Design for Additive Manufacturing of Products Containing Articulated Mechanisms

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Abstract

This paper explores the issues and challenges involved in designing products containing articulated mechanisms for Additive Manufacturing (AM). Clearances in the kinematic pairs are governed by the requirement of precise kinematic functionality and concerns of the AM process. The necessary clearances in a product containing various kinematic pairs in the design for no-assembly (DNA) and design for assembly (DFA), in the context of AM, are discussed through various test cases. This paper, for the first time in literature, presents the issue of making helical joints by AM. It is observed that the joint level design decisions for AM do not guarantee functionality at the product level due to tolerance and body-space interactions with the support material. Geometric features are introduced into the design of the parts to facilitate post fabrication removal of the obtrusive support material and ensure smooth motion. The ideas are presented using AM of a kinematically over-constrained, pulse sensor device.

Keywords: Additive manufacturing, 3D printing, Product prototyping, Design for manufacturing, Joint clearance, Hole features, and Support material

1 Introduction

Additive Manufacturing (AM) refers to a class of manufacturing processes by which digital 3D design data is used to build up a component in layers [1]. Material is deposited additively layer by layer to realize a physical part or a product. Some of the well-known AM technologies are: Rapid Prototyping (RP), 3D printing, and layered manufacturing. In its nascent years, AM was used to make prototypes for visualization. Of late, AM is used to turn out even functional models and end-use products as well. AM is soon becoming one of the most popular and versatile methods of product development and prototyping. However, various challenges in the process of design and final realization hinder the effective usage of AM for a reliable production framework.

An often encountered problem when it comes to manufacturing of articulated mechanisms using AM is that of the clearances between the parts to facilitate their

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relative motion [2, 3, 4, 5, 6]. It is discussed in [6] that the issues of clearances between the parts and the support material are important in AM of kinematic pairs and mechanisms. While most of the mechanisms can be broken down into individual parts which can be fabricated separately only to be assembled later, there is significant value in being able to manufacture articulated mechanisms in a mated position to avoid individual assembly of the constituent parts subsequently. And while using AM to make mechanisms that come pre-assembled, the issue of clearances between adjacent surfaces becomes a major point of contention.

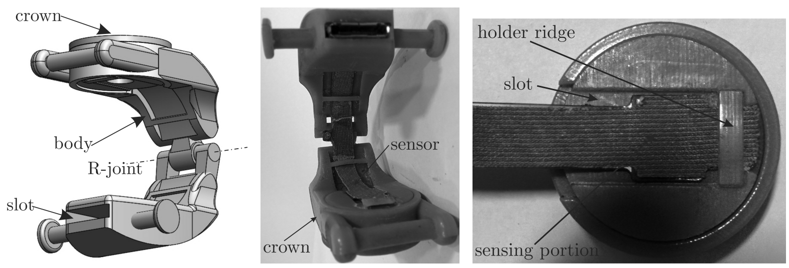
In this paper, the issues and challenges involved in AM of products containing articulated mechanisms are studied through an example of a novel device named *Pulse-Watch*. Empirically tested values of clearances in helical joint (H-joint) for AM are reported for the first time in this paper.

2 Pulse-Watch

The Pulse-Watch (Fig. (1)) is a device which houses a human pulse sensor to measure the pulse. This device consists of a crown, body and a single strap (not shown in figure) using which it is placed at the wrist. The attached pulse sensor wirelessly transmits the data to a computer which can then be further processed or filtered for more effective use elsewhere. Since the device is banded to the wrist just like a watch, it is called Pulse-Watch. The body portion contains a revolute joint (R-joint) for adjustment of the device to wrists of different human subjects. The sensor is like a 0.5 mm thick rectangular strip of copper metal which is routed through the body of the device until the sensing portion is at the bottom part of the crown of the device (Fig. (1)(b)). The bottom part of the crown consists of a slot of depth 0.5 mm and width 12 mm, and a holder ridge that arrests the sensor from movement once inserted into the Pulse-Watch. The end of the pulse sensor strip is tucked into the holder ridge of 0.5 mm thickness as shown in Fig. (1(c)). The width of the slot under the ridge is reduced to 0.8 mm due to the design of the end of the sensor strip.

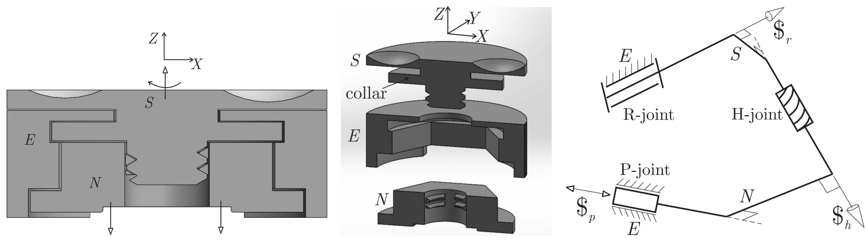
2.1 Kinematic Chain of the Crown

The sensing portion of the sensor strip should touch the skin at the wrist of a human subject, and requires an arrangement where it is gently pressed against the human wrist to enhance the quality of the readings obtained from the sensor. To achieve this, the crown portion of the device contains an articulated lead screw mechanism (Fig. (2)) consisting of a revolute joint (R-joint), a helical joint (H-joint), and a prismatic joint (P-joint) connected in a single loop kinematic chain. There are three rigid bodies in the mechanism, viz., S, E, and N. *S* and *E* are connected by a R-joint, *E* and *N* by a P-joint, and finally *S* and *N* by a H-joint. When the screw *S* rotates counter-clockwise (CCW) and clockwise (CW), the nut *N* translates up and down respectively w.r.t. the encasing *E*. The hexagonal portion of *N* is enclosed in another hexagonal cavity of *E* which arrests the rotation of the it thus resulting in a relative helical screw motion between *S* and *N*. As *N* comes down, it presses the sensor against the skin, changes the ambient pressure on the sensor and hence the quality of the readings. If the ambient pressure is too high (i.e. if the sensor is pressed too hard against the skin), the minor



(a) (b) (c)

Figure 1: Pulse-Watch and sensor. (a) CAD model showing various parts, (b) sensor assembled into the device, (c) sensor and crown assembly.



(a) (b) (c)

Figure 2: Articulated mechanism in the crown. (a) cross-sectional view, (b) exploded view, (c) general kinematic diagram of the mechanism.

variations in the pressure due to the pulse will get overshadowed resulting in a flat-line reading that is of no value to us. Hence, the range of motion of the P-joint is 3 mm. The mechanism should not have any backlash error because any backlash movement of N can lead to loss of contact of the sensor with the wrist.

2.2 Degrees of Freedom Analysis

The kinematic diagram of the mechanism in the crown is shown in Fig. 2. This mechanism has three links ($n = 3$) and three single degrees of freedom (d.o.f.) joints ($j = 3$). Using the Kutzbach mobility criterion for spatial mechanisms, the number of d.o.f. of the mechanism (F) is calculated as -3 which implies that it is a structure. But, the mechanism in the crown is same as the lead screw mechanism which is widely used in engineering practice whose d.o.f. is 1. It is mentioned in [7] (p. 11 in Vol. 1 and p.165 in Vol. 2) that such a mechanism is a *three-link over-constrained mechanism* with $F = 1$. We now briefly derive the reasoning behind this using screw theory. Let $\$_r$, $\$_h$, and $\$_p$ denote the *instantaneous screws* associated with the R-joint, H-joint, and P-joint of the mechanism respectively as shown in Fig. (2)(c). Since the mechanism is a closed loop one, the screws of the joints satisfy

$$\lambda_r \$_r + \lambda_h \$_h + \lambda_p \$_p = 0 \tag{1}$$

for some scalars λ_r, λ_h, and λ_p. The linkage will be a structure or a mechanism accordingly as Eq. (1) has trivial or non-trivial solutions respectively. In the current case, there are four special geometric conditions between the mechanism joint axes:

(a) shortest distance between the screw axes of $\$_r$ and $\$_h$ is zero

(b) angle between the screw axes of $\$_r$ and $\$_h$ is zero

(c) no relative sliding of screw axes of $\$_h$ over $\$_r$

(d) direction of translation of $\$_p$ is parallel to the axes of $\$_r$ and $\$_h$

The first two conditions mean that the axes of $\$_r$ and $\$_h$ are coincident. Screw $\$_r$ being pure rotation (zero pitch), does not allow relative sliding of the axis of $\$_h$ over its axis. Since $\$_h$ is a screw of finite pitch, $\$_r$ and $\$_h$ are linearly independent. $\$_p$ essentially represents translation in the direction parallel to the axes of $\$_r$ and $\$_h$ and thus can be written as a linear combination of $\$_r$ and $\$_h$. So, Eq. (1) has a non-trivial solution. Using Theorem 1 in [8] (pp. 376-377), it follows that, if $\$_p$ belongs to the *Two-screw system* spanned by $\$_r$ and $\$_h$, the mechanism has mobility with 1 d.o.f. This particular screw system can be shown to be the *fifth special two-system* which we skip here. Even though the screw theoretic analysis is concerned only about *transitory mobility*, according to [8](p. 378), fifth special two-system is among those screw systems which guarantee *full-cycle mobility*.

3 Design for Assembly and No-Assembly

Manufacturing of products has to take into account the geometric constraints posed by the mechanisms. Because of the availability of AM, there are two different ways of designing (and hence manufacturing) products containing articulated mechanisms namely, Design for No-Assembly (DNA) and Design for Assembly (DFA). The respective clearances between mating surfaces while manufacturing and other necessary geometric features have to be determined at the design stage of the product itself. This consideration of the manufacturing limitations during the design stage itself, and adapting the design paradigm to match the manufacturing deficiencies is a example of *concurrent engineering practices in the domain of AM*. In DNA, the product is fabricated as a no-assembly part (i.e. in an assembled state) and in DFA, the individual parts are fabricated separately and then assembled. The decision should be governed by the functional suitability and manufacturing ease and cost concerns which are explained below.

3.1 Functional Suitability

Functional suitability should deal with the kinematic aspects and strength concerns. In the present case, the over-constrained nature of the mechanism demands that the direction of translation of the P-joint and the rotation axis of the R-joint are parallel. If the product is fabricated through DNA as per the exact CAD model, the required conditions are all achieved with ease. In DFA, where components are realized separately, satisfaction of those conditions depend also on the quality of the assembly process. If there is a small misalignment of N and S, the mechanism gets jammed during assembly due to obstruction of the movement of N by E. Since the device should not have any backlash error, the clearances between the mating surfaces in the joints should be as small as possible. But such small clearances in DNA has other problems. It is difficult to extricate the support material. Also, there are chances of local fusion of the part material which leads to loss of functionality. To avoid this, we generally adopt larger clearance space with special geometric features on the mating parts [6] to ensure rattle-free kinematic performance even after the loss of the support material. One such design of a R-joint is shown in Fig. (3). In this paper, we do not consider the strength related issues.

3.2 Manufacturing Concerns

The general advantage of DNA is that the number of auxiliary components is reduced; for example, fasteners and retainers that are required to rigidly assemble the joints are eliminated in DNA. Thereby, the associated tool, tooling and operator requirements are also reduced. Additionally DNA consumes less support material than DFA. This reduces the manufacturing cost.

An important concern while using DNA to manufacture articulated mechanisms is that of the clearance between mating surfaces. DFA is some what pretty straightforward in terms of the clearance values like the traditional practices because the assembly happens at a later stage from the manufacturing. AM relies on slicing of the tessellated model (STL file) of the original CAD model, and material addition process with certain resolution in the slice to generate the final product. Hence, the surfaces which are too close to each other may get fused in the final manufactured resultant. One needs to take into consideration the machine and process parameters in DNA. The experiments on clearance values for R-joint and planar joint (E-joint) in DNA are reported in [6]. In that study it was found that the minimum radial clearance for concentric cylinders is 0.20 mm for build directions along and orthogonal to the axis of the cylinders, and the minimum clearance between parallel planes is 0.05 mm for build direction normal to the planes. Values of the clearance between parallel planes for any other build direction are not discussed there. The study of clearances in H-joint for AM is not available in the literature. Since the mechanism of the crown contains H-joint, we next discuss about the issues in the design of H-joint for AM.

4 Design Considerations for H-joint

A typical H-joint consists of a screw and nut whose thread profiles engage with each other. External threads and internal threads are given on the screw and nut respectively. The actual surfaces that are engaging in conjugate motion are the *cylindrical helicoidal surfaces*. In an ideal design, the geometry of both the surfaces should be same for the cylindrical helicoidal surfaces to slide over one another. But from manufacturing point of view, clearance between the surfaces in the design is inevitable. The geometry of the H-joint is characterized by the pitch of the threads, major/minor diameter of the thread profiles, length of engagement of the threads and the clearances between the threads, of the nut and screw. Fig. (4) shows the clearance between the mating threads.

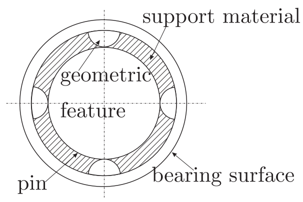


Figure 3: Cross-sectional view of R-joint with features for AM.

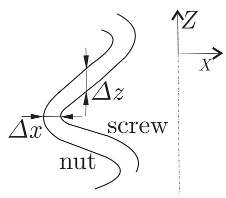


Figure 4: Exaggerated view of thread clearance.

Two variables, viz., Δz and Δx are used to quantify this clearance. Δz is the thread clearance in the axial direction (Z- direction) between the mating profiles and Δx is the radial clearance between the crest of the thread of the screw and the root of the thread of the nut. The clearance between the nut and screw gives freedom for all the 6 d.o.f. movements of the screw w.r.t. the nut. We now explain these clearance induced backlash movements. The clearance Δx between the thread profiles allows rotation about the Z-axis over a small range of motion until flank of thread profile of the screw comes into contact with that of the nut. The clearance Δz leads to translation freedom of the nut along the positive and negative Z-direction. Similarly the root clearance Δx results in translation freedom of the nut along the positive and negative X and Y directions. The nut can have tilt movement, i.e. wobble about X- and Y-axes. The extent of wobble depends upon the clearance variables, axial length of the engagement of the screw and nut, thread depth, and major diameter of the screw. The tilt movement can be reduced by having *large major diameter with good thread depth and smaller clearance*. For shallow threads, the radial clearance becomes the order of the thread depth and proper mating of the profiles may not take place after fabrication.

Now, consider the scenario where the H-joint is part of a mechanism. Ideally a free H-joint has 6 d.o.f. movements as discussed above. But when it is part of a mechanism like the one shown in Fig. (2)(a), some of those six backlash freedoms become dysfunctional. The collar (Fig. (2)(b)) of the R-joint is also a part of S contains a collar which is a part of the R-joint. This collar is constrained by E and does not allow translation in X, Y, and Z directions and wobble about X and Y axes are also inhibited. N is constrained by E to translate only along Z- direction. Hence, translation movements of N in X and Y directions w.r.t. S are inhibited and so are the tilt movements about X and Y axes; only translation movement in the Z direction is allowed. Thus, the only significant side effect of the clearance in the H-joint is the backlash translation movement of N in Z-direction. Therefore stringent requirement is necessary on the axial thread clearance Δz than Δx; Δz should be as small as possible. This shows that not all the joint level decisions of the H-joint on allowable clearances hold prominence when the big picture of the whole mechanism is considered. *Certain kinematic effects due to clearances in a particular joint get nullified by the geometric constraints of the other joints in the mechanism.*

If a standard thread profile is chosen, it suffices to specify only the radial thread clearance as a variable since this is intrinsically is related to the axial thread clearance through the major/minor diameters of the threads and the pitch. For fixed values of pitch and minor diameter of the thread of the nut, different values of the radial clearance can be specified. The major diameter of the external thread of the screw gets

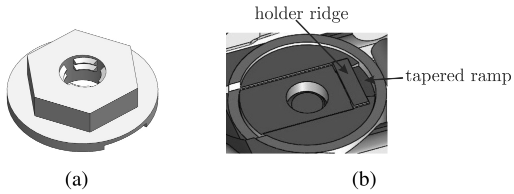


Figure 5: HF in *N*. (a) Four slots in the thread, (b) tapered ramp to direct water jet under the ridge.

varied accordingly. The thread on the screw and nut can be single-start or multi-start. Multi-start threads are used only when the linear movement of the nut is large.

Finally, we come to the manufacturing aspects in the design of the H-joint. For DNA, the clearance between the surfaces has to be a certain minimum to avoid fusion. When a STL file is generated, the gap between the surfaces is irregular and the shortest distance between the tessellated surfaces can be less than the actual clearance given in the CAD model. Hence the *fineness of tessellation* while generating the STL file has to be good. We said above in the clearance discussion that the H-joint should have larger diameter and smaller clearances. But a larger diameter in DNA requires more starting effort to shear the support material over the boundary of the moving surface and later on the effort required to overcome the friction between the support and component materials during operation is also more. The presence of support material in the small clearances and also the one that sticks to the surfaces cause unpredictable movement in the H-joint due to the non-availability of conjugate enveloping helicoidal surfaces for engagement. In the case of a R-joint fabricated as DNA, as the pin rotates, a conjugate enveloping cylindrical surface is generated in the adjoining support material. However this is not true for a H-joint. Hence, it is required that the support material should be properly removed for smooth motion; otherwise there will be deterioration in the kinematic performance. In case of DNA, it is difficult to remove the support material from small clearances in the H-joint. In DFA, the support material can be cleaned easily in the nut and screw after fabrication. Since the ability to clean up the support material is easier in DFA, we recommend DFA over DNA for H-joint.

5 Hole Features

In AM, removal of the support material is a universally accepted post-processing step. Facilitating removal of the support material has a two-part advantage: (i) reduces stiction between the mating surfaces of the kinematic pairs and thus provides smoother motion, (ii) disables the support material from being obtrusive to the movement of any of the actual parts of the mechanism. Hole features (HF) are geometric features like holes and channels that are introduced into the design of the components to facilitate removal of the obtrusive support material. After fabrication, the specimen is washed in a high speed water jet and soaked in water for some time to *loosen up* the support material stuck inside the crevices of the product. HF ensure that during the soaking, water actually reaches the inner cavities and loosen the support material better. In the case of Pulse-Watch fabricated as DNA, the volumetric space between the threads of

S and *N* is helical and is filled with the support material. This makes the path to be taken for the water to clear out the support material a long and winding one. Unless the support material is removed or loosened up, it is difficult to disassemble N from the assembly. To achieve easy removal of the support material, four slots are provided in the thread of *N* as shown in Fig. (5)(a). The slots facilitate the entry of water into the clearance between the threads of *S* and *N* and purge the support material. The number of slots have a very noticeable effect on the mechanism mobility; having too many slots will deteriorate the kinematic functionality of the H-joint, while having too less would defeat the original purpose of providing pathways to remove support material. Four slots were chosen for striking an ideal balance between the two conflicting effects. If the device is fabricated using DFA, the threads of S and N can be cleaned separately without any hassle and then assembled. HF are also provided in N for the easy removal of the support material present under the holder ridge (Fig. (5)(b)). The depth of the slot below the holder ridge is 0.5 mm and it is difficult to purge the support material from this small clearance by directing a water jet or scoop out by other means. A tapered ramp is provided which further inclines down to a depth of 0.5 mm below the surface of the slot. When water jet is impinged on to this tapered ramp, the hydraulic jump creates a flow pattern which directs the water into the clearance below the ridge.

6 Device Fabrication Experiments

The mobility of the mechanism is possible only if all the joints are kinematically mobile. Keeping in this mind, we first selected the whole crown portion of the Pulse-Watch as a test specimen. The drawing of the test specimen is shown in Fig. (6). *In this paper, we restrict only to build directions along the axis of symmetry of the crown* which is the Z-axis. Keeping in mind the build direction, the clearance values between the surfaces are given. The radial clearance between the nearest cylindrical surfaces is given as 0.20 mm and between any two nearest planar surfaces orthogonal to the build direction is 0.05 mm as obtained in [6]. The clearance between the six pairs of parallel planes in the hexagonal portion for the prismatic pair between *E* and *N* is labeled as d as shown in section A-A of Fig. (6). The type of threads chosen is *single-start ISO metric left-hand screw thread*. The major diameter of the internal threads is fixed as 8.00 mm and the pitch of both the threads is 1.5 mm. The radial thread clearance is labeled as c.

In DNA, the entire crown is fabricated as a single part as assembled in Fig. (6). Whereas in DFA, the screw *S* and the casing *E* are fabricated together (as a DNA) with the part *N* made separately and assembled later (basically H-joint is fabricated as DFA as suggested in section 4). Two modes of constructing the crown along its axis of symmetry are performed: *normal* (when *S* is on the top) and *inverted* (when *S* is at the bottom). After fabrication, the test specimen is cleaned with a water jet and soaked in water for few hours to loosen up the support material in the cavities. In case of DNA, the fabricated sample is held in a three jaw chuck at portion *E* and the head of *S* is coerced to rotate CW. The mechanism fails to work if it is fused inside. For DFA, it is checked whether the *N* can be completely screwed into the fabricated self-contained *S* and *E* assembly. All the products reported in this paper are fabricated on

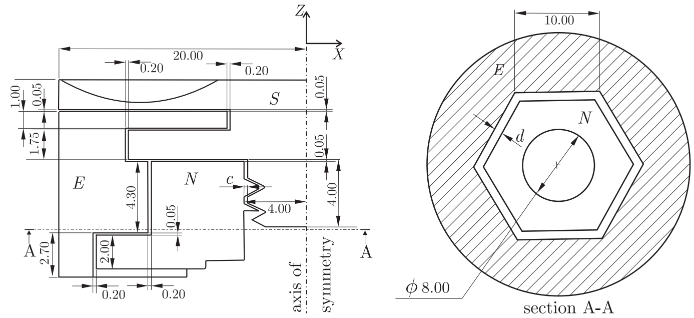


Figure 6: Test specimen geometry (all dimensions in mm).

Table 1: Results of experiments on the crown

S. No.	Design Type	Crown Orientation	Clearance c (mm)	Clearance d (mm)	Kinematic Mobility
1	DNA	Inverted	0.20	0.20	×
2	DNA	Inverted	0.30	0.30	×
3	DNA	Inverted	0.30	0.35	×
4	DNA	Normal	0.30	0.30	✓
5	DNA	Normal	0.20	0.20	✓
6	DFA	Inverted	0.10	0.05	✓

a Objet Eden500V™ 3D printer which uses PolyJet technology. The model material used is polypropylene-like material named VeroBlue/Black and the support material is FullCure-705, a gel-like photopolymer. The build direction is along the Z-axis of the machine with a print resolution of 0.016 mm (layer thickness). The X- and Y-print resolution of this printer is 600 dpi [9] which is approximately 0.042 mm. All CAD models in this paper are prepared in Solid Works™ and tessellation option *Fine* is exercised while generating the corresponding STL files. The 3D printer has two surface finish options, viz., *glossy* and *matte*; the former one is chosen in this paper.

The experiments involve multiple iterations of the crown using different clearance values for DNA and DFA to find the minimum values of c and d which allow kinematic mobility of the mechanism in the crown. The experimental results for various clearance values and design types are given in Table 1. From the experiments on a Objet Eden500V™ 3D printer, it is inferred that:

(a) The direction of build (i.e. whether the crown is facing downwards or facing upwards) makes a difference in the final kinematic mobility of the device

(b) The minimum value of radial clearance (c) required for H-joint is 0.20 mm in the case of DNA and 0.05 mm in the case of DFA

(c) The minimum clearance between the two concentric hexagonal surfaces (i.e. d) is 0.20 mm

Using the experimental results for the crown, we now fabricate the entire Pulse-Watch. The whole device is fabricated as DNA except the part N which is fabricated sepa-

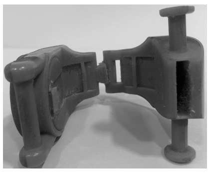


Figure 7: Fabricated Pulse-Watch.

Figure 8: Cross section of specimen showing fused regions (encircled).

rately. The clearance values obtained from experiment 6 are used in the crown portion and the clearance values for the R-joint in the body of the Pulse-Watch are same as those reported in [6]. The build configuration of the device is same as in Fig. (1)(a) and the build direction is along the axis of symmetry of the crown. The layering starts at the tail of the body and proceed towards the crown. The fabricated Pulse-Watch is shown in Fig. (7) and with the sensor assembled into it is shown in Fig. (1)(b).

7 Discussion and AM Guidelines

From the above experiments, it is observed that DNA causes relatively higher translational backlash error of N than DFA because the allowances while manufacturing (and hence the gap left behind when the support material is removed) is higher - radial clearance (c) of 0.20 mm in DNA versus 0.10 mm in DFA. Also, the hexagonal clearance (d) of 0.20 mm in DNA resulted in rotational backlash movement of N w.r.t. E which is undesirable. On the other hand, DNA allows us to fabricate over-constrained mechanisms which contain special geometric relations among the axes of the joints for kinematic mobility. So we see an interesting trade-off here between the above two aspects, and hence the decision to choose between DNA and DFA needs to be made taking them into consideration.

Guideline 1 : *Choose DFA or DNA with kinematic features for tighter clearances*

HF are also seen as visibly improving the post-processing of the final product, easing the removal of the support material. They also do not affect the functioning of the device in any noticeable way if they are judiciously chosen. HF for the ease of post-processing and their impact on kinematic functionality can be two conflicting aspects in DNA that need to be kept in mind.

Guideline 2 : *Incorporate kinematically benign HF for the removal of obtrusive support material in DNA*

To investigate the failure of experiments 1, 2, and 3, the specimen of experiment 1 is cut longitudinally. It is observed that *N* and *E* are fused over a cylindrical surface which is indicated in Fig. (8). Even though clearance of 0.20 mm is given in the solid model as per positive experimental results found in [6], the direction of build (i.e. *normal* or *inverted* orientation of the crown) seemed to affect the mobility of the end-product.

Guideline 3 : *Joint level decisions alone do not guarantee mobility of overall mechanism in DNA*

The Pulse-Watch has a unique set of mechanisms that allow us to try out a combination of DNA and DFA in the same product, and use the result as an empirical test of the viable clearances. The considerations of design, manufacturing and post-processing, makes the choice of DNA and DFA case-specific and *non-exclusive*; design of components, assembly and manufacturing decisions co-evolve in the design for additive manufacturing (DFAM) paradigm.

8 Conclusions

The paper presented the issues in AM of products containing articulated mechanisms where kinematic functionality is expected to be precise. A rational basis for allocation of clearances based upon the functional consequences and manufacturing requirements is provided in this paper. Design modifications like incorporation of geometric features in the mating parts of kinematic joints and HF to remove the support material are suggested to obtain the required kinematic performance within the process limitations of AM thus paving way for successful designs. Though DNA offers a lot of promise in AM, it is showed that the difficulty to purge the support material from deep cavities and curved geometries and the backlash effects of the clearances make DNA not a preferred design decision in some cases. In AM of finished products containing articulation, co-evolution of design and manufacturing process details is essential.

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