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3D-Printing for Cube Satellites (CubeSats): Philippines' Perspectives

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Abstract. The increase in space exploration missions in recent years gave way to the development of a volume-efficient and cost-effective nanosatellite like the cube satellite (CubeSat) which can be developed and fabricated in a relatively short time. With its size and design, CubeSat parts like casings can be produced and assembled through 3D printing to produce inexpensive satellites. Research in this area is undeniably important to maximize the rapid development of CubeSats. While progress has been made, challenges remain in applying 3D printing technology in the development of CubeSats. In this paper, the current status regarding the advancement of 3D printing for CubeSat applications is discussed. First, important issues about the common materials for CubeSat and potentially 3D printing materials for CubeSats are addressed. Second, 3D printing CubeSat parts through the feasible structure design models by combining material and parameter designs are explored from a wide range of references. And also, 3D printing of cube satellite parts by DOST AMCen and STAMINA4Space has also been demonstrated. Lastly, an outlook on the future direction of the 3D printed CubeSat for the Philippines space program is provided.

1. Introduction

A cube satellite (CubeSat) can be very effective in terms of volume efficiency, cost-effectiveness, and short development cycle aspects. One CubeSat unit is known as 1U, with standard dimensions of 10 cm x 10 cm x 10 cm and having a mass no greater than 1 kg. Through the development of new configurations, the modular unit can now be put together to form bigger artifacts (*e.g.*, 2U, 3U, 6U, and so on). A typical CubeSat structure made of aluminum alloy 6061-T6 or aluminum alloy 7075 is shown in Figure 1 [1]. Space Systems Development Laboratories of Stanford University and

California Polytechnic University at California, USA conceived the CubeSat standard and published specific major requirements and constraints as well as important guidelines that each CubeSat must comply with as the design progresses [2, 3].

CubeSats are changing the traditional satellite launching logic. Due to its small size, several CubeSats can be launched by a single rocket or can also be a secondary payload in a rocket launch. Since the first launch into space in the early 2000s, it has made extensive applications, ranging from the testing of technologies and science missions [4], astronomy [5], and space weather [6]. Factors, such as radiation, extreme heat cycles, and low pressure are the common environmental conditions a CubeSat will encounter in space. CubeSats must also have good impact resistance to withstand the reaction forces during the launching process and space operation [7]. Therefore, suitable materials must be selected properly to meet these requirements.

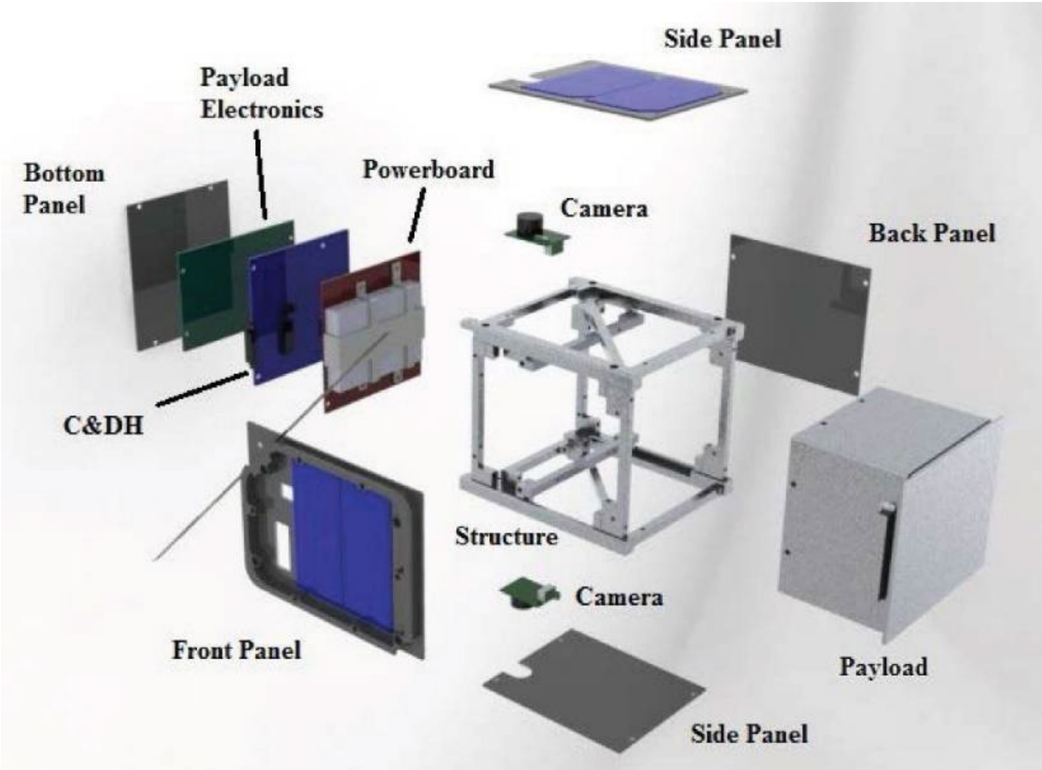


Figure 1. An exploded view of the basic structure and panels with modules that comprise a typical CubeSat. Source NASA.

The Philippines is one of the countries currently expanding its capabilities in satellite technology through its indigenous space development program under the newly established Philippine Space Agency (PhilSA) [8]. With the creation of PhilSA comes the urgent need to develop technologies for space development and utilization and keep up with other nations in terms of space science and technology. Throughout history, the Philippines ventured with several private firms in acquiring and launching its satellites. Earth satellite receiving stations, such as the Agila-1 (1987) [9], Agila-2 (1997) [10], Diwata-1 and 2, and Maya-1 (2016) [11] are among the Philippines initiatives in its space technology history. Those are microsatellites, weighing 10-100 kg, which are either acquired from other countries or developed through foreign partners. Major challenges of the program that hindered its development locally include technological incapacity and insufficient funding. The technology used, coupled with appropriate materials needed, in building those satellites are either not currently available in the Philippines or quite expensive to be fully developed in the Philippines. A CubeSat nanosatellite, on the other hand, is an alternatively inexpensive kind of satellite. Its size and design are suitable not only for those with tighter budgets but also CubeSat parts like casings can be produced and assembled through additive manufacturing (AM) technology, commonly known as 3D printing.

The possibilities of CubeSat manufacturing using 3D printing technology have been getting attention from several researchers [12-14]. The 3D printing, which has been developed from the need for rapid prototyping, attracts significant research in various areas due to its distinctive manufacturing technique. The 3D printing is used to describe a set of different technologies that turn a three-dimensional (3D) computer-aided design (CAD) model into a layer-by-layer constructed 3D object depending on the machine and materials used. The quality of the output, however, is highly dependent on the technique employed, as well as the scale and printing parameters [15-17]. In general, these 3D printing technologies can be classified into seven categories according to ISO 17296-2 [18]. The first process is Binder Jetting that uses a binder and powder-based materials such as metals, ceramics, waxes, and composites. Second is the Material Jetting that produces objects in the same way a two-dimensional inkjet printer does. Under this category are the MultiJet Modelling (MJM) and Drop-on-Demand (DOD). Third is the VAT Photopolymerization which uses a tub of liquid photopolymer resin and has 3D printing technologies such as Stereolithography (SLA), Two-Photon Polymerization (TTP), Digital Light Processing (DLP), and Continuous Liquid Interface Production (CLIP). Fourth, a Sheet Lamination utilizes metal sheets or ribbons that are welded together by ultrasonic welding. This process includes Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM). Another process is Material Extrusion, where thermoplastic is drawn through a nozzle and heated before being deposited. The most common 3D printing technology for this category is Fused Deposition Modeling (FDM). Another one is the Powder Bed Fusion which uses either a laser or electron beam to melt and fuse the material powder. The 3D printing technologies for this process include Selective Laser Melting (SLM) for metals and Selective Laser Sintering (SLS) for polymers. Lastly, the Directed Energy Deposition (DED), a more advanced printing technology that is commonly used to repair or add material to existing components. These are the Laser Engineered Net Shaping (LENS) and Electron Beam Manufacturing (EBM) 3D printing technologies. [17-19].

Nowadays, miniaturized parts with complex designs are accessible through 3D printing technology using less material than traditional manufacturing methods. Once used only for prototyping, it is now rapidly transforming into a production technology [20]. Recently, the Additive Manufacturing Research Laboratory (AMRel) at Bataan Peninsula State University (BPSU) was recognized by the Department of Science and Technology (DOST) as the first 3D printing research facility in the Philippines [21]. Initially, AMRel is serving the students, academe, and industry to test materials and generate 3D-printed products and relevant research projects. Now, materials, such as acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA), etc., are being utilized and assessed at AMRel for practical device applications [22-26]. The Department of Science and Technology also recently established the Advanced Manufacturing Center (AMCen) which houses state-of-the-art 3D printing technologies and metrology tools.

With their focus currently emphasized on helping the Philippines develop its space programs, AMCen and AMReL are looking to explore high-performance polymer materials such as polyether ether ketone (PEEK), PAEK, ULTEM, or even metals, as 3D-printed CubeSat parts/materials. These high-performance polymers can be suitable materials for CubeSats and are known to be strong enough to survive in a hostile space environment. Through the target collaborations with concerned agencies and institutions such as UNISEC Philippines and Sustained Support for Local Space Technology & Applications Mastery, Innovation and Advancement (STAMINA4Space) program, they are targeting 3D-printed CubeSats that can be developed locally. This study will highlight the current status of 3D-printed CubeSats and CubeSat parts, especially its development process. This includes the candidate materials for CubeSat parts 3D printing and demonstrations of 3D-printed CubeSat parts. The potential impacts, such as the cost-effectiveness, research capabilities of researchers and engineers, the establishment of new expertise, stepping up of development, future repairs, income-generating capability, including the insights of the 3D-printed CubeSat development in the Philippines, will be addressed.

2. Methodology

2.1 Design, Conceptualization, and Development Process

Unlike the typical or average-sized satellite which requires 5 to 15 years to develop from planning and placing it to orbit, nanosatellites, like CubeSats, require less than 8 months of development [27]. With the trends of constantly changing technologies, such as in updating technology in telecommunications, CubeSats can be very reliable in providing an optimum technology service at all times. This means that current state-of-the-art technologies can be adopted easily before losing their market-appropriate value. This also includes the detection of needs and placing them in orbit. The NASA CubeSat Launch Initiative (CSLI) [4], for instance, provided an estimated timeline of how long it may take to develop CubeSat from a concept to a functioning satellite in orbit. A CubeSat can be developed, manufactured, tested, and delivered within or less than 9 months, whereas a full development process, including launch, takes 18 to 24 months on average. Table 1 shows the typical timelines for the CubeSat development process with its respective duration according to CSLI.

Table 1. Timelines for the development process of CubeSat

Development Process	Duration
Concept Development	1-6 months
Securing Funding	1-12 months
Merit and Feasibility Reviews	1-2 months
CubeSat Design	1-6 months
Development and Submittal of Proposal in Response to CSLI Call	3-4 months
Selection and Manifesting	1-36 months
Mission Coordination	9-18 months
Licensing	4-6 months
Flight-Specific Documentation Development and Submittal	10-12 months
Ground Station Design, Development, and Testing	2-12 months
CubeSat Hardware Fabrication and Testing	2-12 months
Mission Readiness Reviews	half-day
CubeSat to Dispenser Integration and Testing	1 day
Dispenser to Launch Vehicle Integration	1 day
Launch	1 day
Mission Operations	variable, up to 20 years

Figure 2 delineates the development timeframes that can be overlapped. The overall time frame can vary depending on what CubeSat design goal wants to accomplish. Although there is no definite real time limit, especially in the development phase, the CubeSat concept development and design process are both substantial in deciding which components will work best for the CubeSat system. Another important factor associated with CubeSat development compared to conventional large satellites is the lower cost. These include the cheaper physical materials and parts, labor for development, and launch vehicle fuel [28]. In the span of two decades, the launch of CubeSats proved that serious science could be undertaken by such a small platform that could be constructed within reasonable cost and schedule. The MarCo CubeSat, for example, breaks the barrier in conventional nanosatellites. It is the first CubeSat to go deep into space, above the typical low circular or elliptical orbits deployment distance of 400 to 650 km [7]. From being mostly an academic demonstration, CubeSats are now being developed by multiple international consortiums of universities and space agencies. Its application expansion to commercial and government entities is currently realized. In 2016, the Philippines was one of the countries that recently collaborated in multinational efforts to launch CubeSats in space [29]. That experience opens a new beginning for local scientists and researchers in expanding the capacity of its newly created space program using local design and locally-made satellites.

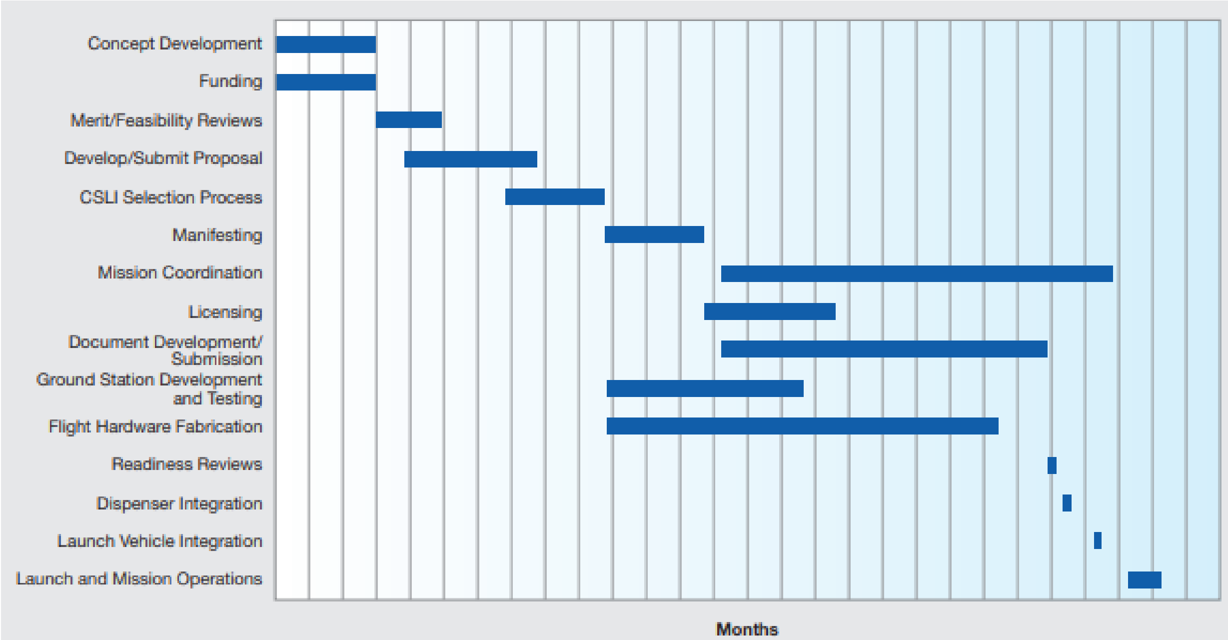


Figure 2. This notional timeline shows how these phases might come together for a project [4].

2.2 Structural Design and Manufacturing Techniques

The satellite's mass, structural stiffness, and strength are some of the requirements in design to ensure the survivability of the instrumentation inside the CubeSat, while by reducing the weight, it is possible to increase the payload, which extends the mission goals and also reduces the launch cost [13]. Generally, CubeSat design is bound by the general constraints and requirements of stiffness and principal eigenfrequency [30]. Metals as a CubeSat structural material coupled with traditional manufacturing techniques, such as sheet metal processes, are the most common methods to meet these requirements. Its structural and mechanical parts generally represent a large percentage of its mass, and therefore, it is important to choose the proper material [14] and structural configuration to minimize mass. Topological optimization is one way to minimize the mass of the CubeSat while maintaining the structural performance of its support structure. This method also helps to minimize the predefined cost function [31].

Depending on the CubeSat design and the material selected, the installation of related subsystems, additional braces, and brackets may be required. These added frame structures are necessary for payload mounting points but definitely add more weight to the CubeSat. In addition, to secure the internal hardware inside the CubeSat, outer panels usually made of metal or fiberglass are needed. With all these added weights, the structural design process that would allow additional mass reserved for components should be considered. A report suggested that 15-25% of mass should be reserved for these additional weights [32], which makes the use of lightweight materials desirable. With 3D printing, the typical way of removing material from the manufactured parts will be avoided, instead, material/part can be made layer by layer. An effective design, consisting of two identical top and bottom plates, four equal sides, and eight identical bases was proposed [12]. Figure 3 shows the 3D-printed design assembled from multiple parts. This design is advantageous for installation and disassembly, making it also capable of carrying more payloads.

In the Philippines' initiative, the STeP-UP Project under the STAMINA4Space program, are fostering CubeSat development mastery through the nanosatellite engineering course they offer [33]. Their first batch successfully developed Maya-3 and Maya-4 (both 1U CubeSats) which were launched recently [34]. These CubeSats will be the future successors of Maya 2 CubeSat [35, 36]. Currently, the second batch of students are accomplishing the same feat as they develop their CubeSats [37].

Figure 3. A CubeSat structure design with 3D-printed multiple parts [12].

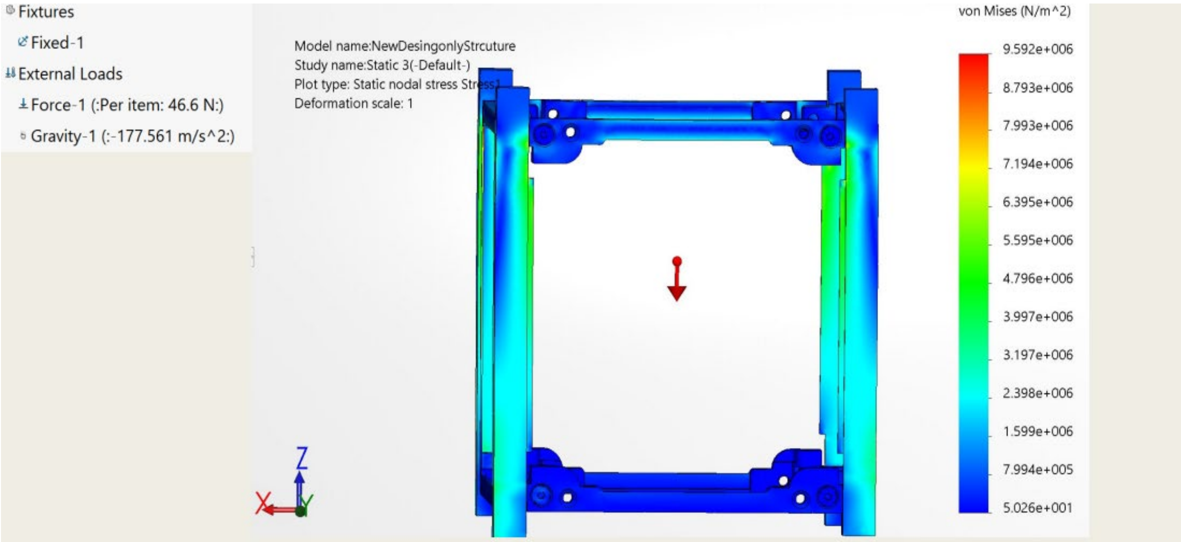
2.3 Materials for CubeSat

At present, the number of CubeSat designed with plastic materials is very small, and new design schemes will open a new road in the manufacturing technology of CubeSat. Candidate materials that were recently used as prototypes in 3D-printed CubeSats are summarized in Table 2, with their selected material properties [14, 38]. The comparisons in Table 2 are based on specific material properties using a standard test piece. For the actual CubeSat structures frame/case, the available literature is currently based on simulations. Figure 4 summarized the structural strength of the CubeSat based on the 1U frame [39]; while quasistatic analysis results of the 2U CubeSat frame shown in Figure 5 are summarized in Table 3 [40].

In the design process, the first to be determined should be the value range of the key structural parameters, by combining the concept of system calculation, such as the design and strength checking calculations. Afterward, the design scheme of the CubeSat structure can be optimized based on the comparison between several feasible schemes. As such, aside from the metal 3D-printed CubeSat frame, utilization of ULTEM and PEEK as 3D-printed parts of the CubeSat are highly desired.

Table 2. Published material property data for selected materials [14, 38].

Material Property	FullCure720	ABS	Watershed 11122XC	ProtoTherm12120	Windform XT	PEEK	ULTEM	PAEK	Al-7075-T6	Al-6061-T6
Tensile Strength (MPa)	50-65	34.5	47.1-53.6	77.2	77.85	95	71.6	160	572	310
Modulus (MPa)	2000-3000	2482	2650-2880	3247	7320	6580	2220	1120	7170	6890
Tensile Elongation (%)	15-25	50	3.3-3.5	4.5	2.6	3.5	5.9	2.53	11	17
Flexural Strength (MPa)	80-110	65.5	63.1-74.2	103	131.52	160		240	-	-
Flexural Modulus (MPa)	2700-3300	2620	2040-2370	3061	6248.5	6810	2500	1020	-	-
IZOD (J/m)	20-30	-	0.2-0.3	0.016	-	430 (unnotched)	107 (notched)	786 (unnotched)	-	-
Heat Deflection (°C)	45-50 (.45 MPa)	-	45.9-54.5 (.46 MPa)	126.2 (.46 MPa)	175.4 (1.82 MPa)	193 (1.8 MPa)	160 (1.8 MPa)	268 (1.8 (MPa)	-	-
Water Absorption (%)	15-22	-	0.35	0.24	-	-	-	0.122	-	-
Tg (°C)	48-50	104	39-46	111	-	-	-	-	-	-
Shore Hardness (D)	83-86	105	-	86.7	-	-	-	-	-	-
Rockwell Hardness (M)	73-76	-	-	-	-	-	-	102	87	107
Polymerized Density (g/cm3)	1.18-1.19	1.04	1.12	1.15	1.101	1.37	-	1.52	2.81	2.7
Aging Temperature (°C)	-	-	-	-	-	-	-	-	121	160
Fatigue strength (MPa)	-	-	-	-	-	-	-	-	159	96.5



Material	Density (g/cm^3)	Ultimate Tensile Stress (Mpa)	Yield Stress (Mpa)	Youngu`s Modulus (Gpa)	Max stress	Tensige margin of Safety	Yield margin of Safety
ABS	1.02	30	60.6	2	9.45	0.59	3.3
AL6061	2.7	310	275	69	9.45	15.4	18.4

Figure 4. Simulation of CubeSat structural strength integrity based on ABS and Al 6061 materials [39].

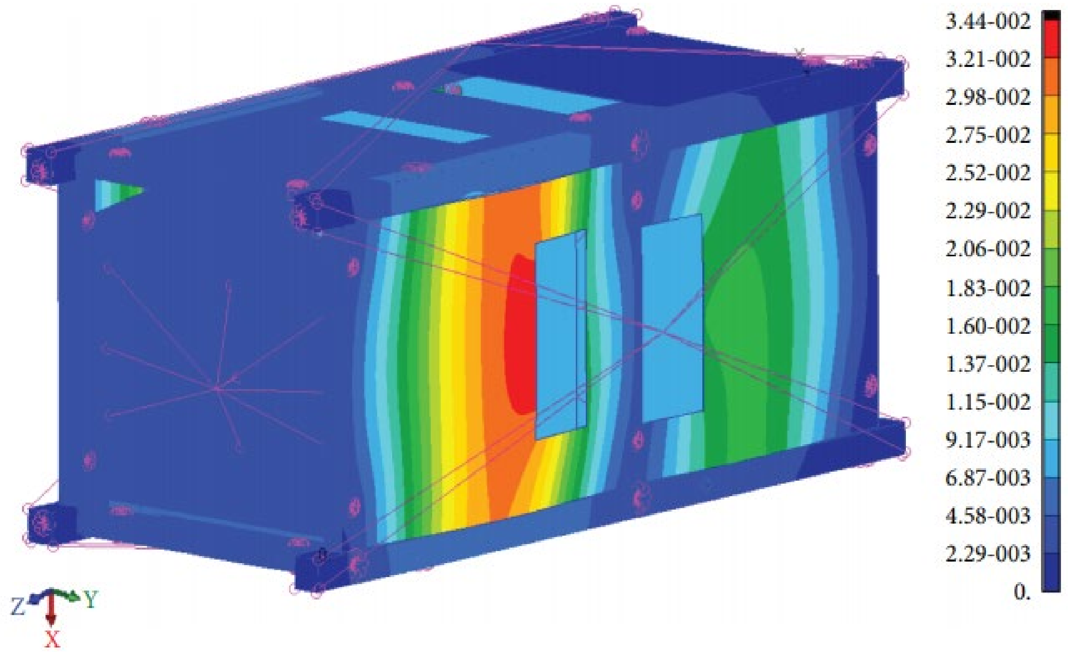


Figure 5. Displacement distribution along the x-axis of 3D-printed 2U CubeSat [40].

Table 3. Quasistatic analysis results of 3D-printed 2U CubeSat using different materials [40].

	x-axis	*y*-axis	*z*-axis
Displacement (mm)	0.031	0.034	0.00372
STRESS—CFRP *(max principal)* (MPa)	6.95	6.55	1.18
STRESS—ALUM *(von Mises)* (MPa)	15.2	11.6	25.6
STRESS—PCBs (MPa)	4.4	4.7	2.06
STRESS—spacers (MPa)	3.8	4	1.5
STRAIN	$6.73 * 10^{-5}$	$6.89 * 10^{-5}$	$7.39 * 10^{-6}$

2.4 3D printing materials for CubeSat

The 3D printing process usually starts with a 3D model that could either be made using computer-aided design (CAD) software or by 3D scanning an object. The 3D model will then be converted to a compatible file format such as .STL or .OBJ. AMF, short for Additive Manufacturing File format, is also being used [41]. In the .STL file format, the shape of the objects can be simulated using triangular facets [42]. The .STL file is then processed using a slicing software/AM system (usually dedicated to a specific 3D printer), which slices the model in several hundred or thousands of layers. In the slicing software, different parameters such as printing speed, layer height (resolution), infill, are being optimized. Additionally, the slicing software also converts the .STL file into the appropriate file type, which is specific to a particular 3D printer (G-code) [43]. The sliced file (G-code) will then be transferred to the 3D printer, and the 3D printer will then build the part. After printing, the part will then be removed and post-processed, and will then be prepared for application [41].

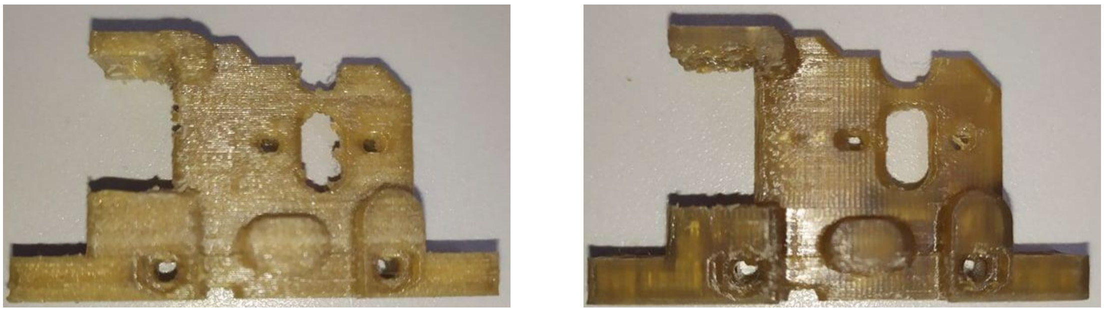
As earlier mentioned, there are several 3D printing technologies available in the market and are divided into several categories [19, 44 - 47]. The most commonly used 3D printers are extrusion-based Fused Deposition Modeling (FDM) also known as fused filament fabrication (FFF), which uses a thermoplastic filament as its printing material. In FFF, the printer prints a 3D object by extruding a molten thermoplastic material following the sliced 3D model [44, 48]. The molten material is positioned layer upon layer until the 3D object/part is created. Stratasys owns the patent for Fused Deposition Modeling (FDM) in 1989 [49]. Common materials being used are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and recently high-performance polymers such as PEEK [50]. This printing technique is relatively fast and cheap but requires support structures especially for complex shapes [19, 44, 51]. The basic components of a typical FFF/FDM printer include the build platform, a heated extrusion nozzle, and the filament material.

The 3D printing technologies presented here provide insights representing almost all 3D printing processes used for rapid prototyping. Specifically, representative 3D printing technologies using different printing materials (*i.e.,* solid-based, powder-based, and liquid-based) have been discussed. However, although 3D printing of various polymers has been somewhat utilized elsewhere, surprisingly, studies on 3D printed PEEK/PAEK/ULTEM polymers are lacking. In particular, studies related to gamma radiation of these high-performance polymers are still far from being fully understood. Basically, the material properties of most polymers are highly vulnerable to unwanted changes if exposed to radiation. In most cases, gamma radiation effects on mechanical strength degradation are common in real applications. The 3D printed components in satellites and spacecraft can be exposed to a specific range of radiation rates deemed as gamma irradiation [52, 53]. The pore structures or print patterns modified using the printer parameter setting in 3D-printed polymers can affect the efficiency of oxygen diffusion inside the material [54]. Worth noting is that oxygen diffusion plays an important part in radiation-induced reactions. FDM-printed polymers with oxygen present in porous, for instance, might alter the reactions of the radicals generated by radiation, losing its ductility, and making it brittle [55]. The resulting embrittlement can widely affect the ageing and structural damage, for it alters the available diffusion pathways for the oxygen diffusion to take place [56]. With these, an in-depth understanding of the effects of gamma irradiation on the mechanical properties of 3D printed PEEK/PAEK/ULTEM polymers has been recognized as an important part of designing and characterization. Therefore, based on these, optimized materials and printing technology suitable for the development of the CubeSat part should be identified and evaluated, accordingly.

3. Demonstration of 3D Printing of CubeSat Parts

The DOST's AMCen and BPSU's AMRel are actively participating in the advancement of 3D printing technology in the Philippines and are likely to expand their continuous innovations to 3D printing of CubeSat using metals and other high-performance polymer materials such as PEEK, PAEK, ULTEM. These are well-known materials suitable in hostile space environments, therefore suitable for CubeSat. Unfortunately, the manufacturing of CubeSat parts and structures through 3D printing is not yet fully explored in the Philippines, except for a Joint Research Agreement between PHL-50 and MIRDC's RAPPID-ADMATEC under the STAMINA4Space program started in 2019, which are currently working to develop optimized CubeSat components through 3D printing [57]. These include satellite parts, such as the frame, star tracker camera baffle, computing unit enclosures, and deployment mechanisms. Design optimizations using different 3D printing software for fabrication and material post-processing were considered because of 3D printing flexibility and customizability features. Furthermore, modeling and simulation studies on the said CubeSat components are being conducted using various software. Al 6061-T6 and Stainless steel 316 metals were utilized to print the listed components using a Direct Metal Laser Sintering Metal Printer. These metals are well known for their toughness and durability, capable of withstanding maximum stresses up to 590 MPa and 460 MPa, respectively. The materials were also selected due to their excellent thermomechanical properties, such as high corrosion resistance, good heat capacities, and low densities. In addition, to control the desired mechanical properties and reduce defects induced during printing, post-processing such as heat treatment, stress relief, solution annealing, and ageing are considered.

Aside from metals, thermoplastics like PEEK and polyetherimide (PEI) were printed using a FFF printer fed for the camera baffles and some parts of the deployment mechanism. These thermoplastics offer remarkable chemical resistance and excellent mechanical properties even at elevated temperatures. Aside from its good corrosion resistance and excellent thermomechanical properties, PEEK was selected mainly because of its self-lubricating property, which is ideal for sliding applications such as deployable systems. Similar to metals, heat treatment after the 3D printing process is required for thermoplastic materials. Figure 6 represents some of the resulting products made of PEEK, before and after the annealing process. This process was done by placing the PEEK sample in an oven with 150 ºC for 1 hour then adjusted to 200 ºC for another 2 hours and left the sample inside the oven until it reached 100 ºC. It can be observed that before the annealing process, PEEK had an original light brown color and the printed layers were visible. After the annealing, the color of the PEEK sample became darker and the printed layers were somewhat unnoticeable. The annealed PEEK sample was also found to be harder and more durable than untreated samples. This process is necessary to maintain its mechanical strength and modify its mechanical properties, depending on the application, by varying the time and temperature in the heat treatment process.



(a) **(b)**

Figure 6. Sample images of 3D printed CubeSat components using PEEK (a) before and (b) after heat treatment.

Unfortunately, 3D printing of thermoplastics is still costly and trivial relative to regular plastics. One of the solutions is to design, simulate, and 3D print parts made of plastic as prototypes. This is a useful solution and cost-effective to check whether the models are printable and functional. Figure 7 (a) shows the 3D-printed part made of draft resin, while a deformity in one of the parts which requires minor modifications in the design and printer setting is shown in Figure 7 (b).

(a) (b)

Figure 7. (a) 3D printed components for the deployment mechanisms using draft resin. (b) Deformed part, requiring minor modifications in the design and printer settings.

With the 3D-printed components made of draft resins, necessary changes in the design and gauge whether design functionality is satisfied before pushing through with the final fabrication stage can be adjusted. Figures 8 (a) and (b) show the assembly and functional testing of 3D-printed components. The 3D printed components were manually assembled with the other mating mechanical parts and actuated to assess and check if they will follow the desired motion and serve their function. Doing so saves time and lessens the wastage of expensive materials.

(a) (b)

Figure 8. Images of 3D-printed resin, taken (a) during assembly and (b) during functional testing.

4. Insights and Future Perspectives of 3D Printing CubeSat Applications in the Philippines

Considering the demands and R&D needs for the design and manufacturing of CubeSat, BPSU is going in the right direction, by focusing on providing technological solutions to researchers, experts, and specialists. Expected outputs of their endeavor include the development of new products, processes, and business models. Outcomes and impacts include the capability to conduct R&D using high-tech equipment and process, thereby being able to continuously generate technologies and products. With the outcomes, test protocols under international standards will be identified. In addition, new protocols or test considerations can be suggested to the international community. These include standardization of materials formulation, manufacturing process, testing procedures, and other standardization efforts.

3D printing is a very hot technology right now, and it is envisioned that most of the colleges/universities will purchase 3D printers in the next few years for prototyping. Even more, it will be very important for 3D printer users to know how to minimize waste (common polymers as well as high-performance polymers) in their operation. In 3D printing, there is at least 20% of waste materials due to the raft and support materials. Finding ways to minimize the waste, as well as develop ways to reuse and recycle it, is necessary. This should be addressed by developing technologies to recycle and reuse waste materials. Procedures and guidelines for the reuse/recycling of 3D printing waste materials (PEEK, metals, etc.) should be developed. The solutions should also be applicable in all institutions as well as by the industry employing these manufacturing processes. Standardization of procedures on re-using and recycling of wastes across the country could be developed and a circular economy should be promoted.

The 3D printing of space-grade polymer/metal parts and characterization of such parts is a relatively new research topic. Very few research groups are doing research activities on these two combined topics. This includes optimized printability of materials, chemical and physical stability of materials against vacuum and ionizing radiations. 3D printing and metrology tools, standardized testing methods, and pre-launched checklist protocols. Like the automotive and aerospace industry, parameters such as strength to weight ratio in design and materials will be important. It will especially be beneficial to involve different institutions to produce quality research outputs to be used by the PhilSA. This project will hone the research skills and capabilities of researchers and engineers and will provide opportunities for them to undertake and participate in delivering place-specific knowledge to their field and industry. The technologies that can be provided by 3D printing will lead the way in seeking new knowledge in the use of 3D printing and advanced manufacturing technologies for CubeSats and other space-related applications. Also, it will create a pool of experts (scientists, engineers, and faculty researchers) that are knowledgeable and skilled in additive manufacturing as well as space and aerospace technologies. Collaborations with local and international partners regarding 3D printing of CubeSat parts and aerospace device parts are important.

The economic impact of this endeavor is indirect. Nevertheless, the outcome of the project will be an enhanced R&D capability in terms of materials assessment and device design. It is expected that there will be a substantial economic impact because of the localization of R&D and testing of space-grade materials. It will come in terms of savings, or potential business in the future. For BPSU, 3D-printed CubeSat can be packaged with the electronic component being developed by Stamin4Space and other local CubeSat manufacturers. They can start and develop a market for CubeSat kits for industry or academic institutions

With the active participation of several institutions in the field of Additive Manufacturing Research and Development, we could expect several forms of impact socially and economically, as material innovation would broaden its applications in various industries aside from space-related technologies. As the Philippines embarks on this journey in space technology, parts/components manufacturing will continue forever and is deemed to be very important in its journey towards developing and manufacturing its materials for the needs of its space program.

The combination of CubeSat and 3D printing technology will open more possibilities in lightweight and reliable multiple scientific and industrial space applications. The study highlighted here, which includes the candidate materials for CubeSat parts 3D printing and demonstrations of 3D-printed CubeSat parts, will support the development of CubeSat as a low-cost mode of space exploration. Currently, the manufacturing of CubeSat parts and structures through 3D printing is not yet fully explored in the Philippines. Both batches that worked on Maya 3 and Maya 4 structural design development can provide a good reference design for assessment and improvement of 3D-printed CubeSats. In the future, working alongside the next batches will be beneficial for both projects, as STeP-UP can have their structural parts manufactured, and BPSU can better verify their 3D printed outputs in a real satellite development environment. Although the STAMINA4Space program research and outputs will be shared with PhilSa, it is worth noting that it will not be producing any device/part for PhilSa. Nevertheless, both PhilSA and STAMINA4Space program made clear that they want CubeSat development to proliferate with academic communities specifically with the youth: high school STEM students, university students, or even opening the outputs of this technology to the whole Philippines (e.g., science HS, university consortiums such as UNISEC). These kinds of projects will support the "Build, Build, Build in Space" (B3iS) flagship program of PhilSA in developing a local space industrial base. This will also open opportunities for the more direct participation of Filipino engineers and scientists and may promote the country's self-reliance capabilities through indigenous scientific and technological capacity development of our local space industry.

5. Summary

This short review discussed the current status of the application of 3D printing for CubeSats. This study also provided insights into the 3D printing materials being used for CubeSat applications. The 3D printing of CubeSat parts by DOST AMCen and STAMINA4Space has also been demonstrated in the latter part of this paper. Some future perspectives have also been provided considering the Philippine setting.

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References

[1] National Aeronautics and Space Administration 2017, accessed on August 4, 2021, Information on https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf

[2] S.-K. Pang and B. Twiggs, Citizen Satellites, Sci. Am. (2011) 48–53.

[3] J. Puig-Sauri and R. J. Twiggs, CUBESAT: Design Specifications Document, Revision III, California Polytechnic State University and Stanford University's Space Systems Development Laboratory (2005).

[4] NAS-National Academies of Sciences, Engineering, and Medicine, Achieving Science with CubeSats: Thinking Inside the Box, The National Academies Press, Washington, DC, USA (2016).

[5] E. L. Shkolnik, On the verge of an astronomy CubeSat revolution, Nat. Astron. 2 (5) (2018) 374–378.

[6] M. A. Viscio, N. Viola, S. Corpino, *et al.*, Interplanetary CubeSats system for space weather evaluations and technology demonstration, Acta. Astronaut. 104 (2) (2014) 516–525.

[7] S. Asmar and S. Matousek, Mars Cube One (MarCO) Shifting the Paradigm in Relay Deep Space Operation, 14th International Conference on Space Operations (2016).

[8] Philippine Space Agency 2019, accessed on August 1, 2021, Information on https://en.wikipedia.org/wiki/Philippine_Space_Agency

[9] Agila-1 1987, Accessed on August 3,2021, Information on https://en.wikipedia.org/wiki/Agila-1

[10] ABS-3 (Agila-2) 1997, Accessed on August 3, 2021, Information on https://en.wikipedia.org/wiki/ABS-3

[11] Diwata-1 2016, Accessed on August 3, 2021, Information on https://en.wikipedia.org/wiki/Diwata-1

[12] N. Zosimovych and Z. Chen, 3D printing CubeSat: a low-cost mode of space exploration, Aeron Aero 2(5) (2018) 320–324.

[13] M. Everett, A. Flores-Abad, K.M. Billah, et al., Orbital Factory II: a 3D printer CubeSat with self-repairing purposes, AIAA SPACE and Astronautics Forum and Exposition (2018).

[14] D. Fluitt, Feasibility Study Into the Use of 3D Printed Materials in CubeSat Flight Missions, California Polytechnic State University, 2012, DOI: https://doi.org/10.15368/theses.2012.122

[15] H. Yong, C.L. Ming, J. Mazumder, et al., Additive manufacturing: current state, future potential, gaps and needs, and recommendations. J. Manuf. Sci. Eng. 137(1) (2015) 014001.

[16] F. Ning, W. Cong, Y. Hu, and H. Wang, Additive manufacturing of carbon fiber-reinforced plastic composites using fused deposition modeling: Effects of process parameters on tensile properties, J. Compos. Mater. 51(4) (2017) 451–462.

[17] G. Zhao, G. Ma, W. Xiao, Feature-based five-axis path planning method for robotic additive manufacturing, Proceedings of the IMechE, Part B: Journal of Engineering Manufacture 233(5) (2019) 1412–1424.

[18] Additive manufacturing—general principles—part 2: overview of process categories and feedstock, 2015, Information on ISO 17296-2:2015.

[19] J.R. Dizon, A. Espera, Q. Chen, R. Advincula, Mechanical characterization of 3D- printed polymers, Addit. Manuf. 20 (2018) 44–67.

[20] 3D PRINTING.COM 2021, Accessed on August 5, 2021, Information on https://3dprinting.com/what-is-3d-printing/

[21] Newsbytes.ph 2019, Accessed on July 10, 2021, Information on http://newsbytes.ph/2019/03/28/dost-inaugurates-phs-first-3d-printing-lab-in-bataan/

[22] A. D. Valino, J.R. C. Dizon, A. H. Espera, Q. Chen, J. Messman, and R. C. Advincula, Advances in 3D printing of thermoplastic polymer composites and nanocomposites, Prog. Polym. Sci., 98 (2019), doi: 10.1016/j.progpolymsci.2019.101162.

[23] A. H. Espera, J. R. Dizon, Q. Chen, and R. Advincula, "3D-printing and advanced manufacturing for electronics," Prog. Addit. Manuf., (2019), doi: 10.1007/s40964-019-00077-7.

[24] R. Advincula, J. R. Dizon, Q. Chen, I. Niu, J. Chung, L. Kilpatrick, Additive manufacturing for COVID-19: devices, materials, prospects, and challenges, MRS Commun., 10(3) (2020) 413–427.

[25] J. R. Dizon, C.C. Gache, H. M. Cascolan, L. Cancino, R. Advincula, Post-Processing of 3D-Printed Polymers, Technologies, 9(3) (2021) 61, doi:10.3390/technologies9030061.

[26] J. R. Dizon, A. D. Valino, L. R. Souza, A. H. Espera, Q. Chen, and R. Advincula, 3D Printed Injection Molds using various 3D Printing Technologies, Mater. Sci. Forum, 1005 (2020) 150–156, 2020, doi: https://doi.org/10.4028/www.scientific.net/MSF.1005.150.

[27] Alen 2021, Accessed on August 6, 2021, Information on https://alen.space/basic-guide-nanosatellites/

[28] W. Shiroma, L. Martin, J. Akagi, et al., CubeSats: A bright future for nanosatellites, Cent. Eur. J. Eng. 1(1) (2011) 9–15.

[29] T. Villela, C. Costa, A. Brandão, et al., Towards the thousandth CubeSat: A statistical overview, Int. J. Aerosp. (2019) 5063145.

[30] C. Nogales, B. Grim, M. Kamstra, et al., MakerSat-0: 3D-Printed Polymer Degradation First Data from Orbit, 32nd Annual AIAA/USU Conference on Small Satellites (2018) 1–6.

[31] Oropallo, W., Piegl, L.A., Ten challenges in 3D printing. Engineering with Computers 32 (2016) 135–148. https://doi.org/10.1007/s00366-015-0407-0

[32] Z. Chen and N. Zosimovych, Mission capability assessment of 3D printing CubeSats, IOP Conf. Series: Materials Science and Engineering 608 (2019).

[33] PHL MICCROSAT 2018, Accessed on August 6, 2021, Information on https://phl-microsat.upd.edu.ph/stamina#:~:text=Under%20STAMINA4Space%20Program%20is%20the,for%20space%20science%20and%20engineering

[34] SteP-UP Project 2021, Accessed on August 5, 2021, Information on https://stamina4space.upd.edu.ph/upcoming-satellites/maya-3and4/#:~:text=Maya%2D3%20and%20Maya%2D4,domestic%20capabilities%20for%20satellite%20development

[35] Department of Science and Technology-Advanced Science and Technology Institute 2021, Accessed on August 7, 2021, Information on https://asti.dost.gov.ph/communications/second-ph-cubesat-maya-2-launched-to-space-station/

[36] L. Resurreccion, Maya-2, PHL's 2nd cube satellite, launched | Lyn Resurreccion". *BusinessMirror*, *(22 February 2021).*

[37] PHL MICCROSAT 2018, Accessed on August 8, 2021, Information on https://phl-microsat.upd.edu.ph/stamina#:~:text=Under%20STAMINA4Space%20Program%20is%20the,for%20space%20science%20and%20engineering

[38] MatWeb-Material Property Data 2021, Accessed on August 10, 2021, Information on www.matweb.com.

[39] M. Herrera, Feasibility of 3D printed materials into space use, Accessed on August 10, 2021, Information on https://grabcad.com/challenges/the-cubesat-challenge

[40] A. Ampatzoglou and V. Kostopoulos, Design, analysis, optimization, manufacturing, and testing of a 2U CubeSat, Int. J. Aerosp. (2018) 9724263

[41] ISO/ASTM,¨ISO,¨ISO/ASTM, 2016. Information on https://www.iso.org/obp/ui/#iso:std:iso-astm:52915:ed-2:v1:en

[42] ASTM F2792. Standard Terminology for Additive Manufacturing Technologies (No. F2792-12a). ASTM Int 2013:2–4.

[43] P.C. Sai PC and S. Yeole, Fused deposition modeling – Insights, Int. Conf. Adv. Des. Manuf. (2014) 1345–1350.

[44] A.C. De Leon, Q. Chen, N.B. Palaganas, et al., High performance polymer nanocomposites for additive manufacturing applications, Reactive and Functional Polymers 103 (2016) 141.

[45] A.H. Espera, J.R. Dizon, Q. Chen, and R.C. Advincula, 3D-printing and advanced manufacturing for electronics. Prog. Addit. Manuf. (2019) https://doi.org/1007/s40964-019-00077-7

[46] J.-Y. Lee, W.S. Tan, J. An, et al., The potential to enhance membrane module design with 3D printing technology, J. Membr. Sci. 499 (2016) 480–490.

[47] Z.-X. Low, Y.-T. Chua, B.-M. Ray, et al., Perspective on 3D printing of separation membranes and comparison to related unconventional fabrication techniques, J. of Membr. Sci. 523 (2017) 596–613.

[48] M. Vaezi, H. Seitz, S. Yang, A review on 3D micro-additive manufacturing technologies, Int. J. Adv. Manuf. Technol. 67 (2013) 1721–1754.

[49] S. Crump, Fast, precise, safe prototype with FDM, ASME PED. 50 (1991) 53–60.

[50] INTAMSYS 2017, Accessed on August 11, 2021, Information on https://www.intamsys.com/intamsys-launches-peek-3d-printer/

[51] A. Sood, R. Ohdar, S. Mahapatra, Parametric appraisal of mechanical property of fused deposition modelling processed parts, Mater. Des. 31(2010) 287–295.

[52] A.R. Jones, A. Griffiths, M.J. Joyce, et al., On the design of a remotely-deployed detection system for reactor assessment at Fukushima Daiichi, Nuclear Science Symposium Medical Imaging Conference and Room Temperature Semiconductor Detector Workshop, Strasbourg, (2016).

[53] K. Gillen, J. Wallace, and R. Clough, Dose-rate dependence on the radiation induced discoloration of polystyrene, Radiat. Phys. Chem. 41(2) (1993) 101.

[54] S. Shaffer, K. Yang, J. Vargas, et al., On reducing anisotropy in 3D printed polymers via ionizing radiation, Polymer, 55(23) (2014) 5969.

[55] L. Kuentz, A. Salem, M. Singh, et al., Additive manufacturing and characterization of Polylactic Acid (PLA) composites containing metal reinforcements, https://ntrs.nasa.gov/archive/nasa/casi.ntrs. nasa.gov/20160010284.pdf.

[56] E. G. Gordeev, A. S. Galushko and V. P. Ananiko, Improvement of quality of 3D printed objects by elimination of microscopic structural defects in fused deposition modeling, PLOS ONE, 13 (2018) 1.

[57] PHL MICCROSAT 2018, Accessed on August 11, 2021, Information on https://phl-microsat.upd.edu.ph/stamina.