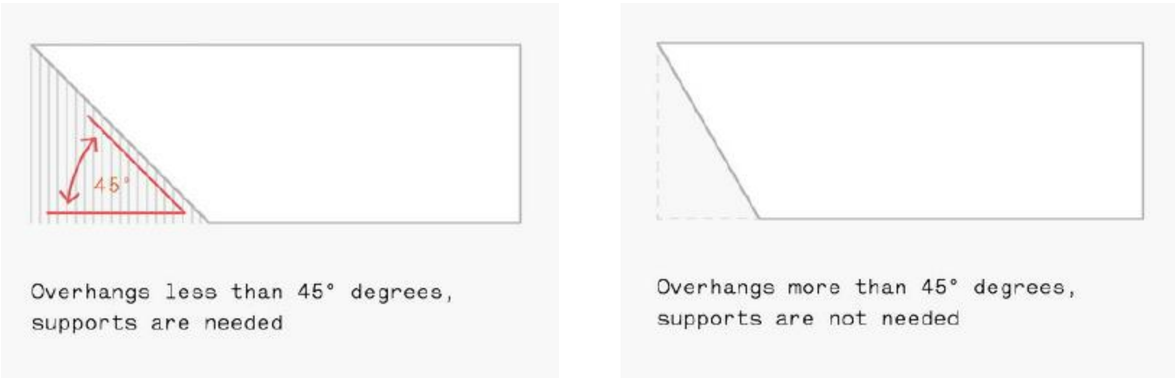


Figure 146: FDM prints require support for overhangs less than 45° [17].

If the angle of the overhang is less than 45° and no support material is used, then the quality of the finish from the manufacturing printing process will be drastically reduced. This effect can be seen in Figure 147.

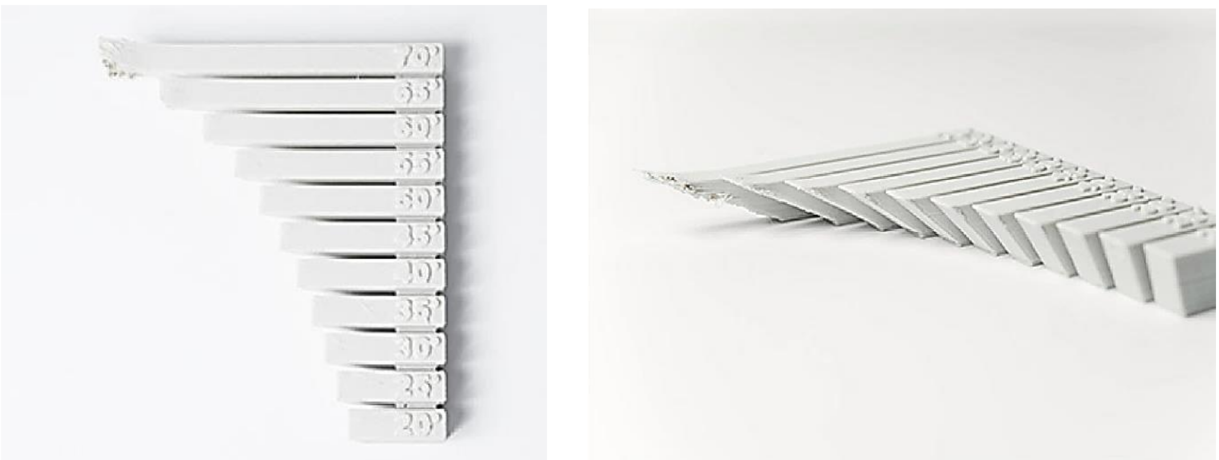


Figure 147: A reduction in surface quality is observed when the angle of the overhang in FDM printing is lower than 45° and printed without any support material [30].

There are three different ways on how material may be supported in FDM printing. These are *dissolvable support*, *accordion support* and *tree-like support* [17]. *Accordion* and *tree-like* support types are shown in Figure 148.

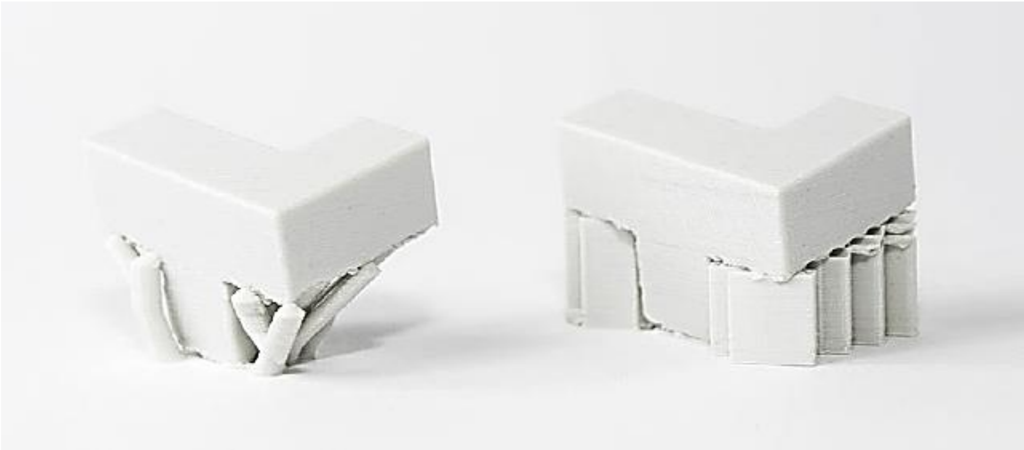


Figure 148: Different types of support. Left: Tree-like support and, Right: Accordion type support [14].

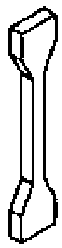
Some FDM printers made up of two printing heads are able to print dissolvable supports during the printing process. This is later washed away during post-processing. This will generally result in a smoother surface finish; however, this comes at an increased manufacturing cost and time. Dissolvable support materials should also match the material properties of the printed part such that the level of layer adhesion between the support and primary material is adequate. PLA and PVA are typically adequately suited for support materials [20], [29]. *Accordion support* is the most common type of support in FDM [20], [31]. This is because it can be achieved using single-head FDM printers. However, this type of support requires more support material than *tree-like support.*

The advantage of *tree-like support* in FDM is the improved surface finish after printing. This is because there is less contact with the primary material during the printing process. However, this type of support may result in unstable parts during printing such that only simple prints can be achieved using this support. The type of material support is generally determined by the designer of the printing operator.

8.1. Anisotropy

One disadvantage of FDM printing is the fact that manufactured parts are generally of an anisotropic nature such that mechanical properties vary in different directions. The strength of parts produced by FDM is typically defined through the adhesion between successive layers rather than through the material itself. Layer adhesion is dependent on the printer settings and its calibration [18], [23], [25]. During FDM printing the designer should take into consideration the orientation of the print to ensure that the performance is not negatively affected by the anisotropic behaviour of the printed part. Table 7 demonstrates the different ways how the performance of a part is affected due to the effect of anisotropic behaviour of the print.

Table 7: The effect of anisotropy of a printed part on its performance [11], [17], [32].

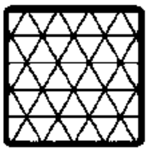
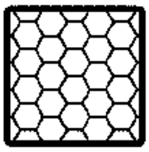
	Printed Vertical (Z-axis) 		**Printed Horizontal** (X, Y-axis) 	
Infill	**50%**	**100%**	**50%**	**100%**
Tensile strength (*MPa*)	4.4 ± 0.6	6.5 ± 1.8	17.0 ± 0.8	29.3 ± 0.8
Force at break (*MPa*)	2.7 ± 1.8	7.8 ± 1.3	13.6 ± 0.8	26.4 ± 1.8
Elongation at max force *(%)*	0.5 ± 0.1	0.7 ± 0.1	2.3 ± 0.1	2.4 ± 0.1
Elongation at break *(%)*	0.5 ± 0.2	0.7 ± 0.1	4.8 ± 0.9	3.7 ± 0.9
Relative tensile strength (*MPa/g*)	0.7 ± 0.1	0.8 ± 0.2	2.5 ± 0.1	3.0 ± 0.1
Elastic modulus (*MPa*)	1031 ± 53	1358 ± 139	1072 ± 38	2030 ± 45

8.2. Infills

The material used for infill in FDM printing is typically a low-density material. The infill percentage is directly proportional to the strength of the part. Most printers utilising FDM printing processes typically print parts with a setting of 20% infill. This is adequate in many applications. Infill material is particularly important in printing of auxetic materials due to the particular structure of these applications. Optimising the infill percentage is related to specifying the application of the product. A part where form is important for the application can involve a very low level infill, such as 10% [11], [14].

A part which experiences much higher loading will involve a denser infill. For instance, a bracket can involve a 100% (or fully-dense) infill material. Table 8 shows the four most popular infill shapes in FDM printing. In standard FDM printing process, a rectangular shape infill is generally used [15]. For a part which will be mounted or screwed the recommendation is a 50% infill. When a lightweight structure is required in combination with strength, a triangular infill is typically adopted.

Table 8: Stand FDM infill and geometries [33], [17], [15].

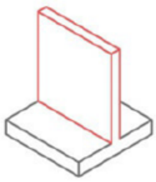
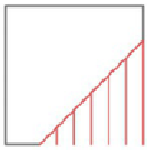
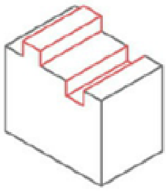
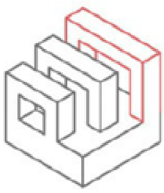
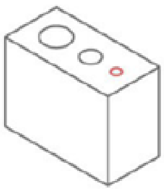
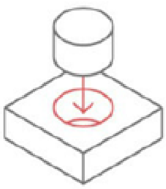
Type	Infill Geometry	Guideline
Rectangular		*This is the standard pattern of infill in FDM. Strength is in all directions and printing is relatively fast.*
Triangular or diagonal		*This pattern is typically used when strength is needed in the direction of the walls. A triangular infill will take a longer time to print.*
Wiggle		*Typically used in designs of parts which will need to compress, twist and be particularly soft such as with the case of nylon and rubbery materials.*
Honeycomb		*A very commonly used infill which is very strong and provides strength in all directions.*

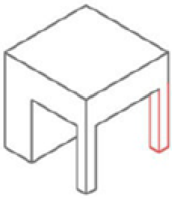
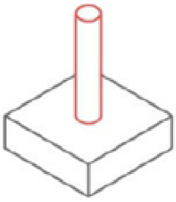
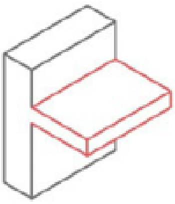
If strength is critical and a lightweight structure is desirable, honeycomb or triangular infills are generally used. Figure 149 shows a rectangular infill with different infill percentages for the same part printed in FDM.

Figure 149: Infill percentage. The variation ranges from 20%, 50% and 75%. (left, centre, right respectively) [17].

8.3. FDM design table

Table 9: A range of 3D printed design features used in FDM printing process [11], [13], [14], [20]–[23], [25]–[30], [34]–[37].

Design	Feature	Recommended value
Wall thickness		***0.8mm*** *FDM can produce wall thicknesses of down to 0.8mm. As a general design rule, wall thicknesses are generally a multiple of the nozzle diameter.*
Overhangs		***45°*** *Overhangs with an angle less than 45° require the use of support material.*
Embossed & Engraved details		***0.6mm wide x 2mm high*** *Embossing and engraving done with FDM should never be smaller than 0.6mm wide x 2mm high for them to be readable.*
Bridges		***10mm*** *10mm is the maximum length for unsupported horizontal bridges so as to avoid sagging.*
Holes		***⌀2.0mm*** *Holes produces with FDM are usually undersized in diameter. Usually, post-processing (drilling) is required for accurate holes. Holes with a diameter smaller than ⌀2.0mm are to be avoided.*
Clearance		***0.5mm*** *A spacing of 0.5mm should be allowed between parts when clearance is required. This varies according to the type of fit required.*

Feature size		***2.0mm*** *A minimum feature size of 2.0mm is required when printing with FDM.*
Pins		***⌀2.0mm*** *Vertical pins produced via FDM should not be smaller than a diameter of ⌀ 2.0mm. Printing different types of lattice structures, can lead to slightly different and decreased values in the dimensions*
Unsupported edges		***⌀3.0mm*** *Unsupported edges which are too long will experience a reduction in quality. Unsupported edges should therefore be not longer than 3.0mm. Printing different types of lattice structures, can lead to slightly different and decreased values in the dimensions*

9 DESIGN GUIDELINES FOR STEREOLITHOGRAPHY (SLA) AND DIGITAL LIGHT SYNTHESIS (DLS)

Vat polymerization AM technologies, such as Stereolithography (SLA) and Digital Light Synthesis (DLS; also known as *Digital Light Processing* or DLP), use light sources in order to cure resin which is typically a photopolymer [15], [36]. SLA and DLS are the most adequate processes for models which require smooth surfaces and high accuracy levels [15]. In this section different characteristics and design guidelines related to both SLA and DLS will be discussed.

9.1. Support structures and Part orientation

In general, SLA and DLS printers make use of support structures [17]. This prevents warping and reinforces all complex features and overhangs. One disadvantage of SLA/DLS is that these technologies do not support secondary material such as with the case of dissolvable support structures. This implies that support structures should be manually removed off the part during post-processing. The surface may therefore not be entirely smooth once the support is removed and thus further processing (such as sanding) may be required [36]. The designer should therefore specify all the necessary post-processing treatment that the part should undergo. Figure 150 shows a part printed in SLA where the final support structure is still attached to the part, which has to be removed later on.

Figure 150: 3D printed part in SLA with support structures still in place [17].

9.2. Top-down vs. Bottom-up printers

There are few design restrictions with using top-down printers. This means that printing parts can be aligned in any desirable orientation. Generally, a flat alignment orientation is chosen as this minimises the need for support structures and reduces manufacturing cost and printing time (see Figure 151).

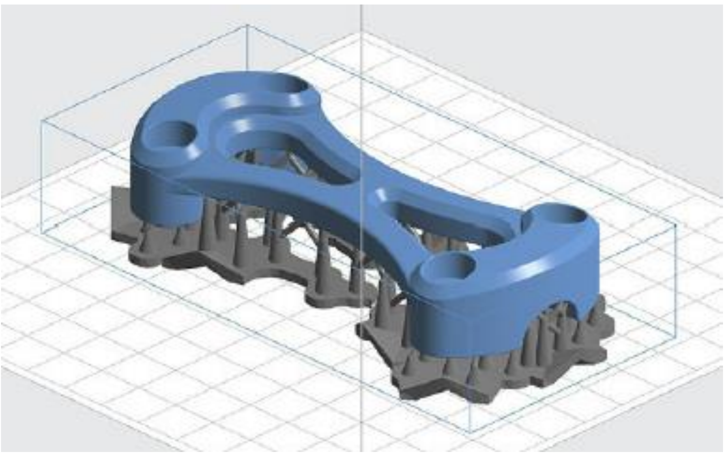


Figure 151: Flat-alignment part orientation for top-down SLA printing [37].

3D printers which utilise bottom-up printers typically involve support structures and more complex part orientations. Designers follow guidelines on how to orient a part when using bottom-up printers. A typical procedure is explained below [17], [37]:

1) Parts are oriented with their longest axis in parallel with the printer's front facing axis.
2) An effort is made such that the cross-sectional area of successive layers is reduced when orienting the part.
3) Enclosed cavities are oriented in such a way not to face the reservoir of resin.
4) The orientation is completed such that all layers build off over the previous layer. In turn, this reduces the dependence of the 3D print on support structures.

Many SLA and DLS 3D printers contain automated part orientation settings and may even suggest a method to create support for the geometry of the given part. In this case, a rule-of-thumb is followed to optimise the orientation for 3D printing. The rule consists of the following four steps [17], [37]. Figure 152 shows these steps being implemented at the design stage during CAD modelling.

a) Align part such that its longest axis and the *x-axis* of the printer are in parallel;
b) Rotate by 60° on *y-axis;*
c) Rotate by 60°on *z-axis;*
d) Create support material.

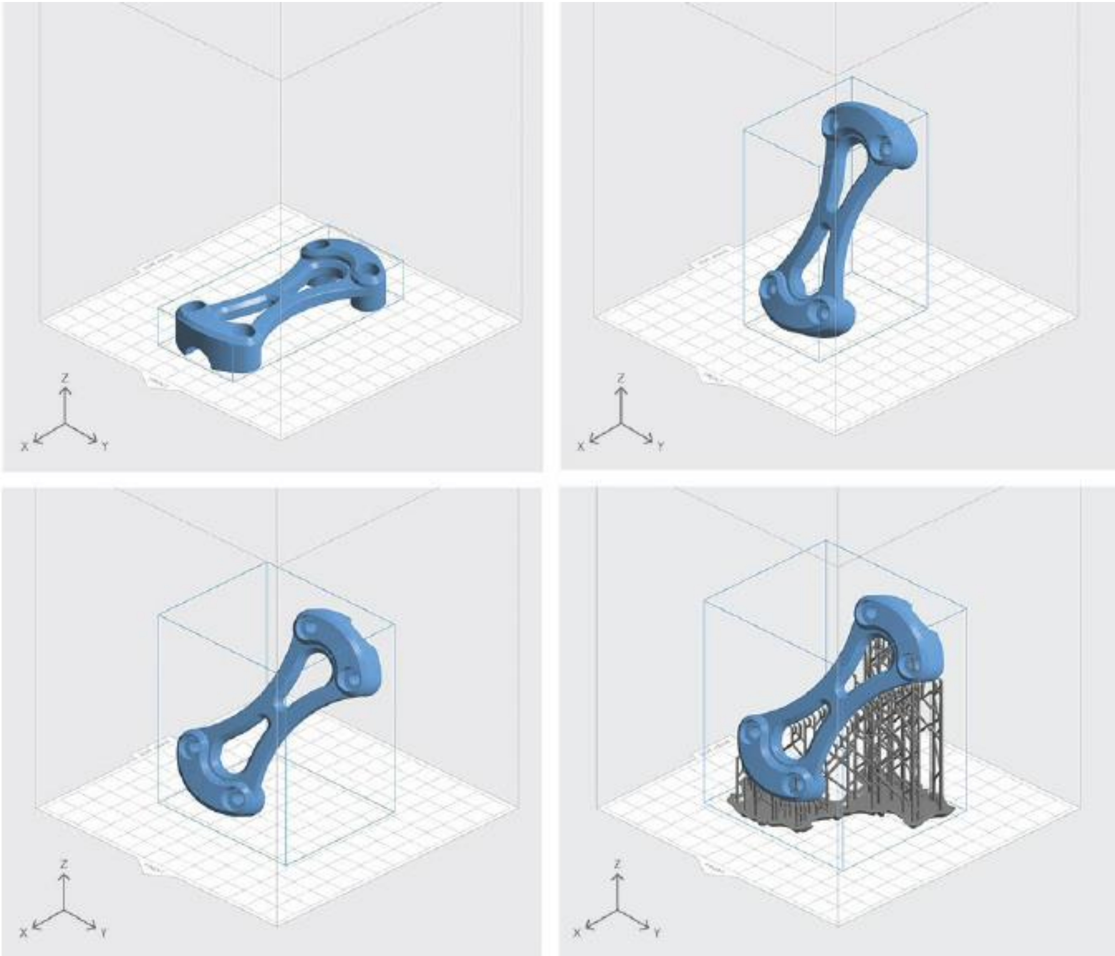


Figure 152: Orienting a part to be printed in SLA/DLS [37].

This procedure is applicable to all parts since positioning is very crucial in DLS. By printing a model at an angle, surface area of each layer is reduced whilst also decreasing the amount of contact the print has with the tank. Reducing the surface area means that the print is subject to less force as the build platform raises with each layer.

9.3. Hollow sections

Hollow designs should always be included in parts printed with SLA/DLS [30], [35], [37]. This is because they reduce material consumption and costs related to printing. Designers should ensure that hollow sections do not require any internal structures to provide support as these may be challenging to remove during post-processing. Hollow sections may also trap air and resin which is undesirable. For this reason, the addition of escape holes will help to eliminate these detrimental effects. Figure 153 shows a procedure to add escape holes during the design stage.

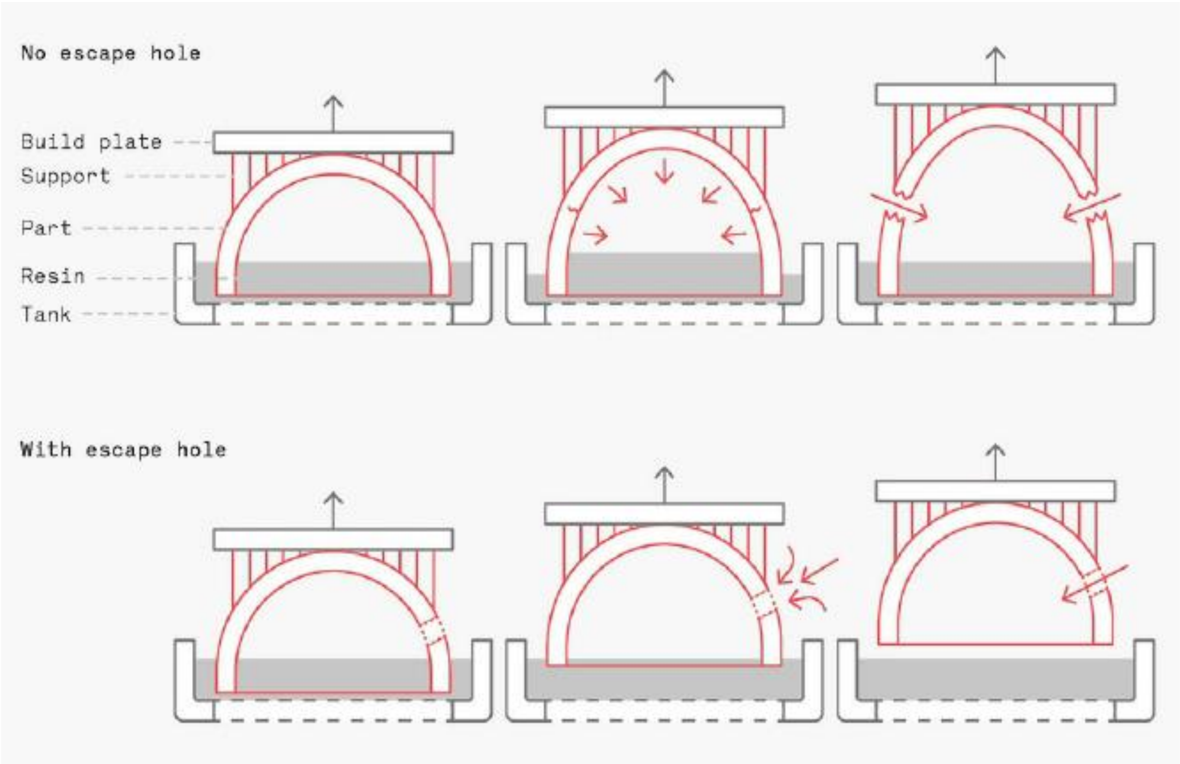
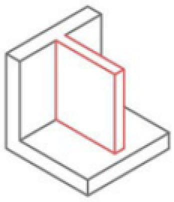
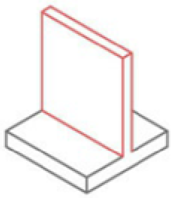
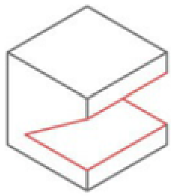
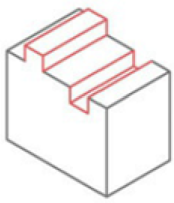
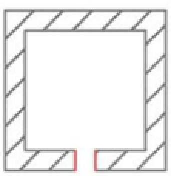


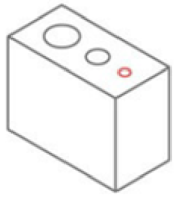
Figure 153: Adding escape holes during the design stage to reduce the detrimental effects brought about by trapped air and resin following manufacturing [9].

The minimum diameter for escape holes should be at least 4mm to allow resin to drain out during post-processing [17]. Escape holes with a smaller diameter can lead to trapped resin which is never removed from hollow sections after manufacturing. Escape holes are to be placed either at corners of the part or at the highest/lowest level of the part in order to facilitate the resin drain [17], [19]. If the part design permits, escape holes are to be placed opposite each other.

9.4. SLA and DLS design table

Table 10: A range of design features used in SLA/DLS printing process [11], [13], [14], [20]–[23], [25]–[30], [34]–[37].

Design	Feature	Recommended value
Supported walls		***0.5mm*** *The thickness of the wall is dependent on its length. Longer walls require thicker sections. Supported walls are never thinner than 0.5mm*
Unsupported walls		***1.0mm*** *The minimum thickness for unsupported walls should be 1.0mm. This will avoid detachment or warping during 3D printing.*
Overhangs		***1.0mm*** *Unsupported overhangs should not exceed a length of 1.0mm. A minimum angle of 19° from the level should be kept.*
Embossed & Engraved detail		***Embossing – 0.1mm, Engraving – 0.4mm*** *Embossing should be done at a minimum of 0.1mm above the model's surface. Engraving should be done at a minimum of 0.4mm below the model's surface. Embossing typically results in better readability than engraved details.*
Escape holes		***4mm*** *A minimum of 4mm diameter should be allowed to permit effective resin drain through hollow sections. The design should involve as many escape holes as the design permits.*

Holes		***0.5mm*** *Holes should have a diameter of at least 0.5mm. Holes less than 0.5mm can close off during the printing process.*

10 DESIGN GUIDELINES FOR SELECTIVE LASER SINTERING (SLS)

Selective Laser Sintering is a type of polymer powder bed fusion technique which sinters powder by utilising laser technology [30]. SLS is a very popular 3D printing technique since this eliminates the need of support structures as the part is entirely surrounded by powered during manufacturing. SLS is typically recommended when the effects of distortion and warping of the parts are to be kept as minimal as possible.

10.1. Shrinkage, warping and distortion.

In order to cater for shrinkage factors during additive manufacturing, SLS parts are typically designed with a 3–3.5% increase in overall geometry [17]. Shrinking is predictable and in general will not affect 3D printing of the model [10]. This is usually an automated step by the printer software. Most issues in SLS printing arise due to distortion and warping of particularly large and flat surfaces which results in very poor-quality print [11], [16], [38]. In this case, large flat surfaces and thick features should be avoided as much as possible.

10.2. Part orientation

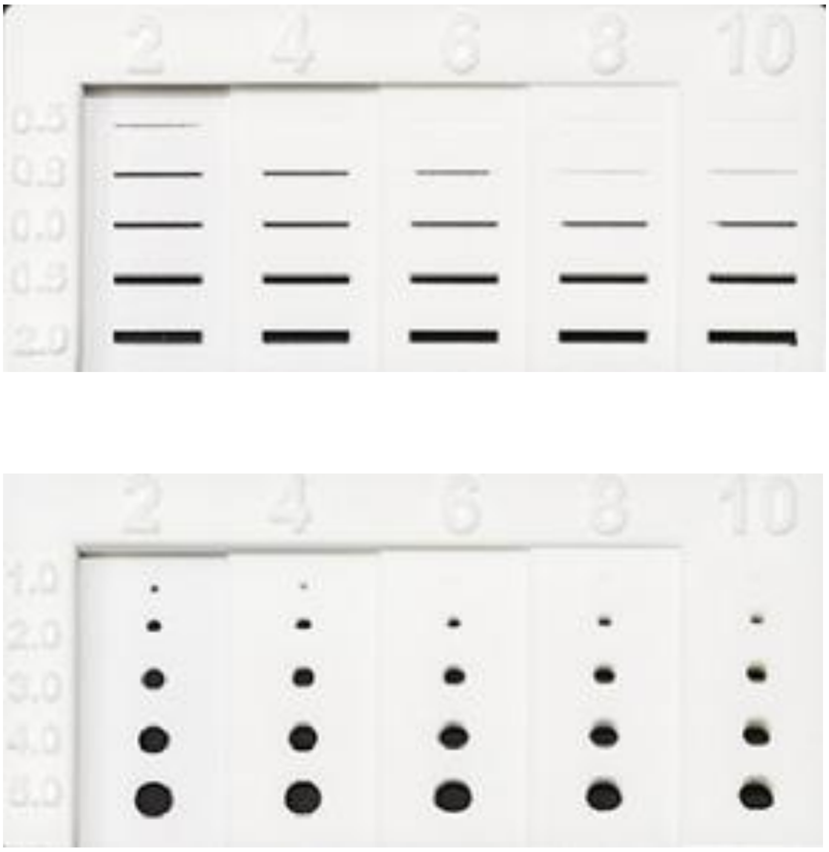
Particularly long features on the model may result in a large temperature gradient due to the laser having to travel a long distance from one point to another. This may effectively lead to warping as a result of differential cooling [17], [30]. In view of these effects, parts are typically oriented in such a way that the fastest heat dissipation rate is attained.

10.3. Reduction in part mass

One way of reducing warping and distortion of the part is to reduce the overall mass at the design stage. When mass is reduced, heat dissipation occurs at a faster rate and thus the likelihood of warping is minimised. On the other hand, the designer should always follow the minimum specified dimensions for manufacturing. A reduction in part mass also implies a reduced cost of manufacturing [36].

10.4. Over-sintering

When non-sintered powder is fused around a design feature, *over-sintering* occurs which results in a loss of detail in the corresponding features. Some features may also entirely close up due to *over-sintering* such as with the case of small holes or slots [36]. A common example of *over-sintering* of holes and slots during manufacturing is shown in Figure 154.



(a) (b) (c) (d) (e)

Figure 154: The result of over-sintering on hole and slot features [17]. Over-sintering is increasing from (a) to (e).

Figure 154 and Tables 11 and 12 can be used by the designer as a reference to assess the suitability of the minimum suggested hole size and slot size in relation to the thickness of wall of the part. One should note that a reduction in wall thickness will reduce the likelihood of over-sintering.

Table 11: Minimum printable slot size relative to part wall thickness in SLS printing [15], [17], [36].

		Wall Thickness				
		2	*4*	*6*	*8*	*10*
Slot Width	0.5	✓	×	×	×	×
	0.8	✓	✓	✓	×	×
	1.0	✓	✓	✓	✓	✓
	1.5	✓	✓	✓	✓	✓
	2.0	✓	✓	✓	✓	✓

Table 12: Minimum printable hole size relative to part wall thickness in SLS printing [15], [17], [36].

		Wall Thickness				
		2	*4*	*6*	*8*	*10*
Hole Size	1	✓	×	×	×	×
	2	✓	✓	✓	✓	✓
	3	✓	✓	✓	✓	✓
	4	✓	✓	✓	✓	✓
	5	✓	✓	✓	✓	✓

10.5. Powder removal

Powder removal in SLS 3D printing is generally achieved by means of compressed air. The designer should include as much escape holes as possible as is the case in SLA/DLS. Escape holes should at least be 10 mm in diameter [30]. Figure 155 shows a 3D printed bracket (SLS nylon) with several slots used in powder removal.

Figure 155: Functional bracket printed with SLS printing technology with several slots for powder removal [39].

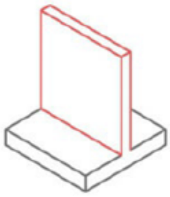
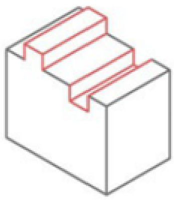
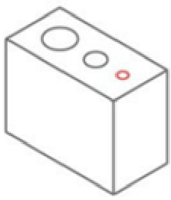
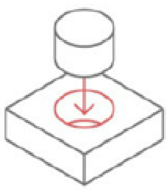
10.6. Hollow sections and Blind holes

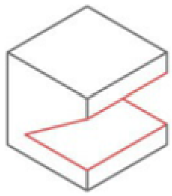
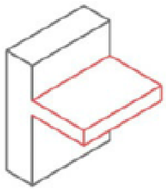
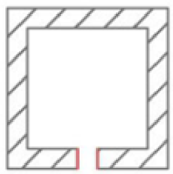
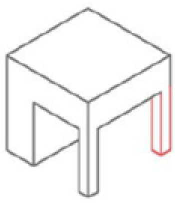
SLS is highly adequate for printing *hollow sections* since this technology does not rely in internal support structures for hollow sections. Hollow sections are generally desired as these reduce the amount of mass and cost of the printed part. *Blind holes* are holes that stop mid-way through the part and therefore do not travel the entire way throughout the model. As a rule-of-thumb, designers should avoid blind holes if the model is to be printed using SLS as it may be challenging to remove powder during post-processing. The designer should aim for through holes, otherwise, small holes with a diameter of at least 2mm should be included at the base of blind holes to assist powder removal [19], [31], [40].

10.7. SLS design table

Table 13 shows recommended values for various design features as applied to SLS technique in AM.

Table 13: Design features used in SLS printing process [11], [13], [14], [14], [15], [20]–[26], [32], [34], [38], [40], [41].

Type	Feature	Recommended value
Wall thickness		***0.7mm – 2.0mm*** *Wall thickness varies with different materials. Wall thickness should be a minimum of 0.7mm for materials like Nylon 12 (PA 12). Wall thickness should be a minimum of 2.0mm for materials such as glass and carbon-filled powder.*
Embossed & Engraved detail		***1mm height/depth*** *All details should be a minimum 1mm above or below the surface in order to ensure maximum visibility. Engraving is generally clearer and more visible in SLS 3D printing.*
Holes		***1.5mm*** *A minimum of 1.5mm diameter should be allowed in order to avoid over-sintering.*
Connecting and moving parts		***0.1mm – 0.3mm*** *The type of connection is relevant to the clearance value. A clearance of 0.05mm on each side is recommended for connection parts. A clearance of 0.15mm on each side is recommended for moving parts such as shafts and hinges.*

Overhangs		***>30°*** *Overhangs should exceed 30°. This is because as the angle of overhangs decreases, there is a higher chance for inner corners within the structure to fuse together.*
Unsupported edges		***50mm length x 1mm thickness*** *SLS can easily print unsupported edges however these would be at a high risk of breaking during the stage of powder removal if these are too long or too thin. As a guideline, unsupported edges should be no thinner than 1mm and no longer than 50mm.*
Escape holes		***1x ⌀10mm (or 2x ⌀5mm)*** *In order to save weight and cost, SLS components should be printed hollow. Escape holes must be included after production to remove un-sintered powder. Multiples escape holes should be a minimum of ⌀5mm.*
Minimum Feature Size		***0.8mm*** *A minimum of 0.8mm should be the size of features such as pins, fins and protruding sections. This will allow the ability of the printer to print such features.*

11 DESIGN GUIDELINES FOR PHOTOPOLYMER JETTING (POLYJET)

PolyJet printing is a technique similar to Inkjet printing however rather than jetting ink drops on paper, the 3D printer jet multiple layers of liquid photopolymer on a tray. Figure 156 shows the principle of PolyJet printing.

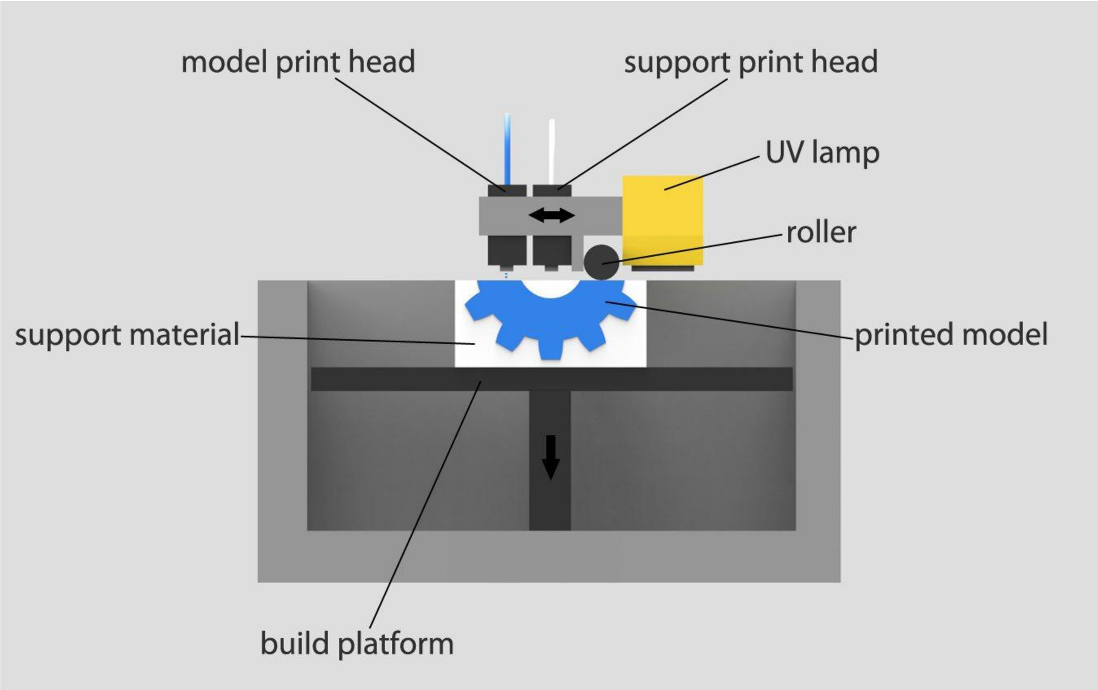


Figure 156: PolyJet printing [57].

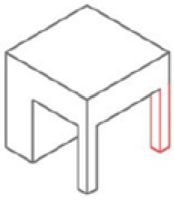
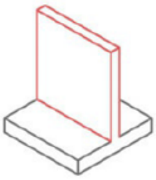
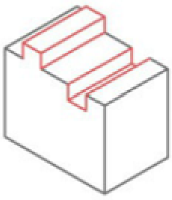
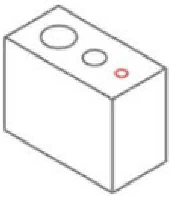
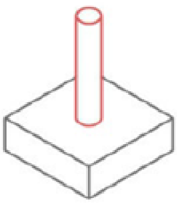
Like all 3D printing techniques, PolyJet begins the process through conversion of the CAD file to STL format. The printing head of the 3D printer will jet and cure photopolymeric material simultaneously through UV light. The printer will add support structures automatically which generally involves the addition of a gel-like material for support. Post-processing in PolyJet printing requires a manual step to remove the supports which involves spraying the model with a WaterJet such that the support material is washed away [56], [58]. There is also the possibility to use solvable support structures in PolyJet printing [58].

PolyJet 3D printing supports multi-material printing. This can be achieved since PolyJet incorporates full colour and multiple material properties into a single model without the need of secondary operations. This makes the technique adequate for realistic printing of parts during conceptual modelling and prototyping. The PolyJet printing process is very fast in relation to all other techniques mentioned, however this is dependent on the part size and required resolution. PolyJet printing is considered a very accurate 3D printing technology and can print layers as thin as 27 microns [56], [58]. The process is unlikely to involve warping and shrinking of the part since the PolyJet technique does not involve heat.

11.1. Design for PolyJet printing

There are several design considerations one should take when designing for PolyJet 3D printing. Table 14 lists some of the key design considerations done in this technology that should be followed.

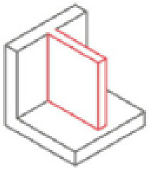
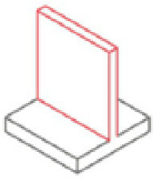
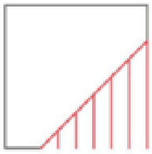
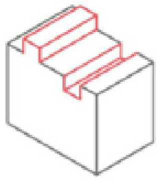
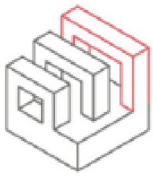
Table 14: A range of design features used in PolyJet printing process [56], [58].

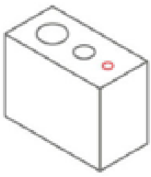
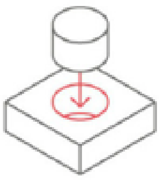
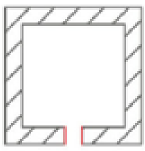
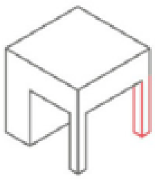
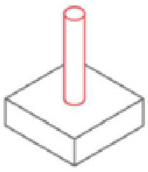
Design	Feature	Recommended value
Feature size		***0.5mm*** *A minimum feature size of 0.5mm is required when printing with PolyJet.*
Wall thickness		***0.25mm*** *PolyJet can produce wall thicknesses of as little as 0.25mm.*
Embossed & Engraved details		***0.5mm*** *Both embossing and engraving should be at least 0.5mm below or above the surface of the printed part.*
Holes		***0.5mm*** *Holes should have a diameter of at least 0.5mm. Holes less than 0.5mm can close off during the printing process.*
Pins		***⌀0.5mm*** *Vertical pins produced via PolyJet should not be smaller than a diameter of ⌀0.5mm.*

12 DESIGN FOR MANUFACTURING – A SUMMARY

Table 15 provides a general summary of the rules and guidelines for each technology explained earlier. This may be used as reference when it comes to selecting the most appropriate 3D printing technology when fabricating the bespoke controllers in the PRIME-VR2 project.

Table 15: Summary of Rules and Guidelines for different manufacturing techniques [12], [14], [14]–[17], [20], [20], [21], [24], [25], [32], [38], [41]–[43], [56], [58]

	Supported Walls	**Unsupported Walls**	**Support**	**Embossed & Engraved Details**	**Horizontal Bridges**
					
FDM	0.8mm	0.8mm	45°	0.6mm width 2mm height	10mm
SLA/DLS	0.5mm	1.0mm	Support required	0.4mm width and height	×
SLS	0.7mm	×	×	1.0mm width and height	×
PolyJet	0.7mm	0.7mm	30°	1.0mm width and height	×

	Holes	**Moving & Connected Parts**	**Escape Holes**	**Minimum Features**	**Pin Diameter**
					
FDM	⌀ 2.0mm	0.5mm	×	2.0mm	3.0mm
SLA/DLS	⌀ 0.5mm	0.5mm	4.0mm	0.2mm	0.5mm
SLS	⌀ 1.5mm	0.3mm for moving parts 0.1mm for connections	5.0mm	0.8mm	0.8mm
PolyJet	⌀ 1.5mm	0.1mm for connections 0.1mm for moving parts	10.0mm	0.8mm	×

13 APPLICABILITY OF DFMA RULES TO AUXETIC STRUCTURES

There is currently a significant ongoing research effort aimed at defining the effects of the geometry of a material within the design space of a particular structure. Local geometrical modification is observed to be directly proportional to a change in mechanical properties of the same material [51]. This inter-dependence can be achieved only through the integration of lattice structures whose configuration is based on nodes and beams.

At the time of writing, it is difficult to interpret the DFMA principles on generic auxetic structures which are mostly composed of empty space that changes depending on the type of force that it is applied. The fact that an auxetic structure moves in space, requires the use of ribbon cables that are long enough to extend when the structure expands and flexible to move when the structure contracts from an assembly point of view. Nevertheless, one has to consider the technical challenges that ribbon cables generated in the analysed controllers and foresee their adaptability to auxetic structure designs to determine whether it is feasible to integrate them or not.

From a manufacturing point of view, the pattern of the lattice is the fundamental element of the geometry of the structure. This is also applicable to auxetic lattices, whether homogeneous or heterogenous. The pattern is based on strut connections between nodes, and the number and position of the nodes. There is a large number of lattice patterns that the structure could accommodate. The most popular lattice patterns mostly suitable for additive manufacturing processes include Cubic, Octet-truss, Hexa-truss, Open-cell foam and Diamond. Figure 157 shows a cross-sectional illustration of four different patterns for the lattice structures, including octet-truss, cubic, hexa-truss and open-cell elementary unit.

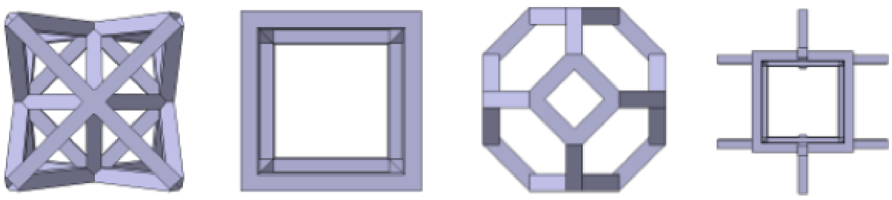


Figure 157: Four different patterns for the lattice structures. From left to right: octet-truss, cubic, hexa-truss and open-cell elementary unit [52].

It is important to test lattice structures in different orientations which is particularly important in the testing of auxetic lattices [53]. The type of pattern can also determine whether the system exhibits a negative Poisson's ratio or not and therefore whether auxetic behaviour will be displayed or not [53]. The testing orientation is generally relative to the applied load in order to establish the mechanical properties in the different directions. The variation in the pattern of the lattice structure is replicated by the angle of the force being applied. For instance, when considering a cubic lattice pattern, this can be divided into two separate orientations upon applying the force at an angle of 0° and at an angle of 45° (refer to Figure 158). The angle of the applied force is therefore very important in determining the mechanical properties of the lattice structure.

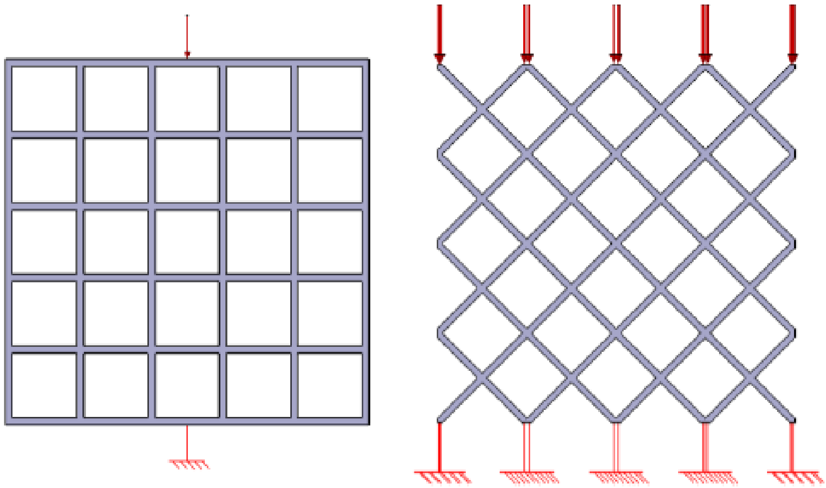


Figure158: Cubic pattern lattice structure at an angle of 0° and 45° [52].

A typical strategy for the computational design of homogeneous and heterogeneous structures usually involves an initial topological optimisation of the design space in order to get a good idea of the distribution of material within system. This optimisation will output a fundamental structure which can be used as a basis to generate a lattice structure design. The computational design and optimisation techniques can also be extended and applied to include multi-material structures which is particularly useful in the field of multi-material additive manufacturing [54]. Additive Manufacturing (AM) is typically beneficial in this aspect since sophisticated geometries can be easily printed via different AM techniques. This is because there is no requirement in AM for specialised tooling and so manufacturing costs can be kept at a minimum.

AM techniques which are adequate for the fabrication of lattice structures including auxetic lattices include: Fused Deposition Modelling (FDM), Selective Laser Melting (SLM), Stereolithography, PolyJet printing, Electron Beam Melting (EBM) and Selective Laser Sintering (SLS) [55]. AM has many advantages when lattice structures are integrated within the material, however, there are several constraints the designer should be aware of at the design stage. Support structures are typically required in order to dissipate heat during printing and to avoid the collapse of any overhangs [52]. Any unmelted powder has to be removed following the manufacturing process which gives rise to the need of post surface treatment.

The current lattice structure design methods are generally not tailored in a way to optimise the requirements in AM. Ongoing research tries to investigate and explore solutions to such an issue. The field of design rules for additive manufacturing and the optimisation of lattice structures seek to improve the reliability in applying these guidelines in AM. There does not exist, to date, a single selection method for the pattern of lattice structures which is applicable in all applications.

14 CONCLUSION

This document gave a detailed account of the most important DFMA principles used in electronic consumer products specifically focusing on VR controllers by analysing how such principles have been applied to the HTC Vive, Oculus Touch and PlayStation Move controllers. These have been analysed from an assembly and a manufacturing perspective. The most important DFMA takeaways are to:

- reduce the number of parts by combining parts together
- design parts which are adequate for a specific additive manufacturing (AM) technique
- simplify the design as much as possible
- understand the working principles behind different AM techniques used in industry which are applicable to the manufacturing of the controllers
- facilitate the assembly process by having vertical stacking, adequately sized symmetrical parts, guiding pins and self-locating parts.
- keep in mind the manufacturing technique to use during fabrication together with the mechanical processing the parts will be subjected to.

There are a number of DFMA takeaways in view of auxetic materials in particular with respect to additive manufacturing. The most important ones are:

- In auxetic structures, the lattice design is the fundamental element of the configuration and geometry of the material. Lattice architecture should be taken into account primarily when choosing the AM technique.
- There are several auxetic lattice patterns suitable for AM. In particular the most popular ones include cubic, octet-truss, hexa-truss, open-cell foam and diamond patterns.
- Testing of auxetic structures should be done in different orientations.
- Auxetic structures should initially be designed computationally. This involves the differentiation of homogeneous from heterogeneous structures followed by a topological optimisation of the design space to obtain the best auxetic architecture suitable for AM.

AM techniques which are adequate for the manufacturing of auxetic materials include FDM, SLM, SLA, EBM and SLS. These considerations have been taken on board the PRIME-VR2 project and communicated primarily with the design and manufacturing team including UOM, L1D and UOS. Potential AM techniques include FDM, SLA and DLS with material selection options including materials with performance characteristics close to ABS for the rigid elements combined with a low shore hardness flexible material. Potential filament materials include PLA and TPU filaments for prototyping and experimentation. Objet and SLA resins are two potential material in terms of the final product. Other possibilities may also include multi-material FDM printing. In all cases each DFMA guideline highlighted above in view of FDM, SLA and DLS apply to the product.

It was observed that the company with the most experience in manufacturing is Sony (established in 1946), followed by HTC (established in 1997) and then Oculus (established in 2012). Nonetheless, Oculus did the best job in creating the smallest and most aesthetically pleasing controller that feels part of your hand and which can be accurately tracked thanks to the several IR LEDs it incorporates.

The intention of this deliverable is to provide foundational thinking as input to Work Packages 3 and 5 in order to guide the mechanical design of the controllers and the respective electronic components. The document will serve as a guideline for the designers to create a functional product adequate for manufacturing satisfying the different requirements for assembly and 3D printing. The document will also be useful in choosing the appropriate manufacturing technique for the bespoke controllers.

As a concluding remark, it is important to keep in mind that the life of VR controllers, which are normally entertainment type of consumer products, heavily depends on the system on which they are used. Due to the fast-paced technological breakthroughs that we had in the past years, such systems do not last longer than a decade as they get replaced by a newer generation technology. One should also understand that controllers are typically not manufactured from AM techniques and this manufacturing technology may have variable impacts on the product and the materials in consideration. In particular, materials used in additive manufacturing behave differently and therefore each DFMA principles will vary with the performance of different materials. Since the aim is to use them in the healthcare industry, it is important to realise the lifetime of such devices in health clinics. The DFMA philosophy targets the early life of a product that is, before reaching the end user. It is important that designers also consider the use, maintenance and disposal and recyclability life phases in their design as these can affect the modes of manufacturing and assembly.

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16 APPENDIX I

16.1. Common Form Features used with Plastics

Whilst designing a part, a designer must consider material properties, processing and external operating conditions apart from the actual form per se in order to make sure that the part does not fail during its lifecycle. Design Safety factors can be pre-considered and factored in the design [7]. Design factors are considered when there will be stress, strain, shear or other forces.

Tres mentions the following design factors:

- design static safety factor – for constant forces on a part
- design dynamic safety factor – for intermittent/cyclic forces on a part (part is subjected to fatigue)
- design time-related factor – commonly related to creep and stress-relaxation on the part whose lifetime decreases with time. A safety factor decreases with time. When a product fails, the safety factor becomes 1. Therefore, safety factors need to be calculated by measuring its properties, say stress, after failure and compare them with the original material properties.
- material properties safety factor – such factor considers imperfections and defects in the material which allows
- processing safety factors – for defects arising during manufacturing such as weld lines, etc.
- operating condition safety factor – for abnormal operating conditions such as high humidity, ultraviolet exposure, saline water immersion, high or low temperatures, presence of corrosive agents, etc.

16.2. Basic plastic part design

The following sub-sections introduce the novice designer to common terms and guidelines for designing basic features used in products. These guidelines are for the development of plastic parts using Injection Moulding.

16.2.1. Wall thickness

The best wall thickness (*t*) of plastic parts is 3mm (0.125in) [7]. A uniform wall thickness should ideally be kept throughout the design as thicker or thinner places will affect the flow of material in case of Injection Moulding. For instance, flow of material from thin to thick will cause warpage. Other wall thickness such as 0.5mm (0.02 in) to a maximum of 6.5mm (0.25 in) are also acceptable but beyond the 6mm wall thickness parts may be inconsistent due to warpage, internal voids and air pockets, causing the parts to fail unexpectedly. With wall thicknesses that are below 0.5mm only very high melt flow resins are used - the chances are that frozen layers are formed on the core and cavity and increasing the injection pressure is not an option because the tool (mould) may split.

16.2.2. Fillets

Plastic parts must not have sharp corners. Corners need to be replaced by fillet radii in order to reduce stress concentrations which cause air voids, sink marks, and air entrapments that weaken the structural of the part. Figure159 (a) shows a poor corner junction with three sharp corners. As one can note, sharp corners create larger wall thicknesses, causing the area not to cool down uniformly and sinking of the surrounding walls and/or air voids. An improved design is shown in Figure159 (b) where the outer corner has been replaced by a fillet having a thickness twice of the wall thickness (2*t*). However, there are still two sharp corners. These are removed in Figure 159(c), making this design the ideal for injection moulding.

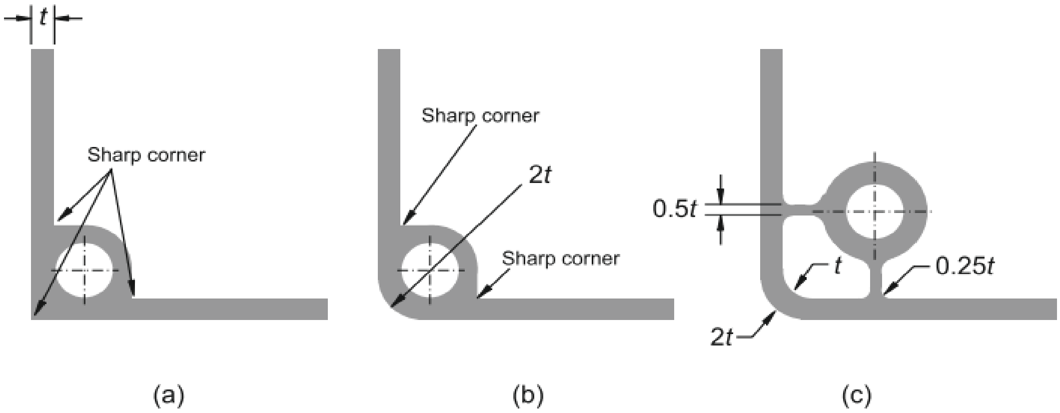


Figure159: Fillet radii (a) poor, (b) better, and (c) best [7].

16.2.3. Bosses

Bosses are used to mechanically fasten parts together. The boss in Figure 160(a) is not deep enough and thus a large area of plastic will be present which will not cool off during the injection moulding cycle. After the mould opens and the pin (forming the boss) is ejected, air voids and sink marks will form.

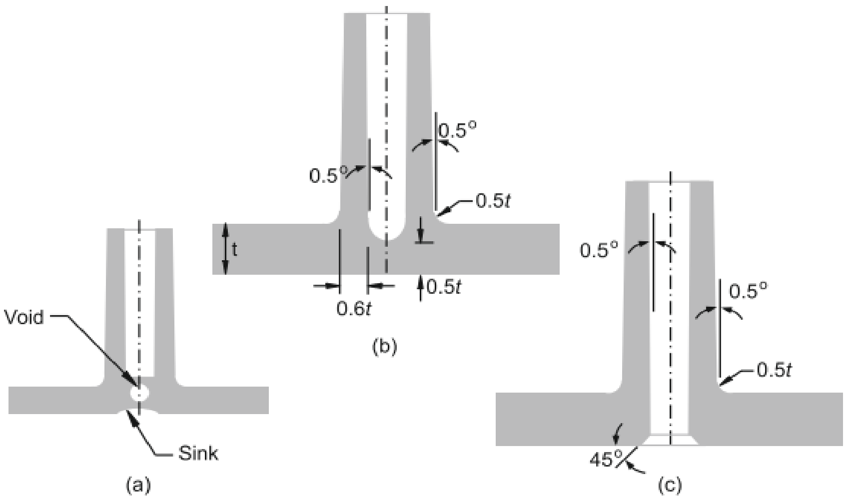


Figure 160: Boss design: (a) poor, (b) good, (c) good

The boss in Figure 160(b) goes a little deeper such that the area under the boss has a thickness of 0.5*t.* This should avoid the formation of sink marks and air voids. However, Tres (2017) remarks that if the opposite surface is very smooth and the injected material is a highly shrinkable resin the sink mark will still be created [7]. This can only be eliminated by opting for the design shown in Figure 160(c), that is, making the boss go through the material. One must also note that bosses should have a tapered design (draft) having an internal and external angle of about 0.5°.

16.2.4. Ribs

Ribs are used to increase the overall strength of a component. As a general rule, ribs with a height smaller than 1.5*t* do not add much value (see Figure 161a). Likewise, ribs exceeding the height of 5*t* create manufacturing process problems as it would be more difficult to eject the part due to vacuum that results from deep ribs. For large ribs, vents should be added at the tip of the ribs to vacuum from prevention.

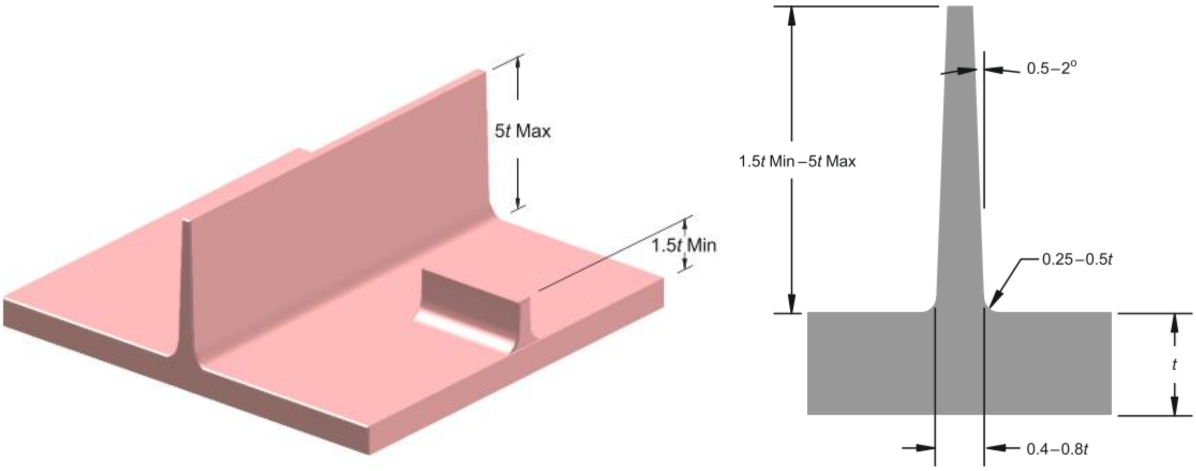


Figure 161: Recommended (a) rib height, (b) rib width or thickness, [7].

In Figure 161b, recommended rib design guidelines are illustrated. Depending on the type of thermoplastic material that will be injected (amorphous or crystalline), the rib thickness is varied accordingly. When semi-crystalline materials are used, since this category of materials, is prone for shrinking, one should make ribs' width very small – example 0.4t for Polypropylene. For amorphous polymers, rib width can be higher: example 0.6t for Polycarbonate. However, when both types of materials are reinforced and filled with glass fibres, rib thickness can be increased up to 0.8*t*.

As with bosses, in ribs draft angles greater or equal to 0.5° per side are imposed in order to facilitate ejection of the part from the tool. Draft angles can increase up to 2° per side for complex structures. Another general rule that Tres (2017) highlights for rib design is that if the rib has a textured design. The draft angle must increase by 2° for each 0.025mm of grain depth. Finally, ribs' bases should be filleted by a radius of 0.25*t*-0.5*t*, not more and not less.

Ribs are added to parts to mainly reduce component weight (and material), improve manufacturability (e.g. reduce injection moulding times) and the performance of the part. With regard to performance, properly located ribs, can increase compression and tensile forces that a part can withstand.

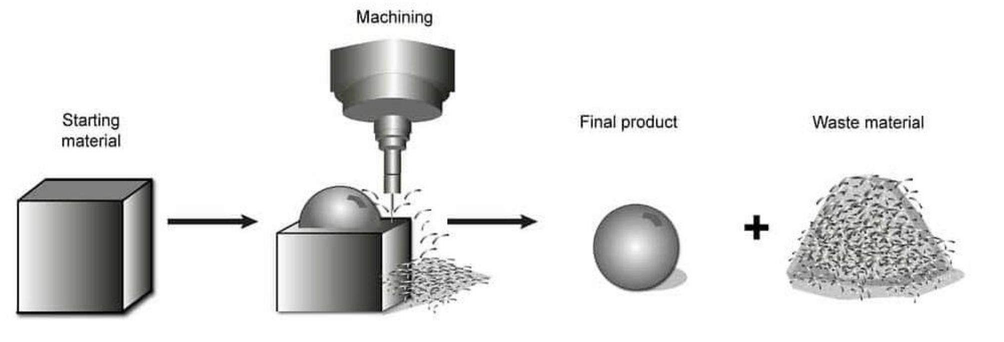
Detailed guidelines on rib design can be found in Chapter 3, Section 10 of *Designing Plastic Parts for Assembly*. *Designing Plastic Parts for Assembly* [7]. Guidelines for interference fit can be found in Chapter 6 of *Designing Plastic Parts for Assembly*. *Designing Plastic Parts for Assembly* [7].

17 APPENDIX II: THE PROCESS CHAIN FOR ADDITIVE MANUFACTURING

17.1. Background to Additive Manufacturing

Additive Manufacturing process allows physical components to be built layer by layer from 3D virtual CAD models. The manufacturing process effectively operates by printing one layer on top of a previous layer until the entire part is finished. Layer thickness may range from a few microns up to around 0.25mm per layer [1]. FDM can print up to around 0.4mm per layer. This is opposed to *Subtractive Manufacturing* whereby unwanted material is removed from an initial block of material [36]. The two processes are shown in Figure 162 below.

(a) Subtractive Manufacturing



(b) Additive Manufacturing

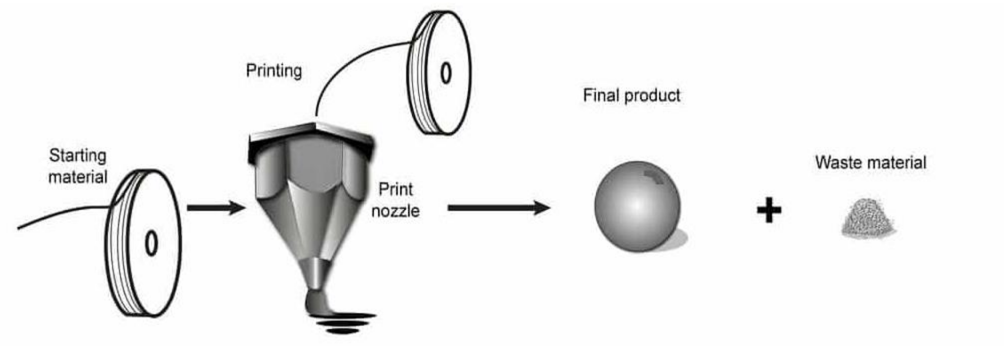


Figure 162: (a): Subtractive Manufacturing, where a part is built by removing material from a block, and (b) Additive Manufacturing, where a part is built layer by layer [36].

17.2. The Additive Manufacturing Process Chain

The additive manufacturing process starts with the creation of a 3D CAD model in a virtual space. Almost all CAD modelling software support model export to additive manufacturing. The model should be watertight such that no gaps exist and all faces of the product are included in the model.

Some CAD modelling software are also capable of fixing the model such that any existing gaps are closed and the prototype can be physically printed. The CAD file will then be converted to a file format recognizable for AM. Typically this is an STL file which stands for standard tessellation language format. In this manner the model is divided into a number of triangles where a higher resolution implies a larger number of triangles. Other more recent AM file formats to STL, include *3D Manufacturing Format* (3MF) and *Additive Manufacturing File Format* (AMF). Figure 163 below shows an open surface model which is *non-watertight* and thus not suitable for AM. Figure 164 compares low resolution, with medium and high-resolution elemental models obtained through the CAD model.

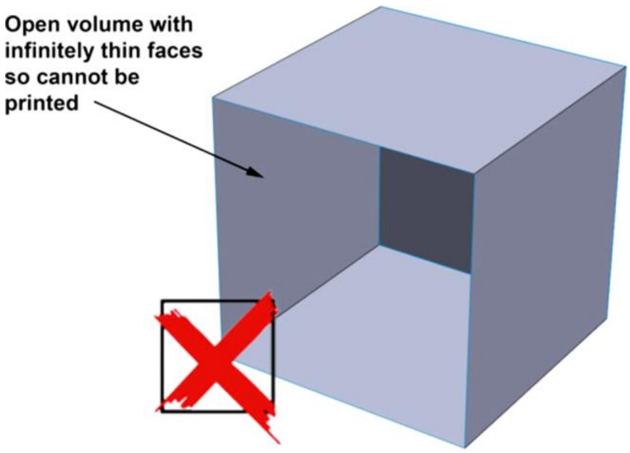


Figure 163: A non-watertight model (open surface). This model cannot be manufactured using 3D printing [11].

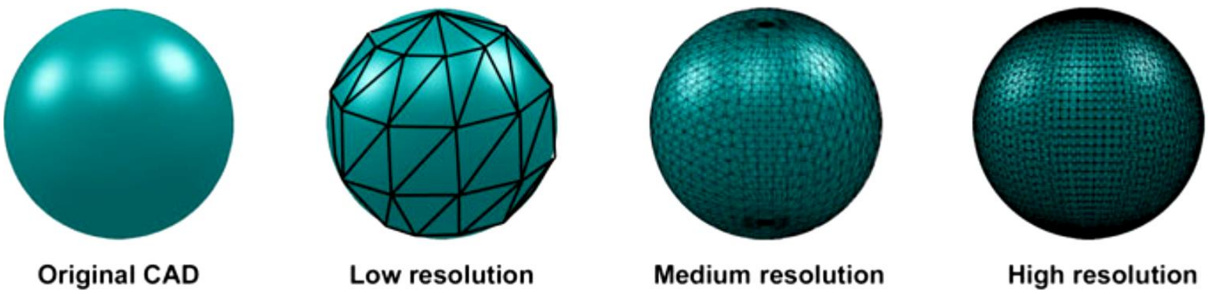


Figure 164: Examples of STL file resolution [11].

Although it is possible to print directly from CAD files, most individuals prefer to transfer the model to STL file since most 3D printers are compatible with this file format. Once the model is translated to STL, this is opened on the printer's software which optimises the orientation of the part in order to print the model. The printing orientation affects the product surface quality, and the integrity of the component. The printer will then slice the STL part into thin layers and set a number of parameters including print speed and time [36], [40], [41]. Some components require support materials as shown in Figure 165. This is defined by the manufacturing process chosen.

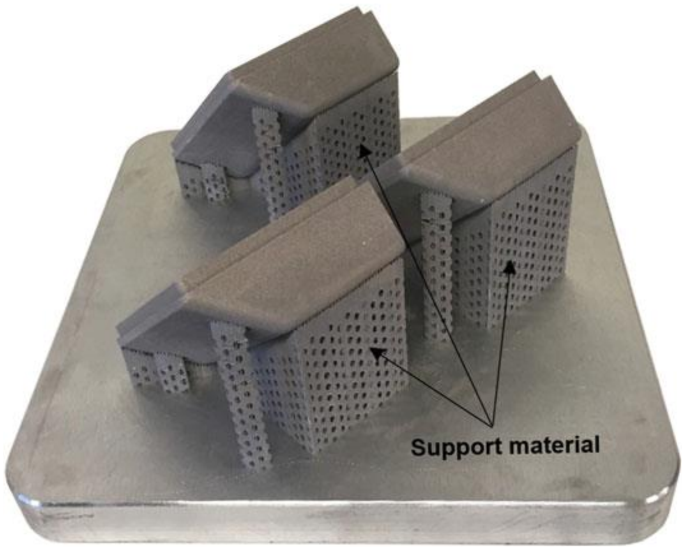


Figure 165: Support material required by some AM processes [36].

Once the file has been sliced by the printer's software the printing process begins and the machine starts building the component layer by layer (Figure 166). Following the printing process, post-processing follows which includes cleaning of the part from any powder or resin, further processing (such as machining), and removal of any existing support structures. Furthermore, post-processing may involve heat treatment and infiltration to increase the strength of the printed part.

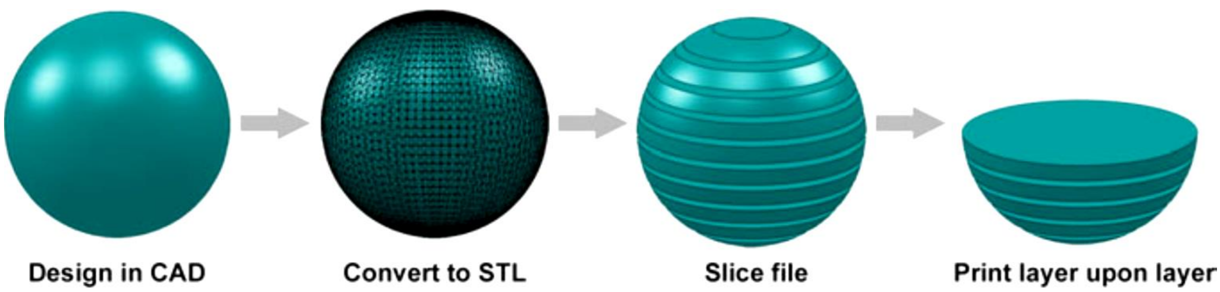


Figure 166: The additive manufacturing process chain [36].

18 APPENDIX III: OTHER WORKING PRINCIPLES IN ADDITIVE MANUFACTURING

18.1. Material Extrusion

The most common material extrusion based additive manufacturing technology is *Fused Deposition Modelling* or FDM. This technology operates by extruding fine material filaments, typically a polymer, in order to trace out each layer of the model being built. The platform holding the model will then move down fractionally in order to make space for a new layer to be printed. The polymeric material will fuse together as this is initially in its molten state and bonds with the previous layer [19], [26], [36]. Figure 167 shows the process of FDM in additive manufacturing.

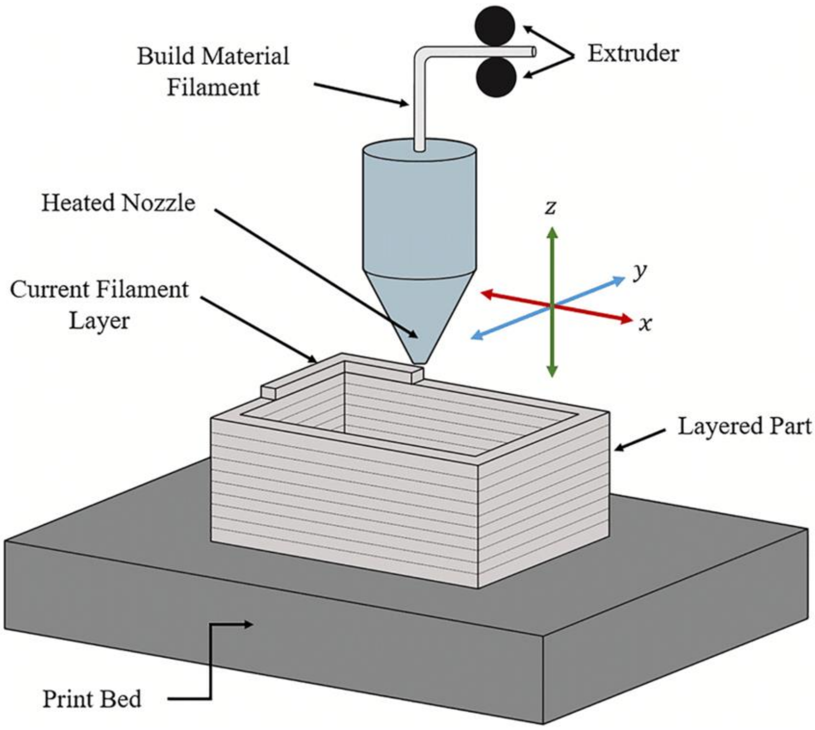


Figure 167: Material extrusion-based additive manufacturing system [45].

Particular consideration should be given to the shrinking factor of the material as some polymeric materials can shrink by up to 20% [36]. Surface finish of the part can also be an issue. In material extrusion the *stair-step effect* can also be observed during printing of uneven surfaces, as shown in Figure 168.

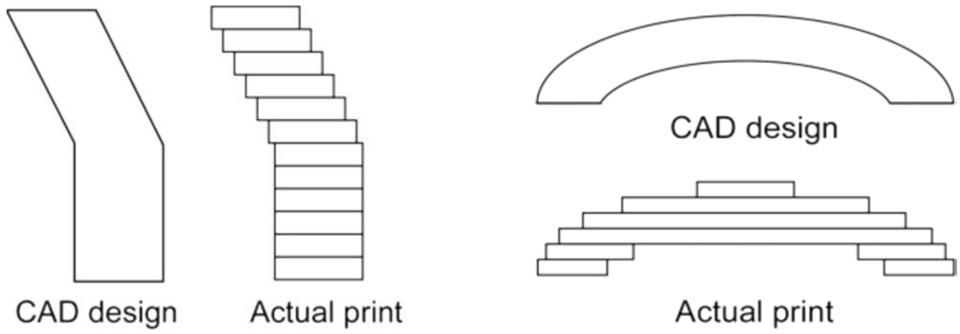


Figure 168: Material extrusion stair-step effect [36].

18.1.1. Characteristics of Material Extrusion

The most common material extrusion based additive manufacturing technology is *Fused Deposition Modelling* and *PolyJet printing.* Some pros and cons for material extrusion AM technologies are listed below [36]:

Pros	Cons
Most affordable machines, particularly with the advent of desktop machines (though desktop machines are not generally considered suitable for manufacturing)	Most anisotropic process. Substantial weakness in Z direction
Prints in standard engineering thermoplastics	Poorest surface quality process
Low cost material available for desktop 3D printers	Requires support material for overhangs
Easy to use machines	Potentially difficult polymer support material removal, unless they are soluble

Typical materials used in material extrusion AM technologies include the following [36]:

Standard materials	Specialty materials
ABS/ASA	Clay filled polymer
Polycarbonate	Brick filled polymer
ABS/Polycarbonate Blends	Wood filled polymer
Nylon	Metal filled polymer
PPSF/PPSU	Concrete
ULTEM 9085 and 1010	Chocolate
PLA	Polyurethane foam
Metal filled polymer filament (bronze, steel, stainless steel, copper, Inconel and others)	Silicone
	Epoxy
	Bio-materials
	HPA/PCL

18.2. Powder Bed Fusion

Powder Bed Fusion (or PBF) 3D printing include *Electron Beam Melting* or EBM and *Selective Laser Melting* or SLM (Figure 169). These technologies function primarily through the spreading of building material, which is in powder form and then making use of a beam of energy to fuse the powder as part of the existing layer being printed. In the case of EBM an electron beam is used whilst in the case of SLM laser is used. The platform is then dropped fractionally and a new layer is formed as before until the entire product is built [27], [30], [33]. These technologies can print with a variety of both metals and polymers.

Typical polymeric materials include polyamide plastics such a Nylon and a large variety of fillers including carbon fibre, glass, aluminium and high temperature polymers such as PEEK [36]. The surface finish is typically matt and a degree of *stair-step effect* is also observed. Metallic material printing using these techniques is also possible and typical materials include aluminium, stainless steel, titanium, cobalt chromium and tool steels [36]. Post-processing may be required on a CNC machine.

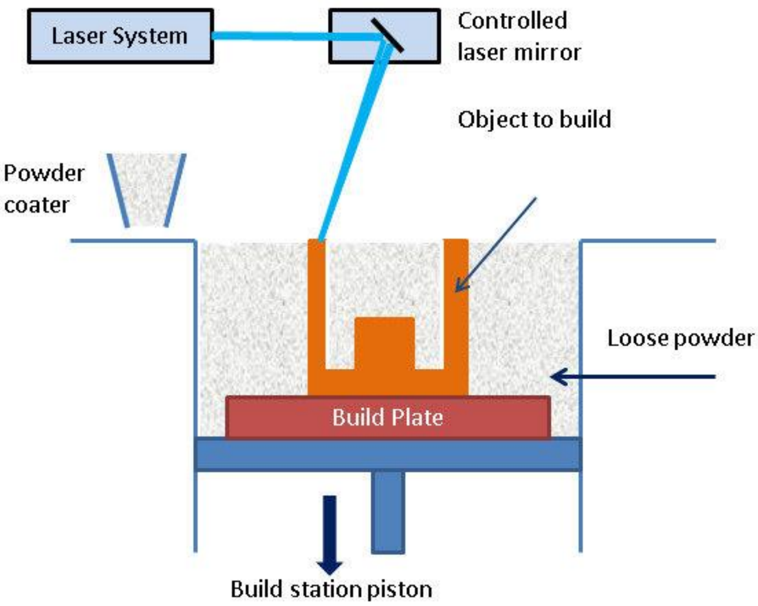


Figure 169: Powder Bed Fusion system [46].

Some pros and cons for material extrusion AM technologies are listed below [36]:

Pros	Cons
From a material point of view, one of the lowest cost production technologies	Metal PBF requires support material for heat transfer, and can require considerable effort to remove
Produces strong and durable parts	
No support material required for polymer powder bed fusion	

Typical materials used in Powder bed fusion include the following [36]:

Polymer materials	Metal materials
Nylon 12, 11 and 6	Stainless steel
Glass filled nylon	Maraging steel (tool steel)
Heat resistant nylon	Titanium 64
Polypropylene-like nylon	Aluminum
Alumide (aluminium-filled nylon)	Tungsten
Carbonmide (carbon-filled nylon)	Nickel-based super alloys
PEEK	Cobalt chrome
	Copper
	Precious metals, such as gold

19 APPENDIX IV: ADDITIONAL DESIGN CONSIDERATIONS IN AM

19.1. Overhangs

There are a number of general design considerations one should make in AM. Every 3D printing building process works on a layer by layer operation such that new material has to be printed over underline material. Models will contain overhangs which are regions of the part or model which are either partially supported by the underline material or unsupported. There is a physical limit for the manufacturing of overhangs during AM [36], [40]. For instance, in the case of FDM the maximum angle for AM of overhangs is roughly 45° [36]. Overhangs should usually be limited within a model since 3D printing using support structures usually results in rough surface finishing. As a general rule, for overhangs smaller than 45°, support is always needed as shown in Figure 170.

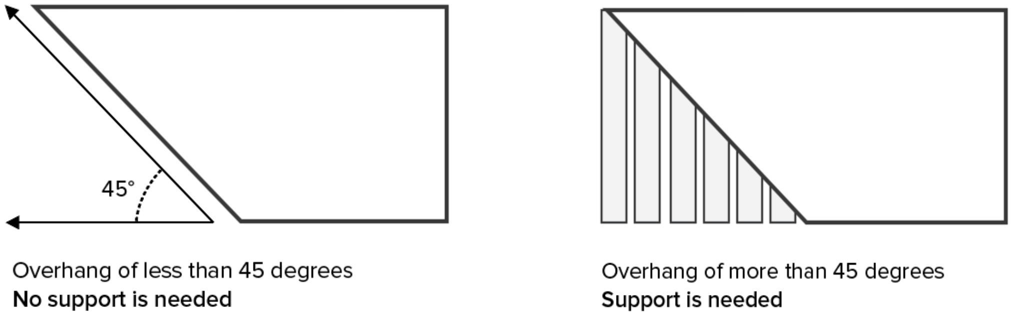


Figure 170: Overhangs larger than 45° require the use of support structures [47].

19.2. Wall Thickness

Another aspect to keep in consideration during AM is wall thickness. Accurate features can only be thin up to a specified limit [19], [34]. Reducing the thickness of the material may result in very weak and fragile parts with a corresponding reduction in quality. As a good practice some designers almost always add thickness to their models. Any 3D printing process can product effective models usually with a wall thickness of greater than 0.8mm [30]. Table 17 shows a recommended table of minimum thickness for different materials along with the corresponding absolute minimum thickness.

Table 17: Material thickness recommendations for different materials [48].

	MATERIAL THICKNESS RECOMMENDATIONS							
Material	**PLA**	**ABS**	**Nylon**	**Vero-white**	**Transparent**	**ABS-Like**	**Rubber-Like**	**Visiclear**
Recomm. Minimum thickness (*mm*)	1.5	1.5	1.5	1.0	1.0	1.0	2.0	1.0
Absolute Minimum thickness (*mm*)	0.8	0.8	0.8	0.6	0.6	0.6	0.8	0.6

19.3. Warping and Breakages

CAD modelling should always take into consideration the physical printing capabilities as detrimental effects due to small wall thicknesses can easily be avoided. Figure 171 and Figure 172 shows deformation and breakage of a part brought about during 3D printing which were unforeseen during CAD modelling.

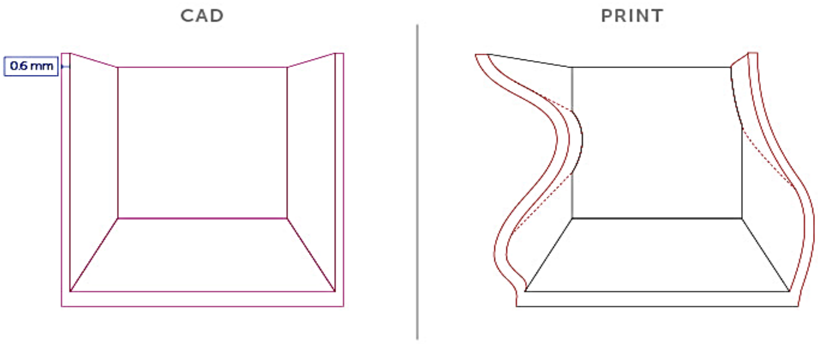


Figure 171: Warping and deformation of the print due to unforeseen design considerations during CAD modelling [36].

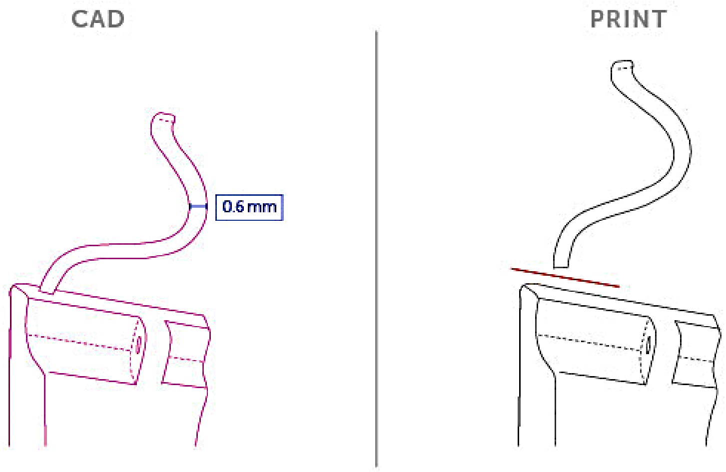


Figure 172: Broken parts due to a lack of consideration during modelling [36].

One feature that is usually overlooked by designers during the deign stage is the fact that materials undergo physical changes during manufacturing. This is because materials are melted, sintered, laser scanned and solidified. This change in heating followed by cooling of the material causes warping during 3D printing and should be taken into consideration during design.

A large and flat surface can be easily prone to warping [9], [13]. This can be usually avoided by correctly calibrating the printer such that there is adequate surface adhesion between the print bed and the part itself. A good design practice is usually to avoid large and flat surfaces and to add rounded corners during CAD modelling [26]. Figure 173 shows ABS material warping of the bottom left corner.

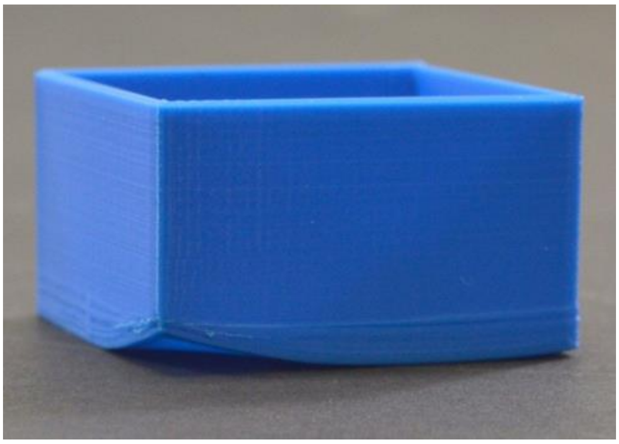


Figure 173: Warping of a print at the bottom left corner [49].

Figure 174 shows the deformation by warping on an object printed in FDM. A method is also presented which provides a way to measure this deformation at the corners of the model.

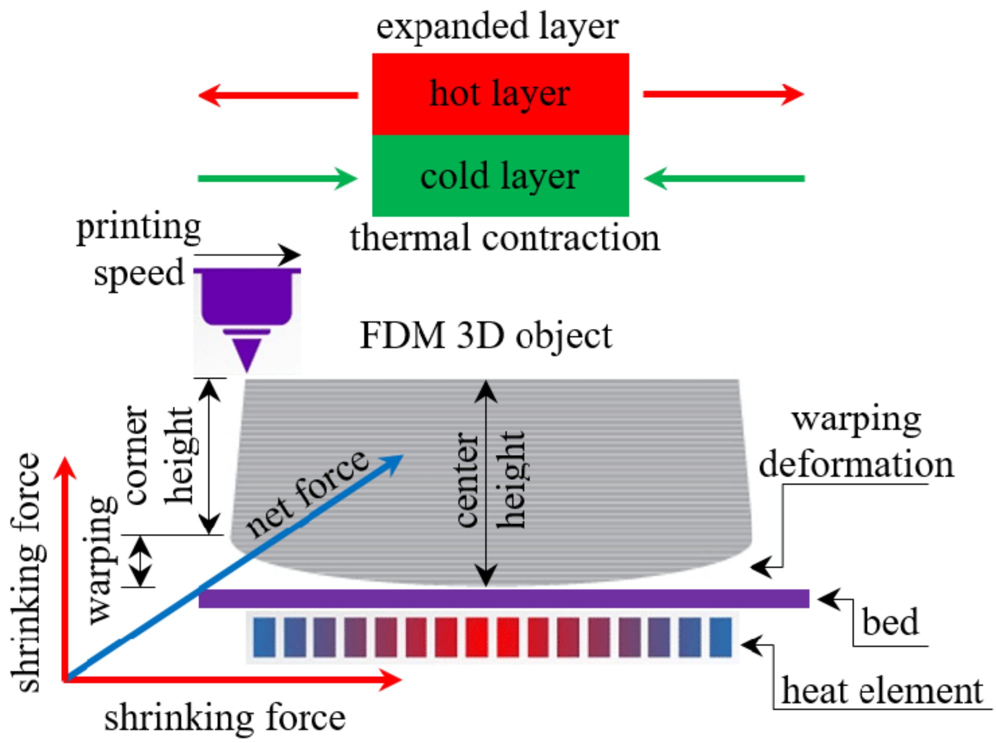


Figure 174: A method to measure deformation of a 3D printed object [50].

The level of detail during CAD modelling should always be kept in mind. The minimum feature size that can be produced by AM should be the main driving principle behind the modelling process [36]. The minimum level of detail is the result of the mechanics and capabilities of the AM process and the selected layer height. Different 3D printing technique involve different levels of detail (Figure 175). Materials and processes used have an impact on the manufacturing cost and print speed of the process so one vital design decision is to determine the how critical are the small details in the design [34].

Figure 175: 3D model of Marvin the Martian. From left to right: FDM (200μm), DLS (100μm) SLA (100μm) and Material Jetting (100μm) [36].