Test rigs for measuring the effectiveness of medical face masks

Group 5 - Final Report

Submitted as part of Design 3 – MACE31041

By:

Kojo Afriyie [redacted]

Suyog Gurung [redacted]

Derek Leung [redacted]

Lewis Mihaylov [redacted]

Harrison Thornley [redacted]

Nader Zakher [redacted]

Table of Contents

Section 1: Comprehensive overview of final design 2

Section 1.1: Bacterial Filtration Efficiency (BFE) apparatus + Mannequin Head apparatus 2

Section 1.2: Air Resistance Testing (ART) apparatus + Mannequin Head apparatus 4

Section 2: Explanation of how the design works 6

Section 2.1: Bacterial Filtration Efficiency (BFE) apparatus 6

Section 2.2: Air Resistance Testing (ART) apparatus 9

Section 2.3: Mannequin Head apparatus 13

Section 3: Demonstration of how the technical specification requirements have been achieved ... 17

Section 4: References and appendices 22

Section 4.1: Research references 22

Section 4.2: Component references 23

Section 4.3: Appendices 25

Section 1: Comprehensive overview of final design

Section 1.1: Bacterial Filtration Efficiency (BFE) apparatus + Mannequin Head apparatus

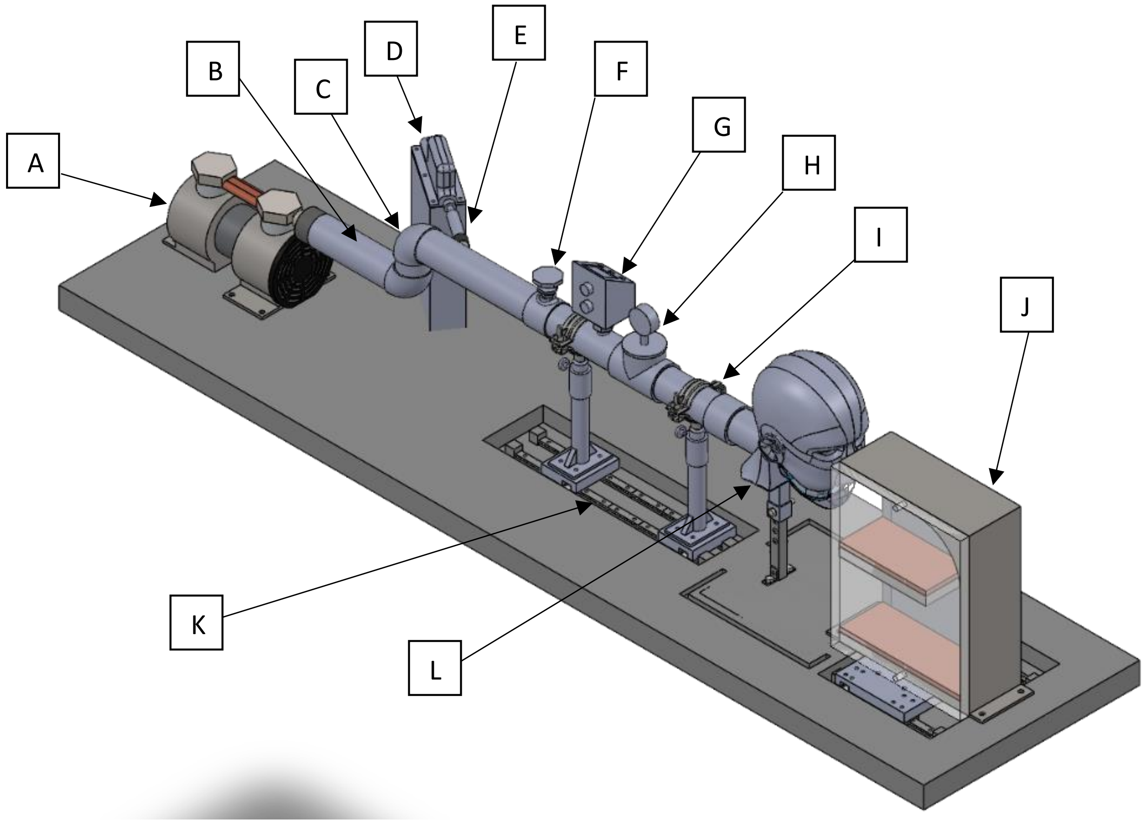

Figure 1: Isometric view of the Bacterial Filtration Efficiency (BFE) apparatus attached to the Mannequin Head apparatus

Table 1: Bill of Materials for BFE apparatus

Item	Component	Description	Quantity
A	Compressor	Pumps air into the system to push the bacteria through the mannequin head	1
B	Pipe	Connects the components throughout the system	
C	Pipe bend	Allows the flow to change direction through the pipes	2
D	Linear actuator	Part of the bacterial solution delivery system	1
E	Syringe	Part of the bacterial solution delivery system	1
F	Globe valve	Regulates the rate of the flow in the system	1
G	Flow meter	Measures the rate of the flow in the system	1
H	Pressure gauge	Part of the ART apparatus, irrelevant to the BFE apparatus	1
I	Clamp stand	Supports the pipes and holds the system in place	2
J	Capture chamber	Contains two agar jelly plates to capture the bacteria in order to test the efficiency of the face mask	1
K	Linear Guide Rail	Allows the system to be moved along the central axis	2
L	Mannequin head	Connected to the BFE testing apparatus via a threaded pipe, directs the bacterial solution into the capture chamber	1

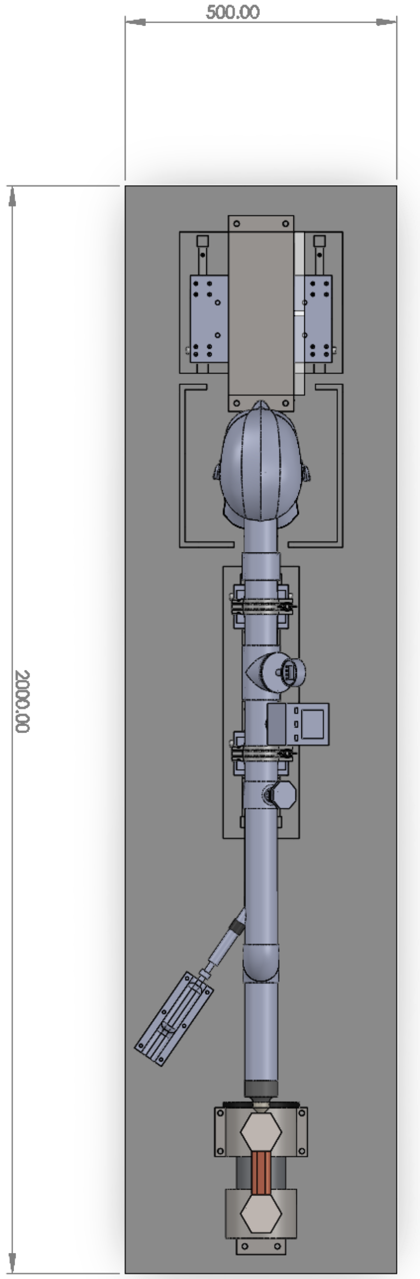

Figure 2: Plan view of the BFE apparatus attached to the Mannequin Head apparatus with baseplate dimensions shown

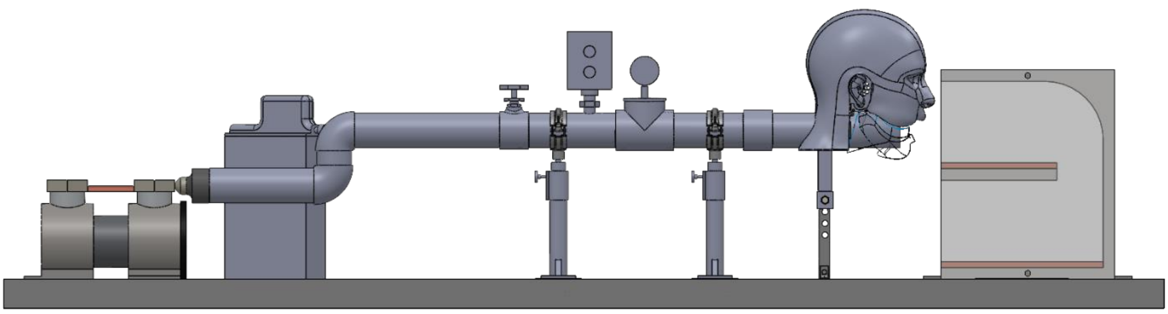

Figure 3: Side view of the BFE apparatus attached to the Mannequin Head apparatus

Section 1.2: Air Resistance Testing (ART) apparatus + Mannequin Head apparatus

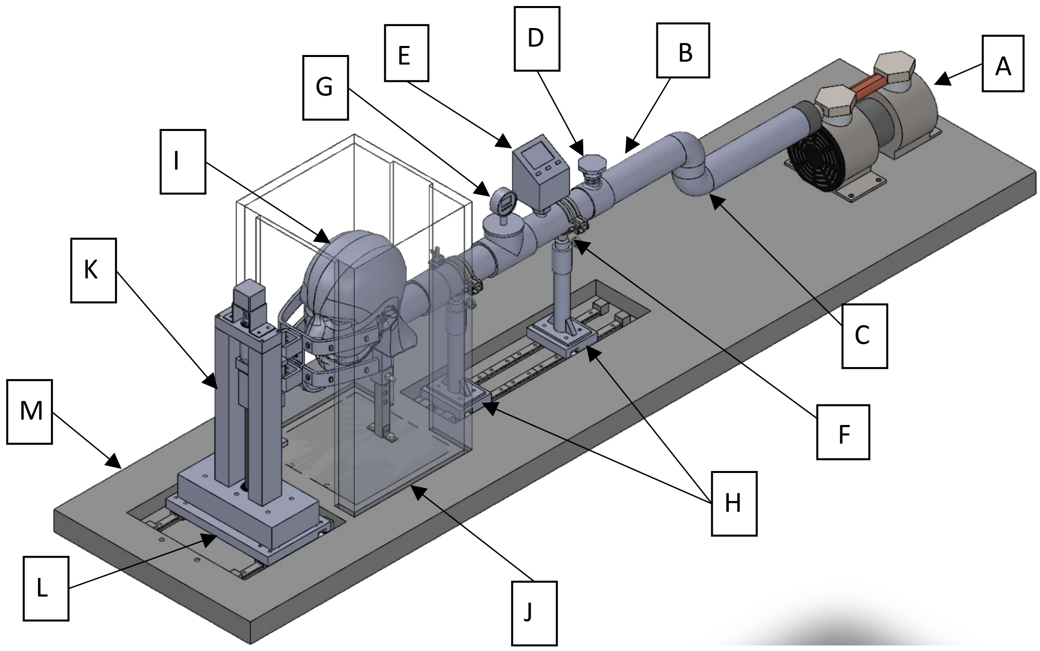

Figure 4: Isometric view of the Air Resistance Testing (ART) apparatus attached to the Mannequin Head apparatus

Table 2: Bill of Materials for ART apparatus

Item	Component	Description	Quantity
A	Compressor	Pumps air into the system through to the mannequin head	1
B	Pipe	Allows air flow and connects the components throughout the system	
C	Flexible pipe	Connects pump to the remainder of the apparatus	1
D	Globe valve	Allow air flow variance	1
E	Flowmeter	Measures air flow supplied from pump	1
F	Clamp stand	Supports the pipes	2
G	Pressure gauge	Measures pressure of air flow before the mannequin head	1
H	Rear guide rails + moving plate assembly	Allows clamp stands to move in the central axis	2
I	Mannequin head	Connects to rear end of the apparatus via a threaded pipe and allows air flow to reach the pressure sensors	1
J	Case	Encloses mannequin and reduces the influence of external factors	1
K	Pressure sensor assembly	Supports pressure sensors	1
L	Front guide rails + moving plate assembly	Allows pressure sensors to move in the central axis	1
M	Baseplate	Used to screw the apparatus to the mannequin head	1

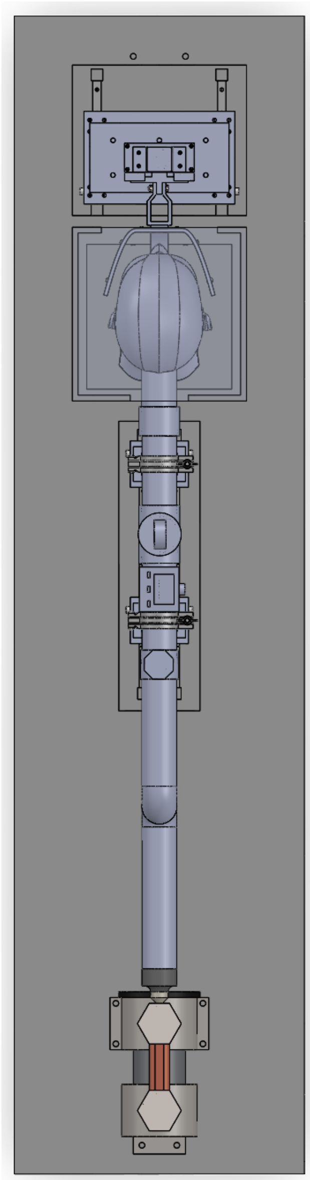

Figure 5: Plan view of the ART apparatus attached to the Mannequin Head apparatus

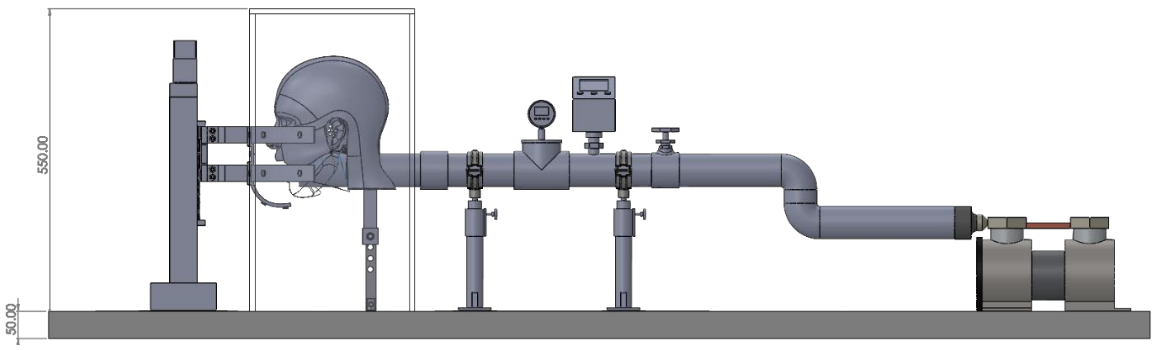

Figure 6: Side view of the ART apparatus attached to the Mannequin Head apparatus

Section 2: Explanation of how the design works

Section 2.1: Bacterial Filtration Efficiency (BFE) apparatus

The Bacterial Filtration Efficiency (BFE) apparatus makes use of an air compressor at the start of the system to push air through the mannequin head. This simulates the process of a person breathing in a realistic manner.

The flow then passes through a globe valve however this is unimportant to the BFE apparatus as the full power of the compressor is required to achieve the required flow rate. It is included in the system to make it easier for the user to swap the BFE apparatus for the Differential Pressure system.

Once it passes through the valve, the air flows through a Y-pipe where it is mixed with the bacterial solution. This bacterial solution delivery system (see figure 7) consists of a syringe, which forces the bacterial solution through a mesh nebuliser, and an Actuonix PQ12 linear actuator, which is responsible for pushing the syringe plunger which introduces the bacterial solution to the system. The Micro air® NE-U22V mesh nebuliser was chosen for this final design because it is capable of delivering particles with a mean size of 3 µm, as specified in the Technical Specification of Requirements. The Actuonix PQ12 linear actuator was chosen because it provides accurate and repeatable movements in order to ensure the validity of the test. Furthermore, the actuator can be controlled by a computer in order to maintain a constant flow rate of 0.01 ml/minute which removes any source of human error when it comes to introducing the bacterial solution. This also makes the apparatus easier for the user to operate as the user now has fewer manual tasks to carry out.

Following its exit from the Y-pipe, the now-aerosolised bacterial solution flows through a VA 520 electronic flow meter in order to ensure the flow rate is at 57 ml/minute. This particular flow meter was chosen as it is able to provide a clear and accurate value for the flow rate. It was also chosen because the value of the flow rate can be sent to the user’s computer which can then alert the user once this desired flow rate has been reached so that the actuator for the syringe can be activated and the test can begin. As previously stated, this sort of optimisation vastly reduces the complexity of the test for the user and also removes any potential for human error.

The flow then travels through pressure sensors however, like the globe valve, this is irrelevant to the BFE.

Next, the flow enters through the back of the mannequin head, travels through the pipes within the mannequin head, and then exits through the mouth and the nose holes before being directed into the capture chamber. The capture chamber has two shelves; an upper shelf, and a lower shelf. The flow enters the capture chamber through the upper shelf which has an agar plate placed inside, allowing bacteria to land on it. The design of the capture chamber causes the flow to then undergo a 180° downwards bend onto the lower shelf which reduces the flow speed and causes the remaining bacteria droplets to fall onto the second agar plate, located on the bottom shelf. The remaining air flowing through the chamber then leaves through the window at the bottom of the chamber. One of the chamber side walls is removable which allows the agar plates to be easily removed and replaced via the side of the capture chamber, thus reducing the time taken to replace the agar plates and reset the test. The interior walls of the capture chamber are coated with a hydrophobic substance in order to prevent any of the bacterial solution sticking to the walls and not landing on the agar plates. This will increase the accuracy of the evaluation of the face masks based on their ability to filter out the bacteria.

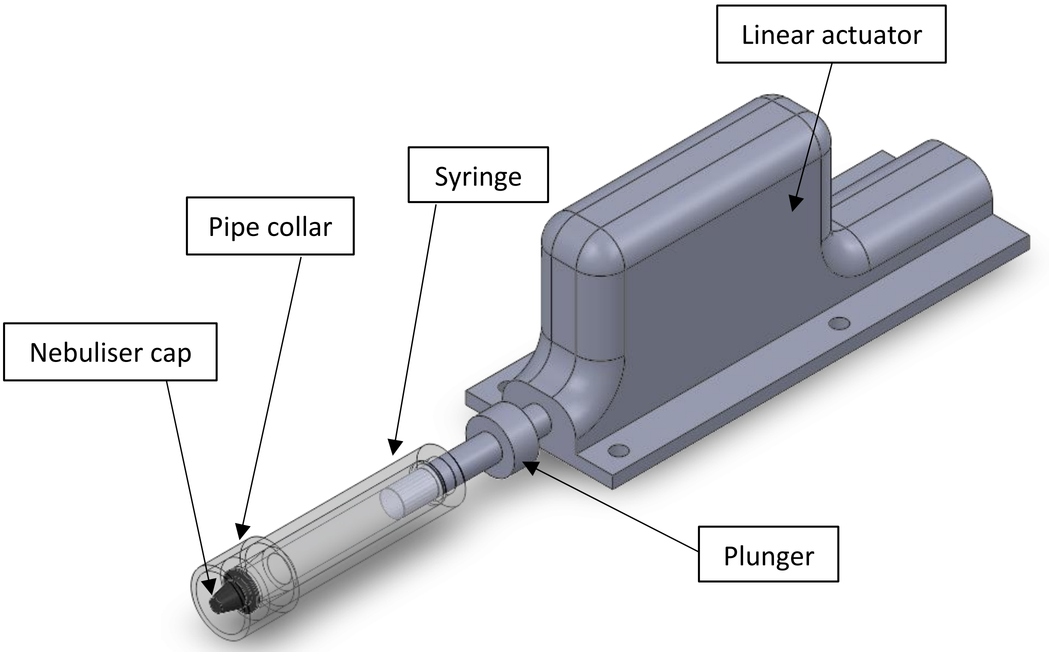

Figure 7: Bacterial solution delivery system

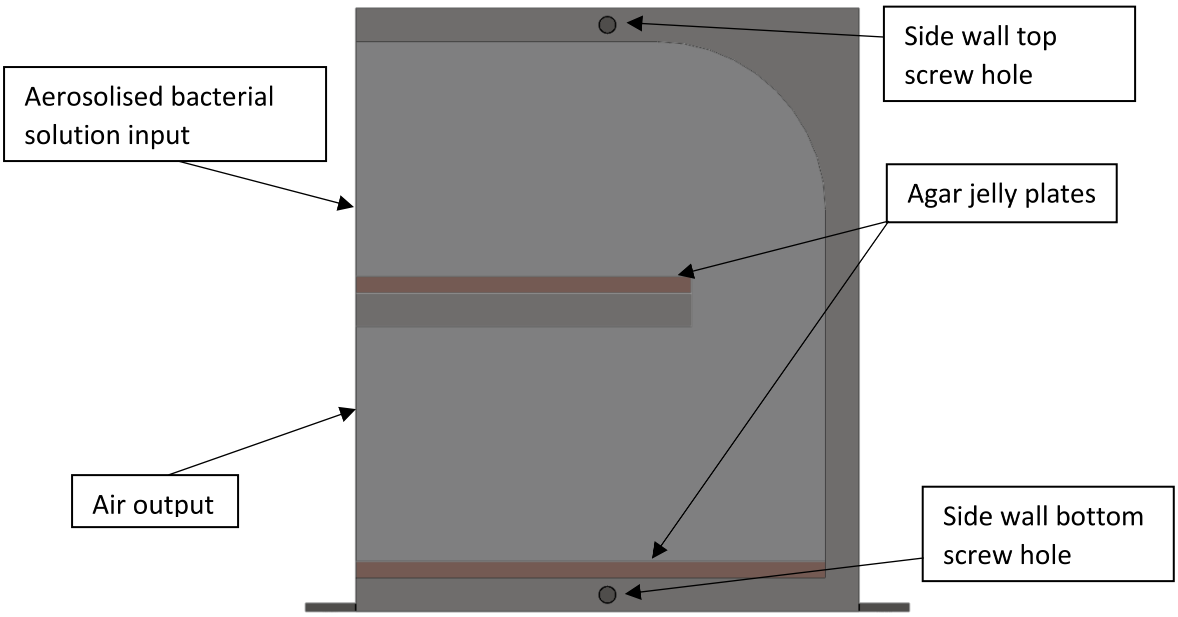

Figure 8: Capture chamber cross-section view

Section 2.2: Air Resistance Testing (ART) apparatus

The air is pumped through the system via an air compressor (Thomson 2380CUU38) at 65.1L/min towards the mask testing area of the mannequin head, with the air resistance (differential pressure) being measured through the gauge pressures before and after the mask (see figure 4).

The air compressor is connected to a valve via a 50mm diameter flexible hose; the height of the rest of the apparatus can be adjusted individually (see figure 9), so the flexible hose allows for different setups for the apparatus to be accommodated.

A Globe valve (UCL-8A) is used to vary the air flow to mimic different kinds of breathing, and therefore allows the same compressor to be used for both the BFE and ART. As a result, the air flow is reduced to 8L/min which meets the technical requirements and can be measured from the flowmeter (VA 520) attached after the valve.

A 50mm diameter PVC pipe then guides the air flow towards the 700G05 digital pressure gauge to measure the pressure before the mask; this is used instead of an analog pressure gauge as fewer mechanical parts mean the pressure gauge is more durable and less likely to sustain damage from normal use (Ralston Instruments, 2020). The pipe is modelled as 50mm as that is, found to be the average human mouth size (Nagi et. al., 2017) (Li et al., 2017). From there, a PVC pipe connects the pressure gauge to the back of the mannequin head. To aid in connecting the pipe to the mannequin head, the pipe clamps are attached to rails which allows for the pipes to move backwards and forwards. The front and rear moving plates can be fixed in position by rail clamps (L1010.CL) (see figure 10).

All the PVC pipes are threaded to reduce joining elements and enable simple assembly of the apparatus. Once the air passes through the mask, there are ADP5171 pressure sensors attached to various points of the curved plates via cages and screws taking measurements including at the ends of the mask where air escapes (see figure 11). The curved plates are made from polycarbonate due to its machinability, recyclability, and being light. A removable case encloses the mannequin head and the curved plates to reduce external factors such as temperature and humidity and is made from Perspex such that the operator can still see through (see figure 12).

The stepper motor (RS PRO 180-5279) attached to the lead screw converts rotational movement to linear movement which drives the XCB6200 nut and allows the vertical platform to move in the vertical axis, useful for when different nose shapes are used or when masks of different shapes are being tested (see figure 13). The curved plates are not extended to the nose as the nose would then block the lead screw system from adjusting the height of the sensors.

The ADP5171 pressure sensors were chosen because the sensors are light and compact which allows a number of the sensors to be joined to the curved plates without jeopardising the structure of the curved plates. Additionally, the energy usage per sensor is miniscule relative to the rest of the apparatus. The RS PRO 180-5279 was chosen since the motor allows for repeatable movement, has good reliability and is regarded as safer than the other kinds of motors (Gastreich, 2018) (machinetoolhelp.com, 2010). To power these components, the motor can be attached to a rechargeable battery and the pressure sensors can be connected to a control unit such that readings can be taken.

Finally, the section of the apparatus in front of the mannequin head would be attached to a horizontal platform on rails to allow the operator to move the apparatus backwards and forwards manually when changing masks (see figure 10), and to allow the apparatus to be adjusted when masks of different shapes are being tested.

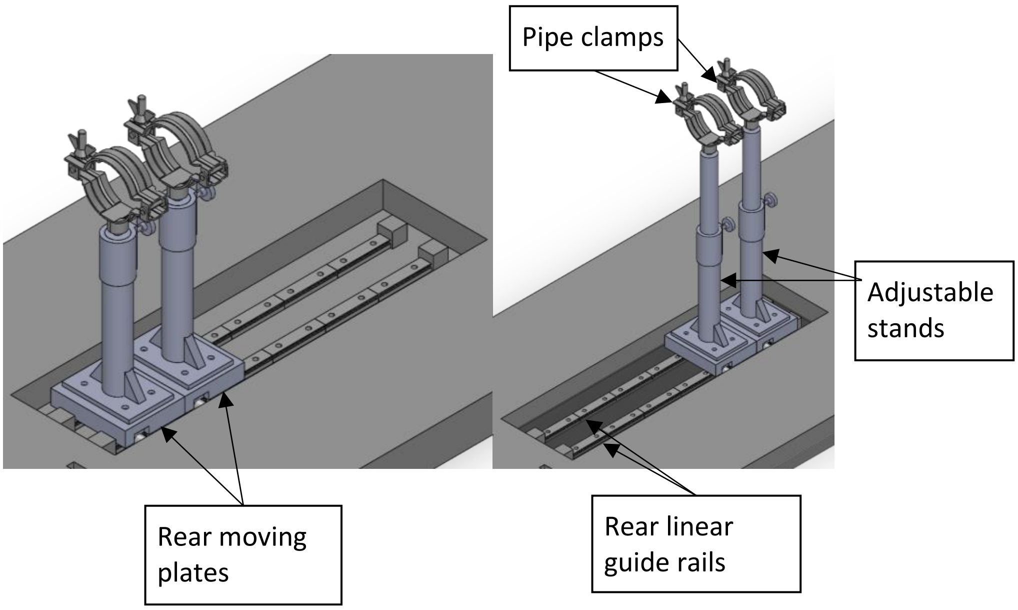

Figure 9: Rear pipe clamps at extreme heights and lengths

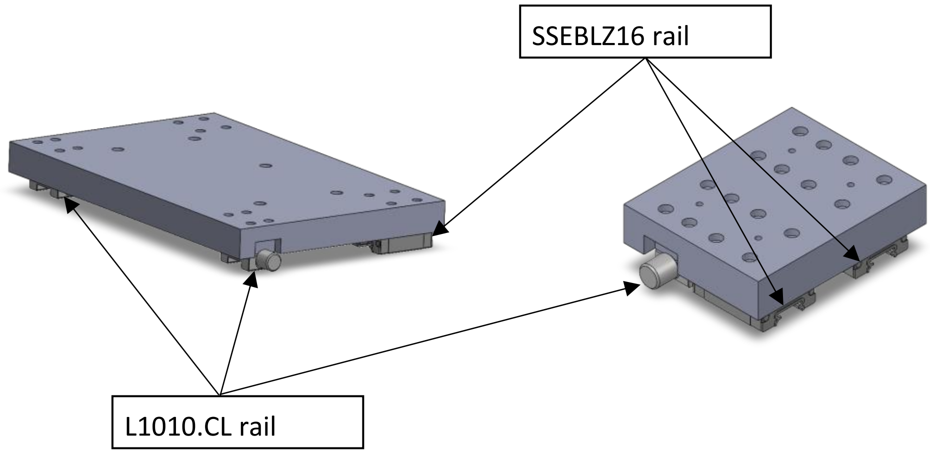

Figure 10: Front moving plate (left) and rear moving plate (right)

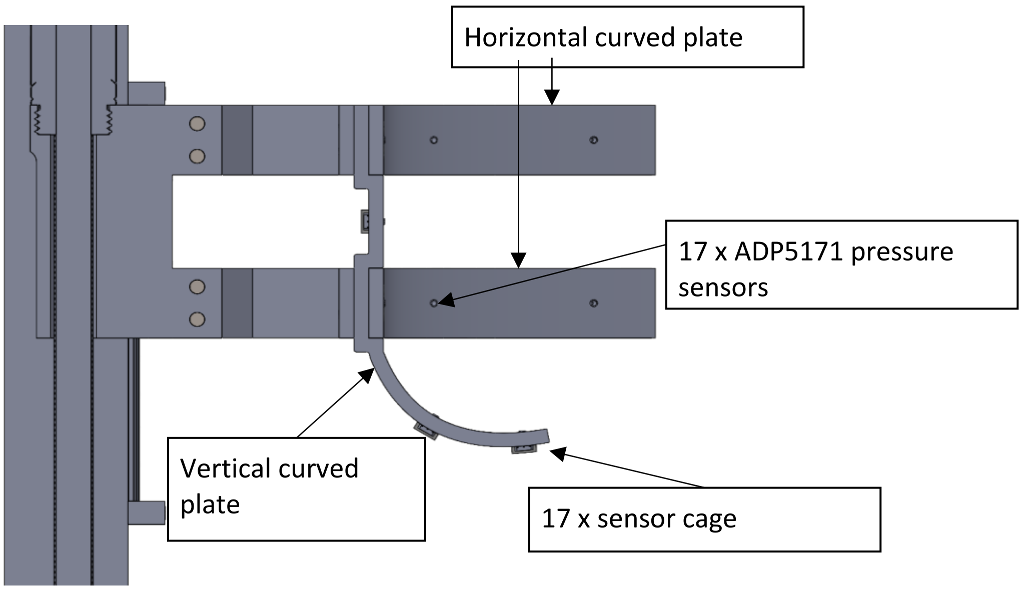

Figure 11: Curved plates with sensor attachments

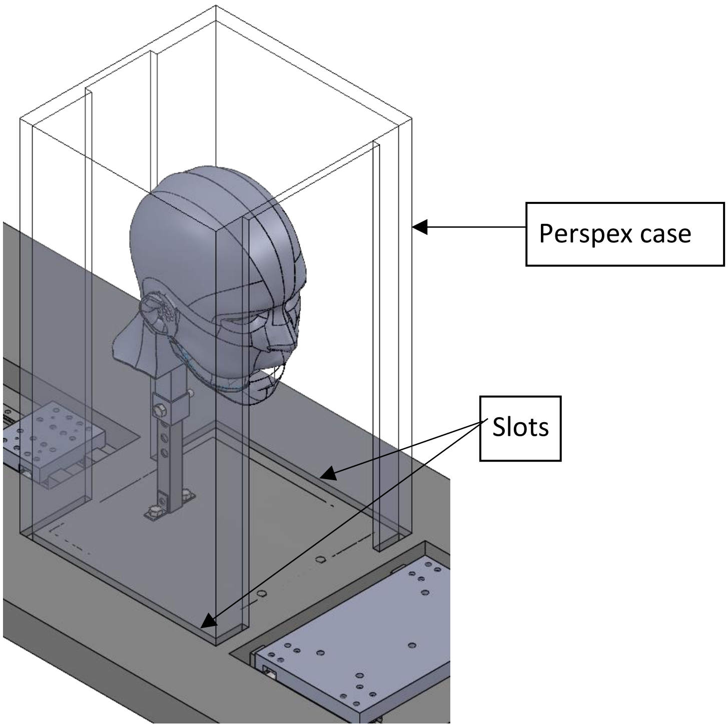

Figure 12: Perspex case with the slots

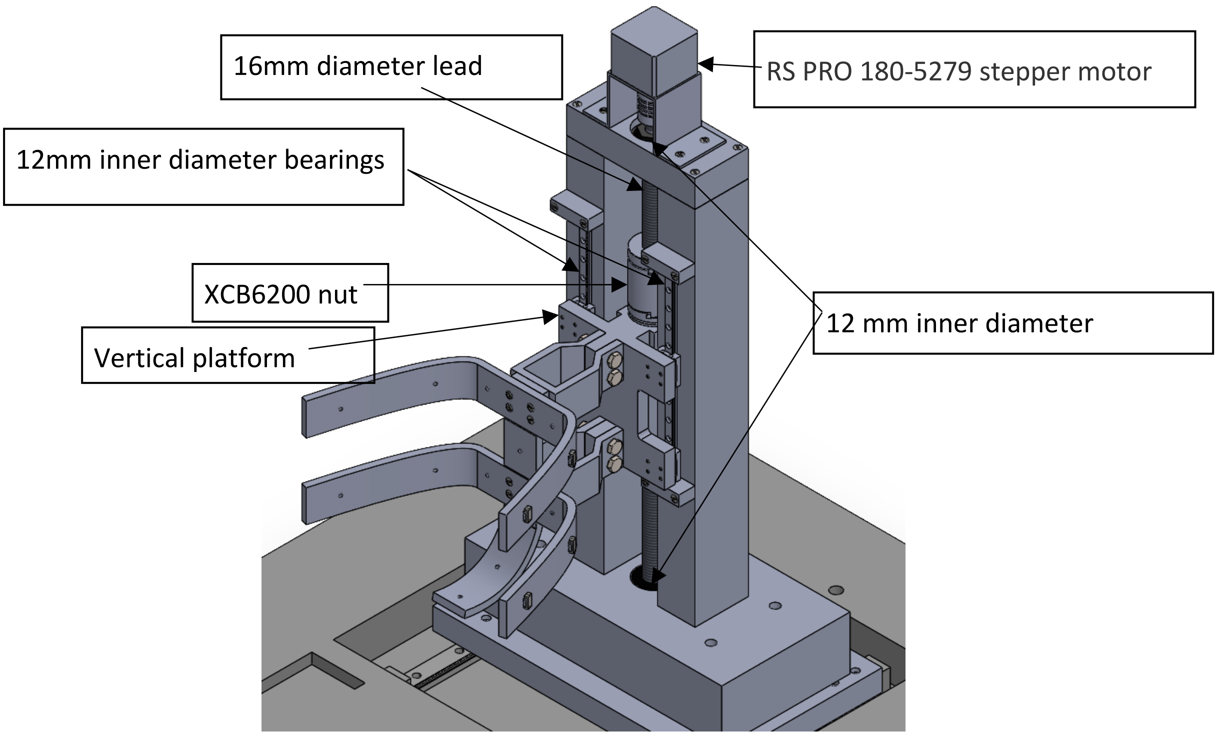

Figure 13: Pressure sensor assembly with the curved plates

Section 2.3: Mannequin Head apparatus

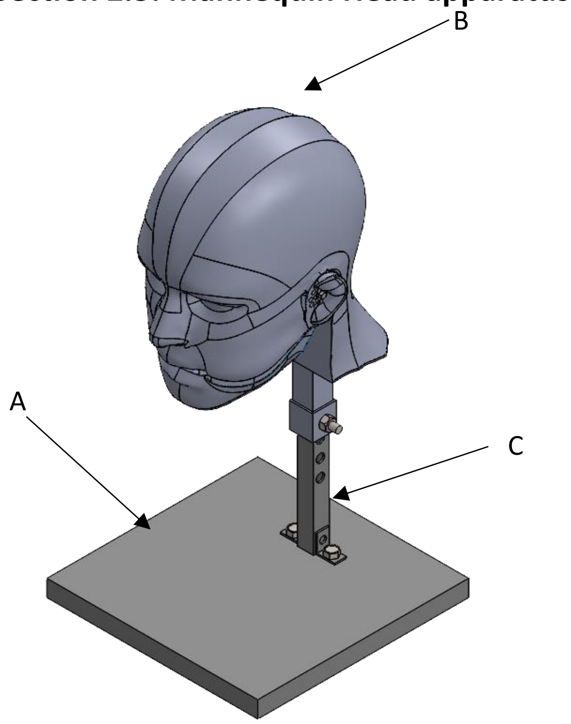

Figure 14: Isometric view of the overall mannequin head design.

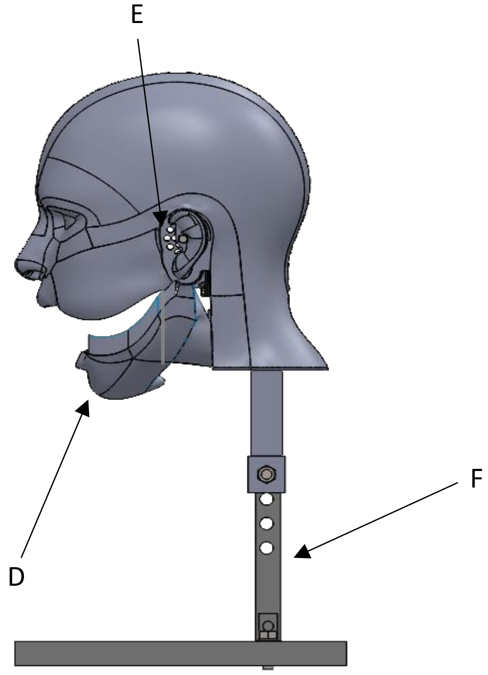

Figure 15: Side view of the mannequin head.

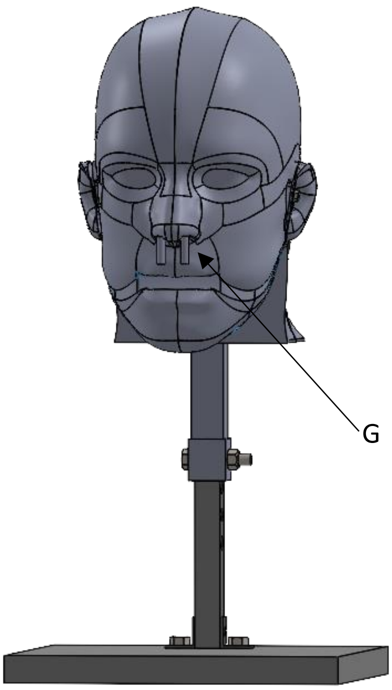

Figure 16: Front view of the mannequin head, showing nose inserts

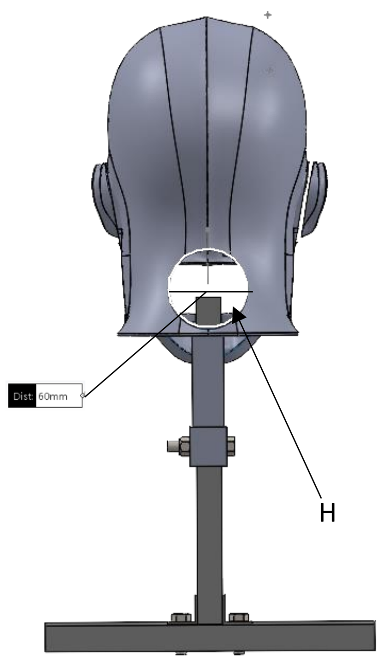

Figure 17: Back view of the mannequin head, showing pipe connection path (with diameter).

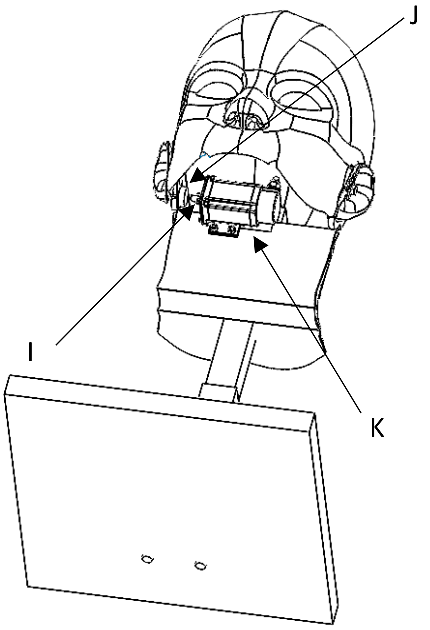

Figure 18: Outlined view of the mannequin head, showing the servomotor and its support mechanism.

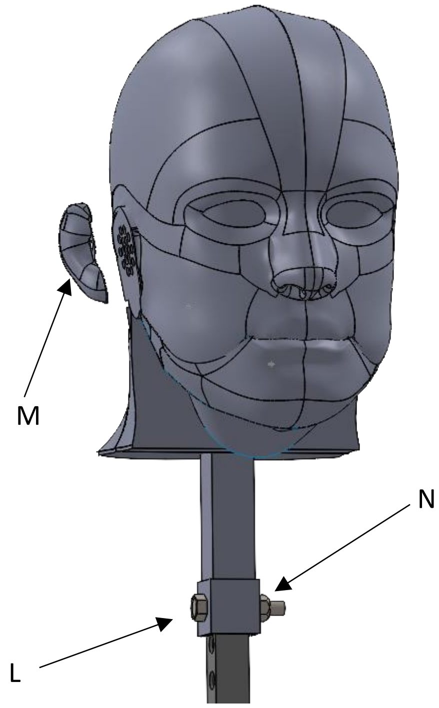

Figure 19: Front view of the mannequin head, showing the jaw closed and the adjustable/exchangeable ears.

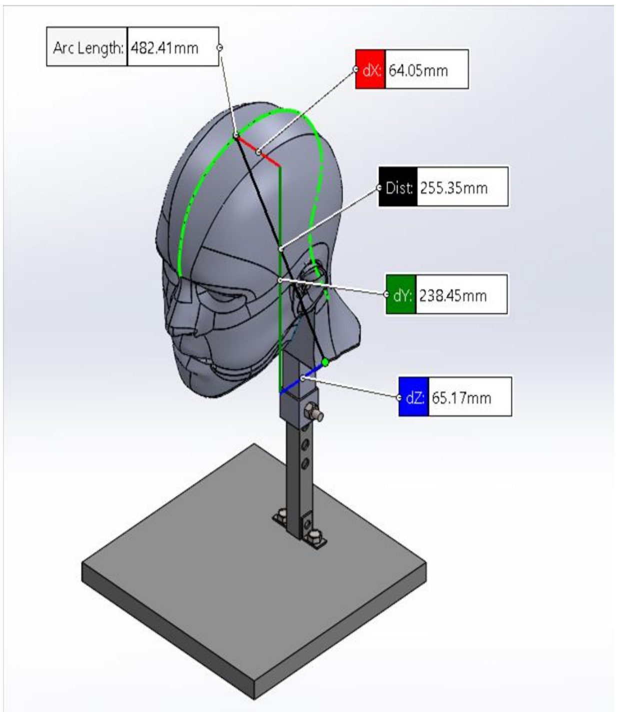

Figure 20: Isometric view of mannequin head with its technical dimensions.

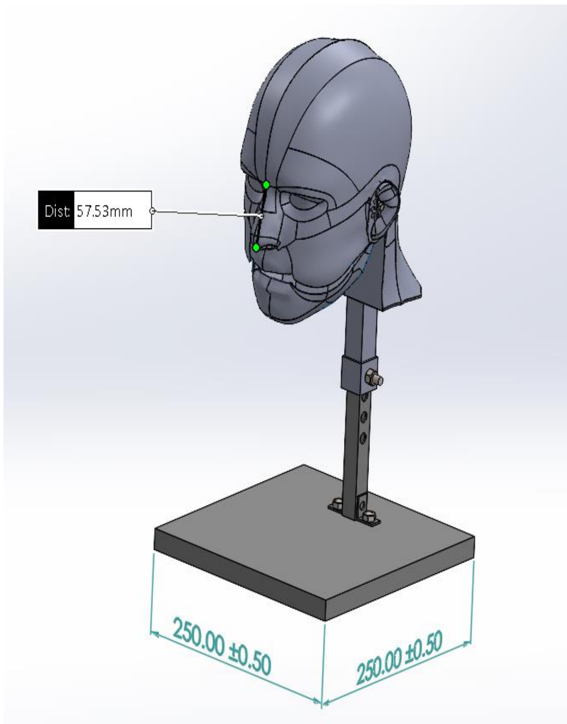

Figure 21: Shows initial nose height and base plate dimensions.

The final mannequin head design utilizes many engineering concepts to ensure that it functions in the most effective and efficient way. This design consists of several different components which together enable the mannequin head to function accordingly in relation to most of the technical requirements provided. As with any engineering solution, it can often be difficult to achieve a perfect solution, especially when there are many constraints (i.e. time) or barriers (i.e. other assessments) that one may face along the way. This design addresses most of the client's requirements however, the design falls short on adjusting the width of the head.

The design consists of a removable plastic (polystyrene) jaw that is fitted on to the head (refer to figure 15). The jaw fits in as a slot fitting to the head through a partially hollow cylindrical shaft (refer to figure 18). This cylindrical shaft is then connected to a metallic shaft which is attached to a Sigma-7 servo motor. The servo motor will create the rotational movement, allowing for the vertical movement of the jaw per the Technical Specification of Requirements (refer to figures 15 & 19). The servo motor will be connected to a power supply (230 V AC), a sensing device and a control circuit, and it is screwed into the supporting foundation to hold it in place (refer to figure 18). The Sigma-7 servo motor was chosen because it can provide enough torque to move the jaw in the required fashion (see appendix 1). The metallic shaft attached will be slightly smaller in diameter than the hollow plastic shaft, and by applying a rotation force to it, it will rotate accordingly. After examining several motors (Totemmaker, 2018), servo motors were determined to be the most reliable option as they possess a high torque to inertia ratio, high levels of precision, and a high level of accuracy (Gastreich, 2018).

The head was chosen to be made of polystyrene plastic. The circumference of the head (refer to figure 20) is within the typical range for adults (Bushby et al, 1992). The design has taken into account the various manufacturing techniques (e.g. 3D printing, injection moulding and polymer casting) that could potentially be used. However, if this design were to be manufactured, it would be ideal to 3D print them since the benefits of this method include faster production, better quality, no limits on geometry types and less waste production (Pearson, 2018). This is in line with the Technical Specification of Requirements in terms of environmental and sustainability awareness.

Based on a study in Iran that consisted of 300 people, the average nose length for an adult (refer to figure 21) was found to be around 57.1-60.8mm (Zolbin et al., 2015). The nose size (i.e. nozzle size) and length can be adjusted by starting with an average nose before adding the required size (i.e. length and diameter) of hollow cylindrical inserts to the nose and using super-glue to attach them to the bottom of nose (refer to figure 16). The use of super glue re-enforces the designs technical requirements regarding the ease of accessibility/operation; as you just have to glue and stick the inserts, which can then be easily removed after each test with the use of an adhesive removal spray, which is compatible with plastics, such as Sonax (Amazon, 2017). Furthermore, the ears have been designed to be exchangeable to cater for the different sizes and positions (refer to figure 19). The ears are screwed and held by bolts to the head, this design has a scatter of 'through holes' which enable any ear, regardless of size to be positioned accordingly (refer to figure 15).

In conclusion, the design of the mannequin head adheres well to the client's technical requirements and has also taken into account manufacturability, as well as the wider impact on the environment. Therefore, the design is eco-friendly, easy to operate and efficient.

Table 3: Bill of Materials for Mannequin Head

Label:	**Name:**	**Label:**	**Name:**
A	Aluminium base plate	H	Pipe-connection hole
B	Plastic (Polystyrene) Head	I	Metallic Motor Shaft
C	L-bracket	J	Jaw-head slot connection
D	Plastic (Polystyrene) Jaw	K	Servomotor (Sigma 7)
E	Through Holes	L	Screw
F	Aluminium channel	M	Detachable ear
G	Cylindrical Inserts	N	Bolt

Section 3: Demonstration of how the technical specification requirements have been achieved

Table 4: Demonstration of how the technical specification of requirements have been achieved

Technical Specification of Requirements	Explanation of how the requirements has been achieved
The design must be suitable for testing Types I and II medical face masks (as classified by BS EN 14683:2019) against (i) bacterial filtration efficiency (BFE) and (ii) air resistance (differential pressure).	No comment/justification required.
The design must be able to test medical face masks with different shapes and means of fastening, e.g. ear-loop fastening and head loops.	For the design to be compatible with medical face masks with varying means of fastening, the mannequin head has detachable ears with different ear slots so that the mannequin head is compatible with any fastening mechanism. Mask straps can also be wrapped around the back of the head. For both the BFE and the ART system, the rails and lead screw mechanism allow the positioning of the front section of the apparatuses to be adjusted in order to accommodate the various shapes and sizes of the face masks.
The design must comprise three independent mechanisms: - Mannequin head and its support mechanism/foundation, - Bacterial filtration efficiency (BFE) testing apparatus, - Air resistance (differential pressure) testing apparatus.	No comment/justification required.
Each apparatus (BFE and air resistance testing apparatus) must be able to connect to the mannequin head to perform one particular test routine and then be swapped by the second apparatus.	Both the BFE and the air resistance testing apparatuses use very similar systems upstream of the mouth; this means the time required to swap between apparatuses is greatly reduced. Additionally, the apparatuses can both be screwed onto a common base plate in front of the mannequin head. The mannequin head's wide base plate accommodates for the case if we were to screw in the BFE/Air Differential system on it. In addition to that, the mannequin head has a 60mm wide (i.e. diameter) back connection hole to allow for the connecting and fitting in of the

	BFE/Air Differential system pipes, accordingly (refer to figure 4).
The dimensions of the mannequin's head (face length, face width, head breadth, head length, positions of nose and ears) must be adjustable within a reasonable range for testing the medical face masks' efficiency irrespective of the head's size and shape.	To account for the adjustability of the mannequin head, adjusting the face's length and width were focused on due to their importance in medical face masks testing (Lin and Chen, 2017). The head consists of several detachable jaws of different dimensions which can be swapped between tests.
The mannequin head must be able to mimic the jaw movement so that the mask's efficiency can be determined whilst the mask is subjected to motion (e.g. a person talking, coughing, chewing, etc.).	The mannequin jaw is operated through the use of a Sigma-7 servo motor. This servo motor allows for rotational movement of the jaw, making it move up and down, accordingly.
The nebuliser for the BFE testing apparatus must be capable of delivering particles with a mean size of 3.0 ± 0.3 µm.	The BFE apparatus uses the mesh cap from the Micro air® NE-U22V nebuliser which is capable of delivering particles with a mean size of ~3µm.
The compressor (air pump) for the BFE testing apparatus must be capable of maintaining a flow rate of 57 l/min.	The compressor used is a Thomas 2380 Series which is capable of delivering a flow rate of 57 l/min and this can be ensured by using a flow meter in the system to regulate the flow rate.
The peristaltic or syringe pump for the BFE testing apparatus must be capable of delivering the bacterial solution at a rate of 0.01 ml/min.	The linear actuator is an Actuonix PQ12 linear actuator which is capable of moving at a maximum speed of 5mm/second under maximum load. This, combined with a syringe plunger of surface area 3.14mm^2, gives a maximum flow rate of 0.0157 ml/sec. Therefore, this linear actuator is able to deliver the required flow rate of 0.01 ml/min.
Flow meter for the air resistance testing apparatus must be capable of measuring an airflow of 8 l/min.	The VA 520 flow meter can measure flow rates from between 0 l/min to 10000 l/min, and since 8 l/min falls within this range, the use of the VA 520 flow meter is appropriate for this design.
The design must be able to operate with normal mains voltage of 230 V AC.	The compressor for the BFE apparatus runs on 230 V however the flow meter and the linear actuator do not. Therefore, these components will be powered by rechargeable batteries which can then be recharged via 230 V AC mains voltage. For the ART apparatus, the same compressor and flowmeter is used as for the BFE apparatus. The apparatus also uses a digital pressure gauge and a motor, which are powered by

	rechargeable batteries. On the other hand, the pressure sensors are all connected to a control unit to allow readings to be taken and for the sensors to be powered. The chosen servo motor model (Sigma 7) to drive the jaw rotation requires a supply voltage of 200 V AC (see appendix 2), which complies with the client's functional requirements.
Device must be designed in order to not pose obvious Health and Safety risks.	All electronic components are 'off the shelf' products and thus have undergone rigorous safety tests. There are no sharp edges in the apparatus designs. Although there are exposed moving parts in the ART apparatus, the operator would not have to be close to the apparatus when operating as readings can be taken remotely from a control unit. Space has been allocated to operate the knobs of the guide rails to prevent fingers of the operator from being trapped. The mannequin head sits firmly clamped to an aluminium shaft which is also screwed to the baseplate, thus preventing the apparatus from dropping, slipping or falling off.
It must be possible for one person to operate the device and perform the tests. This does not include the swapping of the apparatus.	For the BFE and ART apparatuses, all system inputs and outputs are designed to be controlled and monitored through a computer. This allows a single person to operate the apparatus with ease. The mannequin head weighs around 4kg which is light enough to be carried or operated by one person. The ears are detachable, meaning that they can be changed accordingly and just fitted on the head (see figure 6). The jaw movement is controlled by a sigma 7 servo motor which is simply programmed accordingly, thus making it possible for one person to operate the device with ease.
Maximum envelope: 2000 mm long by 1000 mm deep by 1000 mm tall, so that it can fit on a standard lab bench/table. Maximum weight of a working system (mannequin head together with ONE of the two apparatus) to be 100 kg.	The base plate used for the entire design is 2000mm by 500mm (see figure 2), and the head case (most elevated component) reaches a height of 600mm. Therefore the dimensions of

	the apparatus assemblies fall within the maximum permitted envelope size. Plastic has been used where appropriate and feasible, in order to cut down the weight. This is especially significant with the base plate which is made from polycarbonate. The mannequin head is made of Polystyrene plastic to account for the eco-design principles, as well as the ease of operation and accessibility. The full assembly of the mannequin head weighs approximately 4kg, which is quite light for functional requirements.
No special appearance requirement.	No comment/justification required.
Design to comply with relevant standards.	For all the systems, the screw holes are in compliance with the ISO 724. For the ART apparatus, the valve is in compliance with both the EN 60079-0:2006 and the EN 600079-15:2005 standards (KEMA, 2008). The chosen servo motor model (SGM7J) complies with many harmonised standards, including EN 55011, EN 61000-6-2, EN 61000-6-4 and EN 60034-1 in regards with rotary servo motors standards (see appendix 3).
Eco-design principles (e.g., energy usage, material selection, recyclability, repairability) must be used to demonstrate the environmental and sustainability awareness and knowledge into the design development process.	The mannequin head is purposely made of plastic (Polystyrene) in order to account for recyclability. All components of the mannequin head's design require minimum energy for operation. For the BFE, the capture chamber and all of the pipes are made from thermoplastics. This means they are recyclable, and the pipes are also 'off the shelf' which reduces the amount of energy required to manufacture them since a custom design is not required. For the ART apparatus, the pressure sensors were chosen due to the low energy usage. The components were chosen specifically such that they can be used for both the BFE and ART apparatuses. The curved plates section of the apparatus are made from polycarbonate which is both a strong plastic and is highly recyclable. Although PVC is not highly recyclable, the position of the pipes can be adjusted such that the pipes can be reused after trimming off damaged sections of the pipe. A large number of components are off-the-shelf components, so

	custom design is not required. Furthermore, these components can be replaced with relative ease as a result. Finally, the design was done such that all the parts of the system can be taken apart for repairs and replacement with relative ease.

Section 4: References and appendices

Section 4.1: Research references

Ralston Instruments (2020). Analog vs Digital Pressure Gauges. Available at: https://www.ralstoninst.com/news/story/analog-vs-digital-pressure-gauges#:~:text=Digital%20gauges%20perform%20reliably%20and,%2C%20loop%2C%20or%20solar%20power.&text=As%20a%20result%2C%20they%20are,overpressure%20spikes%20than%20analog%20gauges (Accessed: 17/12/2020)

Gastreich, W. (2018). Stepper Motors Advantages and Disadvantages. Available at: https://realpars.com/stepper-motors-advantages/ (Accessed: 17/12/2020)

machinetoolhelp.com (2010). Advantages & Disadvantages of Stepper motors & DC servo motors. Available at: https://www.machinetoolhelp.com/Automation/systemdesign/stepper_dcservo.html (Accessed: 17/12/2020)

KEMA (2008). Type Examination Certificate. Available at: https://docs.rs-online.com/d549/0900766b8156cd82.pdf (Accessed: 17/12/2020)

Nagi, R., Sahu, S., Gahwai, D., Jain, S. (2017). 'Study on evaluation of normal range of maximum mouth opening among Indian adults using three finger index: A descriptive study', J Indian Acad Oral Med Radiol, 29(3), pp. 186-190. Available at: https://www.jiaomr.in/article.asp?issn=0972-1363;year=2017;volume=29;issue=3;spage=186;epage=190;aulast=Nagi#:~:text=Regarding%20the%20normal%20mouth%20opening,35%E2%80%9370%20mm%20in%20females.&text=Gallagher%20et%20al.,males%20and%2041.1%20in%20females (Accessed: 17/12/2020)

Li, X., Jia, C., Zhang, Z. (2017). 'The normal range of maximum mouth opening and its correlation with height or weight in the young adult Chinese population', Journal of Dental Sciences, 12(1), pp. 56-59. Available at: https://www.sciencedirect.com/science/article/pii/S1991790216300873 (Accessed: 17/12/2020)

Pearson, A. (2018). 10 Advantages Of 3D Printing. Available at: https://3dinsider.com/3d-printing-advantages (Accessed 14 December 2020)

Amazon, A. (2017). Amazon.co.uk. Available at: https://www.amazon.co.uk/SONAX-04773000-Glue-Remover-Easy-Spray/dp/B071VX39XX (Accessed 14 December 2020)

Zolbin, M., Mokhtari, T., Hassanzadeh, G. and Arabkheradmand, A. (2015). 'Anthropometric Studies of Nasal Parameters of Qazvin Residents, Iran' 1(1). Available at: https://www.researchgate.net/publication/281107318_Anthropometric_Studies_of_Nasal_Parameters_of_Qazvin_Residents_Iran (Accessed 14 December 2020)

Bushby, K., Cole, T., Matthews, J. and Goodship, J. (1992). Centiles for adult head circumference. [online] 67(10). Available at: https://www.researchgate.net/publication/21710249_Centiles_for_adult_head_circumference (Accessed 14 December 2020)

Gastreich, W. (2018). Servo Motors Advantages And Disadvantages | Realpars. PLC Programming Courses for Beginners | RealPars. Available at: https://realpars.com/servo-motors-advantages/ (Accessed 30 October 2020)

Lin, Y. and Chen, C. (2017). Characterization of small-to-medium head-and-face dimensions for developing respirator fit test panels and evaluating fit of filtering facepiece respirators with different faceseal design. Available at: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0188638 (Accessed 30 October 2020)

Section 4.2: Component references

Flowmeter (VA 520)

CS Instruments (2020). https://www.cs-instruments.com/products/d/flow-meter/va-520-flow-meter-for-compressed-air-and-gas-systems (Accessed :17/12/2020)

Linear rail (pressure sensor assembly) (PU07AR)

RS Components (2020). https://uk.rs-online.com/web/p/linear-guides-rails/6192486/?cm_mmc=UK-PLA-DS3A-_-google-_-PLA_UK_EN_Pneumatics_%26_Hydraulics_%26_Power_Transmission_Whoop-_-Linear+Guides+-+Rails_Whoop-_-6192486&matchtype=&pla-402459306917&gclid=CjwKCAiAoOz-BRBdEiwAyuvA6ynAYIOBHbrJNQxGPcUIMdfPUHit0XlKapMZfJLgJxsjiZTssY4thBoC8xsQAvD_BwE&gclsrc=aw.ds (Accessed: 17/12/2020)

Valve (UCL-8A)

Misumi (2020). https://uk.misumi-ec.com/vona2/detail/221000052091/ (Accessed: 17/12/2020)

Rail clamp (L1010.CL)

Automation Components (2020). https://www.automotioncomponents.co.uk/en/catalog/linear-components/linear-guideways-rails/linear-guideways/clamps-for-guideways/l1010.cl/l1010.cl15/g+m+c+s+a+nr (Accessed 17/12/20)

Flexible Hose (NK-1500)

Misumi (2020). https://uk.misumi-ec.com/vona2/detail/221000801497/ (Accessed 17/12/20)

Pipe Clamp

Misumi (2020). https://uk.misumi-ec.com/vona2/detail/110300297960/ (Acessed 17/12/20)

Guide Rail for Moving plates (SSEBLZ16)

Misumi (2020). https://uk.misumi-ec.com/vona2/detail/110302586530/?CategorySpec=00000190399%3a%3aa (Accessed 17/12/2020)

Pipe Adapter for Pressure Gauge (DHA2-2SS)

Misumi (2020). https://uk.misumi-ec.com/vona2/detail/221004984066/?searchFlow=results2products&KWSearch=adapter (Accessed: 17/12/2020)

Tee Union

Misumi (2020). https://uk.misumi-ec.com/vona2/detail/110300313540/?KWSearch=tee%20fitting&searchFlow=results2products (Accessed 17/12/2020)

Pressure sensor (ADP5171)

RS (2020). https://uk.rs-online.com/web/p/gauge-pressure-sensor-ics/8368935/

Digital Pressure Gauge (700G005)

RS Components (2020). https://uk.rs-online.com/web/p/digital-positive-pressure-gauges/7588897/ (Accessed 17/12/2020)

Lead Screw & Nut (XCB6200)

Thomson (2020). https://www.thomsonlinear.com/en/product/XCB6200 (Accessed 17/12/2020)

Motor (RS PRO 180-5279):

RS Components (2020). https://uk.rs-online.com/web/p/dc-motors/1805279/ (Accessed 17/12/2020)

Pump (Piston pump 2380CUU32):

Metzger (2020). https://www.metzger-technik-shop.de/Piston-Pump-2380-57-l/min-900-mbar-69-bar-230V-oil-free (Accessed 17/12/2020)

Linear actuator (PQ12):

Actuonix (2020). https://docs.rs-online.com/e064/0900766b81682dc6.pdf (Accessed 17/12/2020)

Servomotor (SGM7J):

InvertersUK (2020.https://invertersuk.com/product/sgm7j-04a7a6c/ (Accessed 17/12/2020)

Section 4.3: Appendices

Appendix 1- Moment of inertia calculations for jaw

Mass properties of JAW
Configuration: Default
Coordinate system: -- default --

Density = 0.00232 grams per cubic millimeter

Mass = 30.14154 grams

Volume = 12992.04385 cubic millimeters

Surface area = 32018.10150 square millimeters

Center of mass: (millimeters)
X = -0.13304
Y = 1630.09770
Z = 20.65004

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

Ix = (0.99986, -0.00844, 0.01421)	Px = 57569.21033
Iy = (0.01652, 0.50421, -0.86342)	Py = 76722.76185
Iz = (0.00013, 0.86354, 0.50428)	Pz = 126085.60689

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 57574.44178	Lxy = -167.05028	Lxz = 268.92667
Lyx = -167.05028	Lyy = 113531.34505	Lyz = -21498.14445
Lzx = 268.92667	Lzy = -21498.14445	Lzz = 89271.79224

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 80163090.16115	Ixy = -6703.68911	Ixz = 186.12067
Iyx = -6703.68911	Iyy = 126384.96108	Iyz = 993113.90181
Izx = 186.12067	Izy = 993113.90181	Izz = 80181934.96253

Appendix 2- Sigma 7 Servomotor model (https://invertersuk.com/product/sgm7j-04a7a6c/).

Description

The SGM7J is a **rotary** Servo-motor from Yaskawa's flagship Sigma 7 range of servo systems. SGM7Js specialise in **medium inertia**, **high speed** applications and are available in sizes ranging from 50W to 750W. This version comes fitted with an optional **24VDC holding brake**.

When designing the Sigma 7 range Yaskawa focused on three main development goals:

- **Fast and easy to understand set-up / commissioning** - This is achieved with the help of presets in the amplifier software which allows for the system to be commissioned without the need to learn the full expansive range of parameters beforehand.
- **Outstanding reliability** - With over 12 million servo systems already in the field Yaskawa's Sigma drives are tried and tested to work no matter what is thrown at them. The latest iteration of Sigma servo systems come with a host of new improvements to help increase uptime which reducing maintenance and servicing costs.
- **Increased efficiency and production output** - Sigma 7 motors come with a more optimised magnetic circuit which helps improve motor efficiency and reduces the thermal buildup meaning that additional cooling is unnecessary.

More information about Yaskawa Sigma 7 Servos can be found here: **Sigma 7 200V Brochure**

Technical Specifications

Model Number	**SGM7J - 04A7A6C**
Rated Output (W)	400
Rated Torque (Nm)	1.27
Instant Max. Torque (Nm)	4.46
Power Supply Voltage (VAC)	200
Serial Encoder	24-bit Absolute
Design Revision Order	Standard
Shift End	Straight with key and tap
Options	24 VDC holding brake

Appendix 3: Relevant standards for the chosen servo motor model (SGM7J).

(https://sigma7.eu/wp-content/uploads/Verst%C3%A4rker/AdditionalRessources/Product%20Manual%20Direct%20Drive%20Servomotors.pdf)

Continued from previous page.

Product	Model	EU Directive	Harmonized Standards
Rotary Servomotors	SGMMV	EMC Directive 2004/108/EC	EN 55011 group 1, class A EN 61000-6-2 EN 61800-3 (Category C2, Second environment)
		Low Voltage Directive 2006/95/EC	EN 60034-1 EN 60034-5
		RoHS Directive 2011/65/EU	EN 50581
	• SGM7M • SGM7J • SGM7A • SGM7P • SGM7G	EMC Directive 2014/30/EU	EN 55011 group 1, class A EN 61000-6-2 EN 61000-6-4 EN 61800-3 (Category C2, Second environment)
		Low Voltage Directive 2015/35/EU	EN 60034-1 EN 60034-5
		RoHS Directive 2011/65/EU	EN 50581
Direct Drive Servomotors	• SGM7D • SGM7E • SGM7F • SGMCV • SGMCS-□□B, -□□C, -□□D, and -□□E (Small-Capacity, Coreless Servomotors)	EMC Directive 2014/30/EU	EN 55011 group 1, class A EN 61000-6-2 EN 61000-6-4 EN 61800-3 (Category C2, Second environment)
		Low Voltage Directive 2014/35/EU	EN 60034-1 EN 60034-5
		RoHS Directive 2011/65/EU	EN 50581
Linear Servomotors	• SGLG • SGLF • SGLF□2 • SGLT	EMC Directive 2014/30/EU	EN 55011 group 1, class A EN 61000-6-2 EN 61000-6-4
		Low Voltage Directive 2014/35/EU	EN 60034-1
		RoHS Directive 2011/65/EU	EN 50581

Note: 1. We declared the CE Marking based on the harmonized standards in the above table.
2. These products are for industrial use. In home environments, these products may cause electromagnetic interference and additional noise reduction measures may be necessary.

◆ Korean Radio Waves Act (KC)

Product	Models
Rotary Servomotors	SGM7D

■ Precautions for Korean Radio Waves Act (한국 전파법에 관한 주의사항)

Products with the KC Mark conform to broadcast and communications equipment for business use (Class A) and are designed for use in locations other than in ordinary houses.

KC 마크가 부착되어 있는 제품은 한국 전파법에 적합한 제품입니다. 한국에서 사용할 경우에는 아래 사항에주의하여 주십시오 .

사용자 안내문
이 기기는 업무용 환경에서 사용할 목적으로 적합성평가를 받은 기기로서 가정용 환경에서 사용하는 경우 전파간섭의 우려가 있습니다 .

(주)사용자 안내문은 " 업무용 방송통신기자재 " 에만 적용한다 .

xxii