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IFAC PapersOnLine 55-4 (2022) 13–18

Disadvantage of the FDM method for printing protective masks against COVID-19 and solution

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Abstract: Outages in the supply of basic medical supplies and protective equipment have led to efforts to replace them. The team of BUT employees and students has developed a protective half mask that can also be printed on a standard 3D printer without the use of special materials. The original half mask is intended as an improvised protection that can be easily printed on standard 3D printers with FDM technology. Problematic possibilities of sealing the entire surface of the print due to its porosity were solved with the help of a nitrile examination glove. Commonly available equipment is enough to produce this half mask.

Keywords: Protective half-mask, 3D printed mask, COVID-19 mask, 3D FDM method, filtration material.

1. INTRODUCTION

The rapid onset of the COVID-19 pandemic has caused an acute shortage of medical and protective equipment. One solution is to use local resources and processes to produce these tools, such as 3D printing, which is currently widespread. This technology is so versatile that address supply-demand imbalances caused by socio-economic trends and disruptions in supply chains as highlighted in Choong et al. (2020).

As part of the general lack of protective equipment due to the solution of the pandemic situation in 2020, the team of the Industrial Automation Group operating at the Institute of Automation and Measurement Technology FEEC BUT came up with an improvised solution for protection of the public health but also medical staff.

Thus, a protective half mask was developed that can be printed on a standard 3D printer without the use of special materials. The original half mask was designed so that it can be easily printed on conventional 3D printers with FDM (Fused Deposition Modelling) technology while maintaining a high level of hygiene.

The presented article describes the design of such a mask, its production and testing.

1.1. Disadvantages of FDM printing method for protective masks

A commonly known disadvantage of FDM technology is generally the very problematic sealing of the entire print surface due to its porosity. In other words, there is no guarantee that the print area will be impermeable to airborne particles with the potential presence of viruses that we need to filter out. This disadvantage is further exacerbated as the wall of the print thins. In general, all masks are designed so that the wall of the mask body is as thin as possible (usually 2-4 layers of material), where impermeability can hardly be ensured.

The situation is exacerbated by the fact that not all 3D printers that can potentially be used for printing are optimally tuned and structurally OK. Not every material is also suitable for printing under these conditions.

In view of the above, it can be said that 3D printing using the FDM method suffers in particular from the potential danger of creating a mask whose body will be easily permeable to viral particles, and the use of which will therefore make no sense.

Another problem with masks made by the FDM method is the fact that the creation with this method consists in placing individual layers of material on top of each other, which creates a serrated surface. This type of surface makes decontamination difficult for this type of product.

The third of the significant problems is the fact that the body of the mask itself must be flexible to some extent so that it can adapt to the specific shape of the wearer's face. Although there are materials that allow some flexibility of the printout, we cannot recommend production from our own experience. The main reason is the fact that when printing from flexible materials, even greater emphasis is placed on the design and tuning of the 3D printer and the experience of its user. Thin-walled objects are generally very problematic to print from flexible material.

Last but not least, the FDM method for 3D printing, although already widespread among people, requires a certain amount of experience and a feeling to tune the entire printing process so that optimal quality can be achieved.

10.1016/j.ifacol.2022.06.002

2. RELATED RESEARCH

A large number of half mask solutions can be found via the Internet, which people produce using the FDM 3D printing method. The Thingiverse (2021) web portal is an almost inexhaustible source of these solutions, which can also be downloaded from the portal. We can mention eg (COVID-19 MASK, 2021; Protective Mask, 2020; Custom Respirator, 2020; GEMINUS, 2020, DIY Mask, 2020; HEPA, 2021; COVID-19 Emergency mask, 2021)

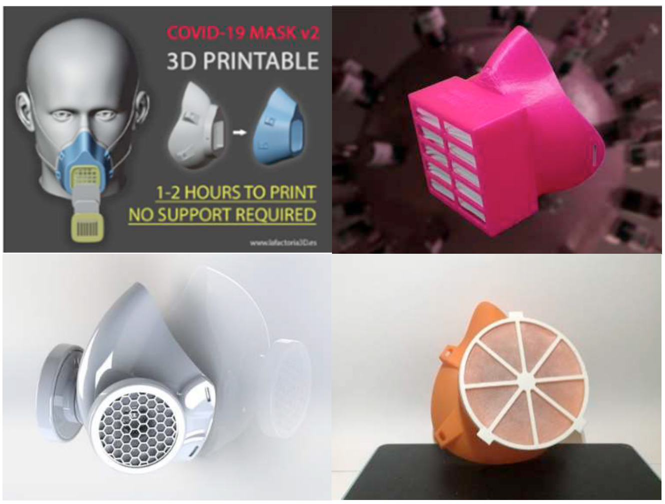

Figure 1. Projects available for free download from Thingiverse (2021).

However, it should be noted that none of these masks take into account the major disadvantages of FDM printing. At the time of the massive spread of COVID-19, it was even the case that the production of FDM technology itself began to be promoted for the production of other protective devices, such as shields or frames for cloth drapes, as reported by Yuxin et al. (2021).

In addition to FDM technology, several solutions have emerged for professional mask printing using other types of printers, such as HP Jet Fusion (Bulletin, 2020), but not for the amateur 3D printer community.

Belhouideg et al. (2020) summarizes PPE (Personal Protective Equipment), which can be produced using 3D printing, which highlights the protective mask, face shield and, in addition, the printing of a resuscitation valve to regulate the percentage of oxygen supply based on the standard product. template.

One of the parameters of the mask is the tightness, which, like the size, must ideally adapt to all users. The open-source project of WASP (2021) tries to solve this problem by using a 3D scan (or photogrammetry technique) of the face and printing a modified mask on a 3D printer. Although this method should have the best results, the authors state that it is not always possible for the mask to fit perfectly on the face. Another disadvantage of this approach is the fact that the user has to adjust the shape of the mask using a 3D modeling tool. Measurement of facial biometric data was also discussed in an article by Swennen et al. (2020), which, like WASP, optimized the model depending on the face shape. However, this approach may not be the most comfortable to wear for a long time. Another aspect is human facial expressions, which denies the previous intention of ideal tightness. A wear study of personally optimized breathing mask seals was performed by Cai et al. (2018).

Another approach to the production of PPE for respiratory protection is to create masks of various sizes. Han's Korean research (2004) also looked at setting the right size scales. We have adopted this approach especially for the sizes of children's masks.

The initiative in the development and production of face masks is reported by the report of Thomas et al. (2020). The authors also present an evaluation of the properties of the created equipment, where there are limitations caused by air permeability through the filter, filtration properties (up to the N95 level), but also the availability of material for production in the acute time. The air permeability could be solved by increasing the filter area, but to such a level that the useful properties deteriorate.

The lack of PPE not only affected the availability of respirators, masks or masks, but also had a significant impact on the filter materials market. The availability of filter material was addressed in a study by Zhao et al, (2020) or Konda et al, (2020). However, none of the studies focused on products designed specifically for household filtration, such as vacuum cleaner bags.

3. DESIGN OF BUTMASK

A common disadvantage of FDM technology is, as already mentioned, the generally very problematic sealing of the entire print surface due to its porosity. BUTMASK has solved this technological shortcoming in an original way by using standard nitrile examination gloves as a seal. This increases the tightness of the mask on the face and ensures that only the glove material certified for contact with the skin is in direct contact with the face. Thanks to this, the user is able to easily decontaminate the half mask.

The BUTMASK half mask underwent development in a very short time, when the BUT-H1 and subsequently BUT-H2 versions were presented. The main advantage of the BUT-H1 mask was the low price and also the geographical distribution of production (who has an FDM printer can produce), which is, by the way, one of the paradigms for "fourth generation" products in Industry 4.0. The half mask was conceived from the beginning as an improvised protection, however, it passed preliminary tests according to the EN 140 standard at the Research Institute of Occupational Safety. The certification did not take place because the mask was developed as an improvised aid in a period of scarcity, which, however, disappeared after some time. Independent control and development support was also provided by the company MALINA - Safety s.r.o., which is one of the leading manufacturers of filters and protective aids in Czech Republic, and the Institute of Instrumentation of the Academy of Sciences of the Czech Republic.

The production of the BUTMASK half mask does not require expensive 3D technologies, which are generally in short supply (eg HP MultiJet Fusion), but the most common, and therefore the most widespread 3D printers among users are sufficient. The tightness of the mask does not depend on the quality or thickness of the print, as the printed part performs the function of a skeleton, a tight fit on the face and impermeability of particles is ensured by a flexible sleeve made of gloves. As a result, the inner part of the mask is not exposed to a potentially contaminated environment. External decontamination is performed by removing the glove, disinfection of other parts is performed by immersion in a vircidal solution.

The first version of the BUT-H1 mask was based on the basic concept and idea of sealing. The development of the first prototype was spontaneous and the emphasis was on tightness and universal size. During the testing, there were problems with discomfort and the way the mask was attached. Therefore, another version called BUT-H2 was developed in quick succession.

Figure 2. Fully assembled half-mask BUT-H1

The advantages of the improved version BUT-H2:

- Significantly improved user comfort. The original version of the mask, if the user did not fit the size and shape well, was very uncomfortable for some users. Adjustments were made to the shape of the mask to reduce discomfort, especially in the area around the nose, other adjustments better distribute the pressure on the face.
- More sizes to choose from. With hard plastic prints, it will never be possible to achieve the comfort and facial adaptability offered by commercial soft plastic products. Therefore, it is important to find the size that best fits your face with the mask. In an effort to meet the needs of users, significantly more sizes were prepared (Fig. 3) than is common for commercial products (eg very small sizes XS and XXS).
- Reduction of leaks when sitting on the face. By optimizing the shape of the mask, most users not only have a significant increase in comfort, but also a very important reduction in leaks. The original version of the mask already showed very good results in the approximate measurement of tightness, the new version seals even better.
- Optimized space for improvised filter placement. Due to the fact that the materials of the original bags for the premium brand vacuum cleaner (Miele bags, S-bag Electrolux / Philips) were tested as a very good, improvised filter medium in orientation tests, we adjusted the space and attachment of the filter so that the active surface of the filter the media was compressed as little as possible, and the filter could work as well as possible.
- An innovative way of mounting. For a good tightness of the mask, it is necessary that the mask holds well on the head, so it is recommended to cross the harness (upper harness above the ears, lower cross and lead over the top of the head).
- Indirect ventilation with louvers. The filter is partially protected by fins so that particles and droplets cannot fall directly on the filter. The slats also direct the exhaled air downwards, not straight away from the wearer.
- Increasing the filter area by approx. 50%, while maintaining a small dead space (mask inner volume).

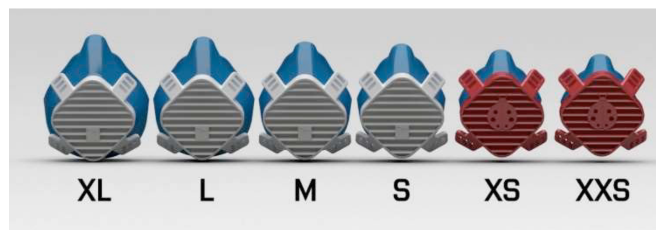

Figure 3. BUT-H2 half mask in several sizes, always with the same filter area

4. SOCIAL CONTRIBUTION

At the time of the creation of this mask (Spring-Summer 2020), there was a coronavirus crisis in the world, which to some extent still persists. All the materials and tools needed to fight the pandemic were either inaccessible to ordinary people or disproportionately overpriced. During this period, a number of projects using 3D printing technology for the production of protective equipment appeared in the world and in the Czech Republic. Examples are shields from Prusa Research or the CIIRC RP95-3D half mask in Bulletin (2020). Both projects targeted a different segment of 3D technology. Professional printers such as HP Jet Fusion, based on sintering powder resins, are also suitable for printing airtight structures such as masks. In contrast, 3D technologies commonly available to the general public are imperfect in terms of their intended use. FDM technology stereolithographically forms a thermoplastic producing structures of sufficient strength containing microcracks. In general, this technology without additional modifications was not recommended for the production of masks.

3D printing communities were spontaneously forming among the public, and the potential for distributed production of protective equipment continued to grow. The production of shields has tested these communities, but the production of respiratory protective equipment has not been recommended to these groups with reference to potentially porous material. The development of the BUT-H1 half mask based on FDM technology brought to the market a solution available to all enthusiasts as well as professional 3D printers.

The new version of the mask, like its predecessor (BUT-H1) from the end of March 2020, was intended mainly for non-commercial purposes, such as community 3D printing. The materials for the production of the mask, as well as all documentation is publicly available under a Creative Commons license type BY-NC-ND.

Several companies have shown interest in commercial production. The ability to produce more masks was an attractive alternative to cloth drapes and Chinese respirators of dubious quality. Despite the fact that it was an improvised protective device, a number of medical facilities, which at the time were facing a lack of protective equipment, also resorted to its printing and use.

5. SUITABLE FILTER SELECTING

During the development, a test of suitable filter materials was prepared, which was prepared by the Institute of Instrumentation of the ASCR. Orientation measurements were performed using a particle counter. The test focused on materials commonly available in the commercial network even during the peak of the pandemic. Materials that appeared to be readily available in relatively reasonable quantities on the market were chosen as the main source of filter fabrics. Specifically, these were mostly vacuum cleaner bags. Both branded and non-branded bags, listed by the manufacturer as "of the highest quality", were selected for testing (anti-allergenic or HEPA labelled bags). For comparison, we obtained samples of NANO-fabrics developed in cooperation with the Technical University of Liberec. The samples were provided by the company SPUR a.s., which produces the material. For comparison of samples with less available professional material, a nano fabric with P2 certification according to EN 149 was chosen.

The following samples of filter materials were analyzed:

- No. 1: Nanofiber fabric - SpurTex VS (1cm2) - comparative nanofabric
- No. 1b: Nanofiber fabric - SpurTex VS (10x10cm2) - comparative nanofabric
- No. 2: Vacumcleaner bag - Miele FJM HyClean (1cm2)
- No. 2b: Vacumcleaner bag - Miele FJM HyClean (10x10cm2)
- No. 3: Vacumcleaner bag - s-bag Anti-Allergy (1cm2)
- No. 3b: Vacumcleaner bag - s-bag Anti-Allergy (10x10cm2)
- No. 4: Non-woven fabric PS fibers10um + cellulose (cleanroom wipes KM) (10x10cm2)
- No. 5: Vacumcleaner bag - SWIRL MicroPor (10x10cm2)
- No. 6: Vacumcleaner bag - ETA (10x10cm2)
- No. 7: Surgical drapea

their ability to filter particles of different sizes (0.3µm; 0.5µm; and 5µm). The filtration efficiency of individual samples is shown in Table 1 resp. in Figure 4.

Table 1. Filtration efficiency of house common materials

Sample	0,3 µm	0,5 µm	5 µm
1	63,36 %	97,19 %	97,54 %
1b	70,16 %	94,43 %	98,36 %
2	26,40 %	89,28 %	93,44 %
2b	94,16 %	98,27 %	99,18 %
3	99,96 %	100,00 %	100,00 %
3b	100,00 %	100,00 %	100,00 %
4	43,62 %	61,74 %	95,08 %
5	99,99 %	99,94 %	100,00 %
6	58,83 %	77,96 %	99,18 %
7	65,46 %	86,08 %	96,67 %

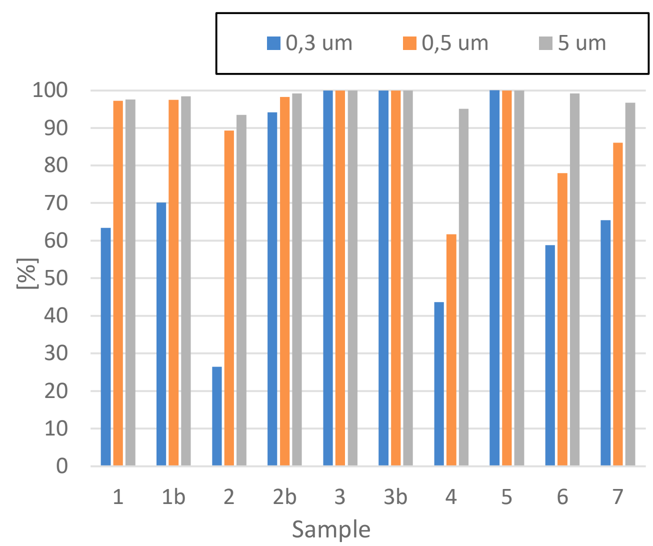

Figure 4 Filtration efficiency of house common materials

6. CONCLUSIONS

Two materials (samples 3 and 5) were selected from the measurement results, both from the group of vacuum cleaner bags. Due to the relatively limited breathability of the relatively small filter area, based on the results of these measurements, a design modification of the mask was made to increase the filter area and thus the BUT-H2 design.

Independent organizations, such as the Institute of Instrumentation of the Academy of Sciences of the Czech Republic, also took part in production and educational activities. Thanks to them, several dozen completed masks were distributed to the St. Anne's University Hospital. Furthermore, a video was created for the completion of BUT-H2 masks. SUPŠ and VOŠ Jablonec na Nisou also contributed in production and distribution, offering printed masks for professionals and volunteers who need protection greater than the veil can provide.

The response to the mask passed through a significant part of the Czech media. BUT-H1 was written on the portal Novinky, Deník N, Lidovky, Blesk or Lupa.cz. The TV report on Prima CNN masked from BUT in the context of the contribution of Czech scientists in the field of combating the lack of protective equipment. The mask has also found its way into foreign media such as the Currenttime internet television, owned by Radio Free Europe, which disseminated information about BUTMASK from BUT in Russian-speaking countries.

The simplicity and unpretentiousness of the production of half masks has spread beyond the borders of the Czech Republic, and references have come, for example, from the United States of America. There, thanks to a BUT graduate working abroad, nurses at Henry Mayo Newhall Hospital in California were equipped with half masks from BUT, who were also acutely struggling with a lack of protective equipment. The hospital even tested the so-called "fit test" on the masks, which confirmed the good sealing ability. In the USA, this test was a sufficient condition for the professional use of repair respiratory masks in medical facilities.

According to the references of satisfied users, the mask got into both the first line of the fight with SARS-CoV-19 and the ordinary working sphere. Workers working in dusty environments or foresters working with sprays also felt the lack of protective equipment. All of the images here and many others have voluntarily provided their photographs for Covid-19 enlightenment purposes. From Red Cross sorting centre, GP surgeries to administrative staff. Everyone wanted to protect themselves and their surroundings, and they didn't care what kind of protection they chose.

ACKNOWLEDGEMENT

The completion of this paper was made possible by the grants:

No. FEKT-S-20-6205 - "Research in Automation, Cybernetics and Artificial Intelligence within Industry 4.0";

No. FV40196 - "Research and development of the monitoring beds for immobile persons from the perspective of the risks of bedsores - decubitus";

No. FV 40247 - "Cooperative robotic platforms for automotive and industrial applications”;

No. FW03010100 - “Research and development of detection and monitoring of people with dense coverage in shopping centers in order to optimize shopping flows and, in the event of crises and epidemics, access control to these areas”.

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Appendix A. TECHNICAL DESCRIPTION OF THE MASK

The mask consists of two main parts, the mouthpiece (frame) and the filter holder with a clamping system. The complete set is completed with a nitrile or latex glove, harnesses, kitchen rubber bands and filter material. The choice of glove size depends on the flexibility and size of the mask frame. Nitrile examination gloves, which are not as flexible but are stronger than latex rubber gloves, have proved to be the best. Another advantage is the health safety of allergy sufferers. Powdered gloves should not be used as there is a risk of powder inhalation.

As part of the development and distribution of online materials, a detailed guide for the preparation and completion of the improvised mask was created. This manual also contains recommended manufacturing requirements and materials, see Table 2.

Table 2. Recommended slicer settings

Nozzle	0,4 mm
Layer height	0,2 mm
Top solid layers	3
Bottom solid layers	3
Outline shells	2
Infill	40 %
Support	No
Raft	No

All materials for production are available on the website (https://www.vut.cz/mask). The written materials are supplemented by instructional videos published on the YouTube portal in Czech or English version.

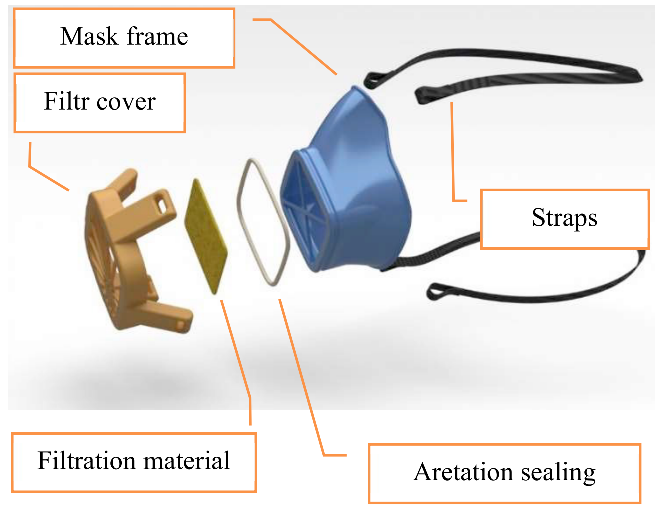

Figure 5 All parts of mask BUT-H1

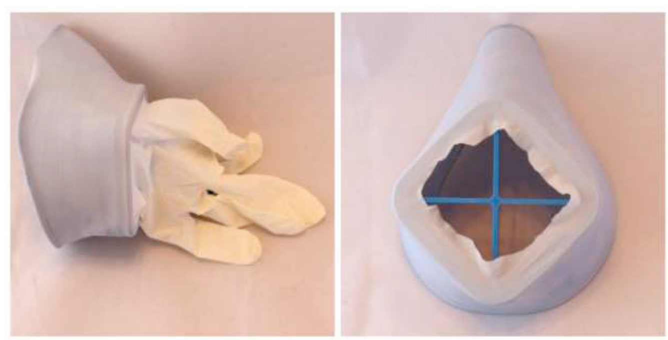

Figure 6 Gloves cover assembly

The mask of our design already in the first version had a relatively small "dead volume". As a result, the vast majority of exhaled air immediately leaves the mask. Orientation measurements confirmed that only a minimum of exhaled CO2 is inhaled with the mask. In this respect, the mask has all the prerequisites to meet not only the requirement of the standard for gas masks, but also the much more demanding requirement imposed in this respect on products for medical purposes.