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Optimization of support structure in multi-articulated joints of non-assembly mechanisms

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Abstract

Manufacturing of efficient multi-articulated joints in a single process is quite competitive and demanding these days. Conventional manufacturing processes are very limited in terms of producing the entire assembly as a single component. Therefore, additive manufacturing (AM) processes seem to be an attractive option for producing multi-articulated mechanisms in a single step. However, due to some overhanging features like holes, edges, and joints in non-assemblies, AM processes use some support structures. Thus, the addition of support structures rises the manufacturing time and material cost of the product. Besides this, the removal of support material from the complex features and joints also increases the post-processing. To cope with this problem, this study focuses on the reduction of manufacturing time of multi-articulated joints by minimizing the support material. For this purpose, two major effective parameters including support structure type and support placement are considered in this study. In support structure, normal and tree supports are taken into consideration while in support placement two discrete cases including 'support everywhere' and 'touching buildplate' have been studied. Four distinct non-assemblies consisting of multi-articulated joints are manufactured using different combinations of support structure type and support placement. Analysis of variance has been performed to analyze the significance of input parameters. Normal support structure touching the build plate yields comparatively lesser build time and support material. This optimum case is then compared with manufacturing the non-assembly with no support. The comparison shows that the non-assembly manufactured without any support offers minimum build time and support material nevertheless, it creates distortion in some features near the build plate due non-adherence of initial layers. For this reason, printing non-assembly without any support is not observed as an adequate option and printing with normal support at the buildplate is suggested for the non-assembly mechanisms.

Keywords: Multi-articulated joints; Non-assembly mechanisms; Support material; Build time

1 Introduction

Fabrication of complex geometries is often seemed to be time-consuming and challenging. Complicated assembly mechanisms whose manufacturing does not involve any post assembly operations are renowned as non-assembly. Specifically, when it comes to multi-articulated joints in the non-assemblies, it is very difficult to manufacture the whole assembly with the conventional manufacturing processes in a single process. Therefore, the manufacturing of an entire assembly in a particular process without any post assembly processing is quite captivating [1]. Due to these characteristics, the multi-articulated joints in the non-assembly mechanisms have found their latest applications in industrial robotic systems [2]. In additive manufacturing, the formation of support structure between the multi-articulated joints in the non-assembly mechanisms affects the moving efficiency of the joints by increasing internal friction [3]. Moreover, intensive care is required in designing the multi-articulated joint mechanisms of the prosthetic body part to acquire an efficient

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part controlled by the body power [4]. Only additive manufacturing (AM) processes have the ability to fabricate such non-assembly mechanisms in a single step without any requisition of post processing [5].

Generally, AM processes fabricate a complete product with the addition of material layer by layer. In comparison with traditional processes, AM can manufacture customized and complex parts having internal support at a very low cost [6]. The prime advantage of this process is that it enables the manufacturer to produce complex geometries irrespective of any specialized manufacturing skills and labor [7]. Owing to exceptional competencies, the AM processes are widely practiced in electronics, marine, aerospace and medical fields [8-10]. Various additive manufacturing techniques are available to produce a part, nevertheless, they differ in the way of depositing layers in manufacturing. Methods using soften, liquid, or powder materials to produce layers are Fused deposition modeling (FDM), Stereolithography and Selective laser sintering. Each method has its own benefits and limitations, however, the selection of the method depends upon production speed, surface quality, cost and range of the materials used [11]. Among the number of AM processes, FDM is the most economical and widely used process which has the ability to produce complex parts in a safer and office environment [12]. FDM constructs the part layer by layer using the bottom-up technique with some thermoplastic materials including polyphenylsulfone polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and polycarbonate. In this process, filament material is converted into semi viscous state and then extruded from the extruder nozzle while moving along the predetermined printing path to complete the part by generating the sequential layers. Normally the printer head has two extruders; one for the extrusion of the main component material and the other for the support material. Support is indispensable for the spherical overhanging features of the component that are perpendicular to the laying direction of material [13]. The 3D model of the part is converted into thin layers that define the printing tool path using some slicer software. Besides this, other print settings including print temperature, print speed, support material, layer height, and infill density are also defined and then generate the extruder's path to create the boundaries [14]. To make the process economical and efficient, the infill of the part is usually kept hollow by defining infill density and infill patterns offered by the algorithms in the slicer software.

Most of the AM techniques use support structures to assist the printing of parts/products having overhanging features, holes, edges. Building of supporting layers is also inevitable in the non-assemblies especially in multi-articulated joints [15]. Considering various guidelines regarding revolute joints spherical, universal joints and the clearance between the joints, manufacturing of non-assemblies has been studied in the previous research. However, the reduction of the support structure is also a serious concern for the manufacturing of multi-articulated joints as it does not add any value to the final product and also affects the moving efficiency of the joints. Three major wastes associated with the support structure are; the time taken by the printer to produce support significantly increases the manufacturing time, the filament material consumed in the production of support and the last one is the time required for removing the support and finishing. To reduce the support structure, various approaches including optimization of part's print orientation, usage of soluble support material, optimization of structure and placement of support baths have been practiced generally [16]. For this reason, Jiang et al., [17] tried to optimize the printable bridge length by minimizing the support material. Their results suggested that printable bridge length can be increased by controlling fan speed, print temperature and print speed without using any support. It was observed that support structure can also be significantly reduced by optimizing the printing orientation and the placement of the individual parts [18]. Vaidya and Anand [19] applied Dijkstra's shortest path algorithm in order to reduce the support volume. Further, the support accessibility constraints were also introduced in order to ensure the easy removal of the support structure after manufacturing. Strano et al. [20] applied an optimization algorithm based on mathematical 3D implicit functions to design and build the support structures. The technique had successfully designed and optimized the support structure by providing robust support only at the weight concentration points and minor supports elsewhere. Vanek et al. [21] proposed a tree like structure support for the 3D model to reduce the support material and manufacturing time. Their study considered the length and angle of the supporting strut for the optimization of the support structure. Schmidt et al. [22] introduced a space-efficient network of support using struts to maintain the structure strength called support graph. They reduced the support structure material by 75% and build time by an hour than conventional support structures. Das et al., [23] optimized the build orientation that reduces the support structures while meeting the geometric dimensioning and tolerancing criteria. They developed a mathematical model for the minimization of support structure which indicates the relationship between build orientation and both geometric dimensions and tolerances. Zhao et al. [24] presented the novel technique 'inclined layer printing' which print enables the printer to build part without any support. In their technique, overhanging features are built by the inclined layers supported by the adjacent layers. In the previous research, authors proposed various techniques to minimize the support structures. However, the minimization of support structures in multi-articulated joints of non-assemblies is still need to be considered.

The current study focuses on the reduction of support material in the multi-articulated joints in the non-assembly mechanism of a moveable horse structure. For this purpose, two key parameters including support structure type and support placement have been considered to reduce the build time and support structure. In support structure, normal and tree supports are examined while 'support everywhere' and 'touching buildplate' are taken into consideration for support placement. Analysis of variance has been performed to check the significance and percentage contribution of support structure type and placement in the response measures including build time and support material. Optimum case from the previously discussed cases is compared with the assembly build with no support structure to further optimize the build time and support material.

2 Methodology

In order to reduce the support structure without compromising on the surface quality and moving efficiency,

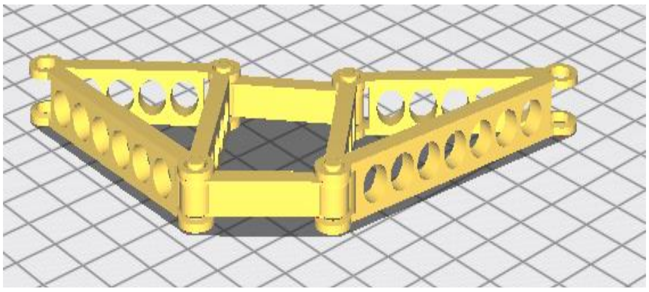


Figure 1. Selected non-assembly depicts the printing orientation

support type and support placement have been considered. In support type, manufacturing of non-assembly with tree like structure has been compared with the normal support structure, due to the significance of tree support in the literature [25, 26]. Two support placements have been considered including 'touching build plate and support everywhere' for the printing of non-assembly. In the support touching build plate, support is only placed on the base of the non-assembly. Four different combinations have been obtained using two factors shown in Table 1. To investigate the effects of selected variables, all other printing parameters are kept constant and given in Table 2. Build orientation of the non-assembly is shown in Fig. 1. To analyze the efficiency of the variables, printing time and weight of the support material have been measured. Weight of the support material has been measured on a weight scale after removing it from the actual part.

Table 1. Input variables and measured responses

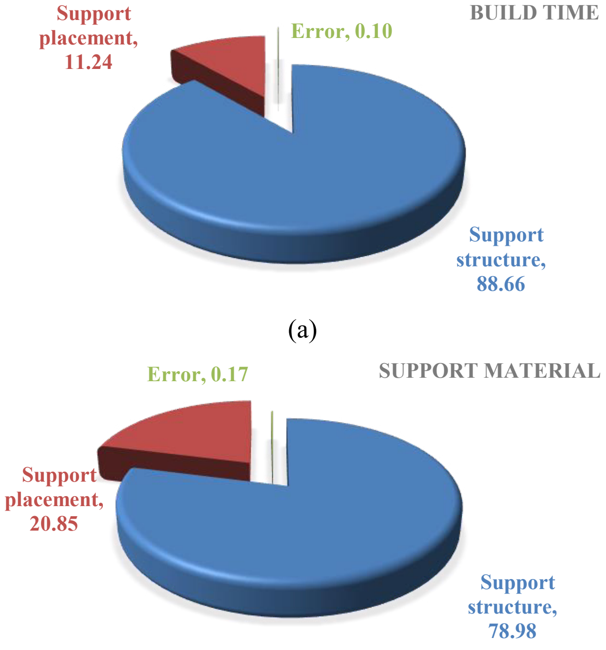
Exp. No.	Support structure type	Support placement	Build time (min)	Support material (g)
1	Tree	Support everywhere	281	3.91
2	Normal	Support everywhere	182	2.36
3	Tree	Touching Build plate	248	3.15
4	Normal	Touching Build plate	142	1.45
5	No support	-	127	-

Table 2. Other print parameters for the manufacturing of non-assembly

Sr. No.	Parameters	Specifications
1	Layer height	Normal (0.15 mm)
2	Line width	0.35 mm
3	Infill width	0.42 mm
4	Print and infill speed	70 mm/s
5	Travel speed	150 mm/s
6	Initial layer speed	20 mm/s
7	Retraction distance	6.5 mm
8	Retraction speed	25 mm/s
9	Build plate adhesion type	Brim
10	Brim width	7 mm
11	Brim line count	17
12	Print material	Acrylonitrile butadiene styrene
13	Nozzle temperature	210 °C

3 Results and discussion

Four different models printed showing distinct features. As non-assembly involves the multi-articulated joints, all types of support have different effects on the build time and support material used. Analysis of variance has been performed to analyze the significance of parameters used. Effects of parameters including a support structure and support placement on build time and support material have also been discussed in this section.



(a)

(b)

Figure 2. Percentage contribution of input parameters in (a) build time (b) support material

3.1 *Analysis of variance*

To analyze the significance of input parameters including support structure and support placement, analysis of variance has been performed. p-value less than 0.05 in the analysis depicts the significance of the input parameters [27]. From Table 3, it has been observed that support structure is the most significant input parameter for both build time and support material. Based on the analysis, percentage contribution of input parameters has been determined. From Fig. 2, it can be visualized that support structure is a major contributing factor for both build time and support material with the contribution of 88.66% and 78.98% respectively. On the other hand, support placement has less contribution in both build time and support material. Moreover, the regression models have been developed for the build time and support material are given in Eqs. 1 and 2. Models developed for build time and support material are also significant with p-values of 0.032 and 0.041 respectively.

Table 3. Analysis of variance for build time and support material

Source	DF	Adj SS	Adj MS	F-Value	P-Value
		Build time			
Regression	2	11838.5	5919.2	483.2	0.032
Support structure	1	10506.3	10506.3	857.65	0.022
Support placement	1	1332.2	1332.2	108.76	0.061
Error	1	12.2	12.2		
Total	3	11850.7			
		Support material			
Regression	2	3.33785	1.66892	296.7	0.041
Support structure	1	2.64063	2.64063	469.44	0.029
Support placement	1	0.69722	0.69722	123.95	0.057
Error	1	0.00562	0.00562		
Total	3	3.34347			

$$Build\ time = 213.25 + 51.25 \times Support\ structure - 18.25 \times Support\ placement \quad (1)$$

$$Support\ material = 2.7175 + 0.8125 \times Support\ structure - 0.4175 \times Support\ placement \quad (2)$$

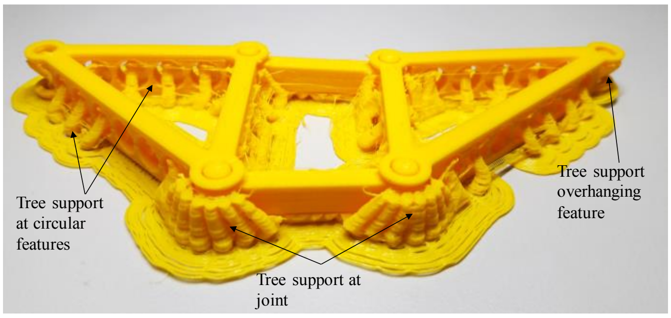


Figure 3. Non-assembly with Tree support placed everywhere

3.2 *Case 1 (Tree support - Support everywhere)*

Non-assembly using tree structure take a longer time to complete the print as compared to normal support. It starts with all types of support from the base surface or buildplate. To make a thin layer of support between the joints, a full branch of support has been initiated from the base surface which seems to be a material and time-consuming measure. However, the removal of support structures between the joints and circular geometries is quite convenient and doesn't affect the print surface quality therefore, very minor post-processing is required for finishing. Due to a lesser connection with the support structure, the movability of the joint has also been observed to be fine. In this experiment, the massive construction of support structure from the base surface seems to be infeasible alternate as displayed in Fig. 3. It noticed that the tree support takes 281 min to complete the non-assembly which does not seem to be reasonable. This type of support structure and placement has also increased the weight of the support material to 3.91 g.

3.3 *Case 2 (Normal-support everywhere)*

In this support structure, the printer build supports for each overhanging feature like joints and circular features in the non-assembly. However, the printer starts to print the support structure from the most recent or upper layers of the features of the non-assembly can be seen in Fig. 4. In this structure type, support material and build time are comparatively lesser than tree structure. It has been observed that shifting from Tree support to normal support, build time of the non-assembly is significantly decreased to 182 min and support material is reduced to 2.36 g. It has been observed that supports build in the circular features of the non-assembly are stiff and rigid and difficult to remove due to strong adherence with the actual part surface as shown in Fig. 4. Removal of support structures from the joints and fragile features needs more attention which seems to be a time-consuming activity after the printing. It is also observed that the support removal process affects the part surface and sometimes cause damage upon removal. Movement of the joints is also affected by the improper removal of the support structure which is a serious concern of this support structure as compared to tree structure support.

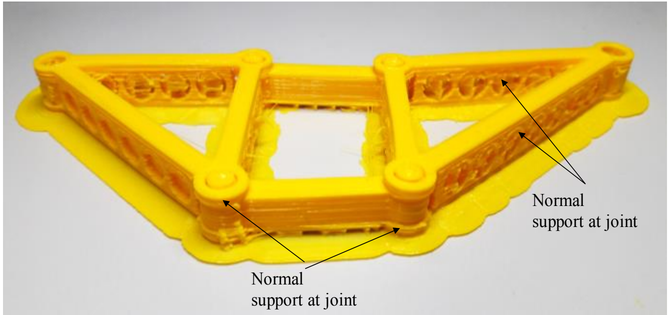


Figure 4. Non-assembly with normal support placed at everywhere

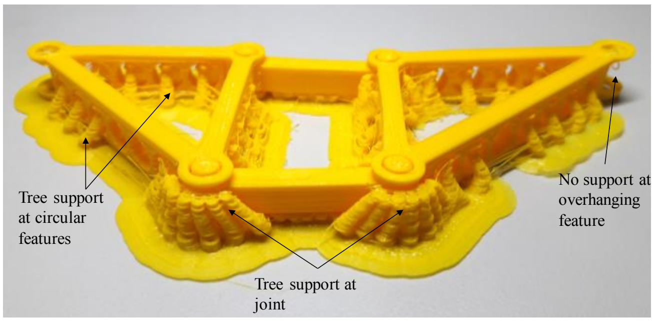


Figure 5. Non-assembly with Tree support placed at only build plate

3.4 *Case 3 (Tree-touching build plate)*

This case is similar to case 1 to a certain extent of support placements (support everywhere and touching build plate). In both cases, tree structure initiates from the outer sides and supports overhanging features of the joints and non-assembly. Touching the build plate means the printer is going to start all types of support from buildplate or base surface. This is the reason that both cases take more time and support material to build the non-assembly (Table 1). Though the build of this case (tree structure-touching build plate) is lesser than case 1 (tree structure-support everywhere) which is observed to be 248 min. A similar case has been observed with support material which has been reduced to 3.15 g. From Fig. 5, it has been clearly observed that the tree support for the joints seems to be inappropriate because it does not support the overhanging feature of the joints accurately. As most of the support structures lie on the outer side, so removal process of the tree support structure is finer.

3.5 *Case 4 (Normal support - Touching build plate)*

In this case, the support structure type is 'normal' and placed only at the build plate to support the non-assembly from the base. The purpose of this support type is quite similar to the brim is to keep the non-assembly components in contact with the build plate of the printer. No other support has been placed at the joints and below the overhanging features of the non-assembly as shown in Fig. 6. This support offers lesser time and support material among all cases studied. Due to the absence of the abundant support structure, the least build time (142 min) is observed as compared to other support structures. A slight support structure at the base has a weight of only 1.45 g. Further, it is quite easy to remove the support from the base.

Figure 6. Non-assembly with normal support placed only at build plate

Figure 7. Non-assembly without any support

It has been observed that the circular feature in the structure of the non-assembly that are made without any support has a fine surface and accuracy due to lack of physical contact of non-assembly features with any support structure and reduced post processing. The joints made without support are free to move as compared to others made with support structures placed in the joints. It is due to the reason that the optimum clearance between the joints and fast cooling of layers prevents the upcoming layer to adhere to the previous layer and this phenomenon allows the joints to move adequately upon fabrication. The joints are only kept moveable with sufficient clearance between the components if there is large clearance the support structure between the joints becomes inevitable and if the clearance between is small there are chances that the layers of two components adhere with each other.

3.6 Case 5 (Without support structure)

It has been observed that the non-assembly mechanism made without any support offers minimum build time (127 min) as compared to previously discussed cases due to the elimination of the support construction time. It has been observed that the absence of support at the build plate prevents the non-assembly to adhere to the build plate, therefore, upcoming layers are failed to comply with the previous layers. The shape of the part deteriorates due to the distortion created at the base features as shown in Fig. 7. This distortion also affects the movability of joints. For this reason, the multi-articulated joints in the non-assembly mechanisms build without any support are not observed as an appropriate alternative.

4 Conclusion

This study aims to minimize the support material and build time in the construction of the multi-articulated joints in the non-assembly mechanism of a moveable horse structure. For this mean, support structure type and support placement are considered as key parameters to reduce the support structure without creating any distortion in the profiles and affecting the movability of the joints. In support structure, normal support and tree like support have been considered to analyze their effects on build time and support material used. Two distinct support placements including touching build plate and support everywhere are also studied to explore the better alternative. For this purpose, four distinct models of non-assembly mechanisms using different support structures have been built. Build time is obtained from the duration of construction of the non-assembly. Support material removed from the different features of the non-assembly has been weighed after the support removing process to analyze the effectiveness of the selected parameters. With the comparison of the results of build time and support material, the following conclusions have been drawn from the study:

- In comparison with the support placement, the support structure has a significant effect on build time and support material used. Percentage contribution of support structure in build time and support material is 88.66 % and 78.98% respectively. While support placement is comparatively less significant having contribution of 11.24 % and 20.85 % in build time and support material respectively.
- In support structure, normal support offers lesser time to complete the print, and relatively small amount of support material is consumed. However, its removal process is quite complicated after the printing process due to the presence of some intricate contours in the geometry of non-assembly. While Tree-like support utilized more material as it takes to start from the base surface which also increases the build time of the non-assembly. Meanwhile, it is quite convenient to remove from the complex features as it lies on the outer side.
- Support placement also affects the build time and support material. Choosing 'support everywhere' generates supports at all the necessary and non-necessary places in the non-assembly mechanism which depicts the wastage of time and support material. In tree support, the support structure is also constructed everywhere even choosing placement 'touching buildplate'. While in the case of 'touching build plate' normal support only constructs the support at the base of the complete non-assembly to adhere it to the buildplate.
- The combination 'touching build plate and normal support' offers the least support structure and build time and is observed as the optimum case among all. The overhanging (circular) features are accurately built without support structure which also reduces the post-processing. Moreover, the movability of multi-articulated joints is also fine due to the absence of the support structure and appropriate clearance between the joints.
- The non-assembly mechanism builds without any support structure also presents a minimum build time which seems to be attractive however, the absence of support structure at the base, the non-assembly doesn't adhere to the build plate aptly which creates the distortion in the different features of the non-assembly. Owing to this issue, constructing non-assembly without any support is discouraged.

The analysis depicts that non-assembly having multi-articulated joints can be built adequately with the combination 'touching build plate and normal support' and offers the least build time and support material. Therefore, this optimum combination can be recommended for construction of multi-articulated joints in the non-assemblies. The distortion observed in the different features of the non-assembly mechanism can be quantified by analyzing the dimensional accuracy and surface quality of the features in the future study. Further, the parameters that are kept constant in this study can be considered in future studies to reduce the support structure and build time in the non-assembly mechanisms.

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