DESIGN AND DEVELOPMENT OF MULTI-MATERIAL EXTRUSION IN FDM 3D PRINTERS

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Abstract - *Today, in the world of additive manufacturing, FDM plays an important role, being a cost effective and comparatively fast process. FDM 3D printing is one of the oldest and most common technologies in 3D printing, there are still some energizing developments entering the market. The primary goal of these developments is to increase the print speed, print quality, use of multiple colors and advance materials. Traditional FDM printers have a single hot end extruder assembly, thus being able to print only one material or one colour at a time. Hence to fulfill the ever-growing need to 3D print objects with multiple materials or colours, this research emphasizes on the design, development and selection of a fast and effective mechanism suitable for extrusion of multiple filaments to be used in a single print. The main advantage of the proposed mechanism is that replacement of a damaged hot end or extruder is very fast and simple, thus saving the machining time and cost. Additionally, other attachments, such as laser heads, can be easily and speedily attached and replaced for multipurpose use of the 3D printer.*

Keywords – Fused Deposition Modeling, 3D printing, FDM, Multiple material, Extrusion, Dual extrusion

1. INTRODUCTION

From the development of 3D printing, we have come a long way with numerous developments regarding printing speeds, accuracies, surface finish, costs, etc. in various 3D printing technologies. But for a long time now, in FDM printing, only single material or single colour printing was an option. Recent developments have opened doors for more research and development regarding the use of multiple materials in a single print.

Traditionally the fdm printer has an extruder assembly driven by a stepper motor which pushes the filament into the hot end assembly which mainly consists of a heat sink, heat brake, heating block and a nozzle. The plastic filament is pushed into the hot end by the extruder. The extruder can be a direct or Bowden extruder. In the Direct extruder, the extruder assembly is placed directly above the hot end, thus reducing the chances of slack of filament between extruder and hot end, resulting in faster retraction, less powerful motor and better handling of the filament. Whereas, in the Bowden extruder, the extruder assembly is placed away from the hot end and both the assemblies are connected by a polytetrafluoroethylene(PTFE) tube through which the filament passes. Bowden extruder assures lighter carriage, cleaner movements and compact size. The heating block heats the filament up to the required melting temperature and the molten plastic is then extruded through the nozzle. The object is printed layer by layer with the flowing melted plastic. The constant pressure applied by the extruder pushes the melted filament through the nozzle at a constant rate, resulting in a uniform extrusion.

Although a number of advancements have been made, still some things need to be developed. Firstly, the printing speeds are quite slow and it gets slower as the number of layers are increased to obtain a more dimensionally and aesthetically accurate prints. Secondly the surface finish and aesthetics are not as good as compared to other methods of 3D printing but this imperfection can be overcome by post processing of the prints which would require more time and cost. Thirdly, use of multiple materials and colours in a single print. This research highlights the design, development and choice of the most rugged, accurate, reliable and effective approach towards use of multiple filaments.

2. MULTI-MATERIAL EXTRUSION

2.1 Need of multi-material extrusion

Earlier fused deposition modelling (FDM) 3D printers had only single extruder but couple of years back multiple extrusion was introduced in the market. The invention of multiple extrusion has opened infinite number of possibilities. Addition of multiple extrusion does not result in any change in the printing process. The printer automatically switches between the filaments as per the program. Having different filament means the printer will simply print the filament it needs at that point of time. The user no longer have to pause the print, remove the filament from the extruder, feed in the new filament and resume the print every time a different material is required. Today there are number of multiple extrusion printers available in the market. They have number of benefits but multiple extrusion printers have drawbacks as well. The advantages and disadvantages of Multiple Extrusion are discussed below:

Advantages:

1) Color – Dual extrusion 3D printers helps to enhance aesthetics through the use of multiple colors. This can be very useful in printing 3D models related to educational purposes especially from medical and engineering field because through the use of multiple colors functional areas can be easily differentiated.
2) Support Structure – Dual extrusion enables the use of dissolvable support materials like Polyvinyl Alcohol (PVA) and High Impact Polystyrene (HIPS). These materials are extremely useful as they are easily dissolved in liquid and hence they eliminate the need the remove the support and also improve the part finish.
3) Easily Designed and Constructed.
4) In case of independent multiple extrusion, additional printing options like mirror printing and simultaneous identical prints are possible.

Disadvantages:

1) With addition of each extruder, the maximum range of X-axis decreases, effectively reducing the print volume.
2) Only two to three extruders can be added at a time without drastically reducing the print volume.
3) Requirement of extra hardware for each hot end and extruder.
4) In order to avoid re-heating on each and every layer, extra energy is used to heat all the hot ends simultaneously.

2.2 Various alternatives for multiple extrusion and their challenges

1) So obtaining a single print with multiple filaments can be done by pausing the print and changing the filament every time a different colour or material is to be printed. This can be done manually or automatically, but it would take a tremendous amount of time for the print, approximately 9 to 10 times more time than that for a single colour print. And imagine the time it would take when there are multiple colours on a single layer, it would take forever! And the added inaccuracies and misalignment would probably make it the most impractical option.

2) Another approach would be using two sets of nozzles, with two different hot ends and extruders. And if the extruder is direct type, as it is required for a lot of materials, positioning of both extruders side by side would be another issue. And above all of that the increased weight on the carriage, reducing the printing speed and increasing the print time. Further the nozzles cannot be at the same height while printing, as the idle one would scratch the printed surface. So another mechanism or some solution to shift nozzles vertically and their accurate switching while printing. And all this so that we can use only two different filaments for a print. Using the same mechanism for more than two filaments would just make the head assembly and carriage heavier and difficult for assembly and maintenance.

3) A more practical approach would be using a single extruder and hot end assembly and using a selector mechanism which selects the filament to be used before it enters the extruder. So the old filament would be cut and purged and then the new filament would be selected and pushed all the way up to the extruder. So most importantly, the design of the selector mechanism would be too complex, for manufacturing as well as assembly and maintenance. It would require a lot of tuning and adjustments because even a slight inaccuracy in mechanism would fail the selection and hence the print. The older filament in the extruder and hot end would have to be purged (getting rid of the left over filament) every time, resulting in a lot of wastage of material and time. The selector mechanism would require at least 1-2 stepper motors and the filaments would need an individual motor to push them up to the main extruder via the selector, thus increasing the cost and weight of the entire assembly.

4) Another way to achieve it would be directly using multiple hot ends and extruders with the selected filaments already loaded in them. So these preassembled printing heads can be picked up by the carriage of the printer, perform the required printing, place the head back at a pre-decided place and pick up another head with the next required filament already loaded in it. So the main challenge would be designing the pick and place mechanism, assuring precise alignment each time a head is picked. The more number of head assemblies would surely increase the cost and size of the printer, but since the weight of the heads will be on the main body, printing speed would not be affected. And if the printer is able to print at high speeds, the carriage would probably pick and place the head within a few seconds, hence saving the printing time. The main advantage of the design would be that in case of any issue in extruder or hot end, the entire head could be easily replaced, without affecting the printing and reducing printer downtime. Another possibility would be that other heads such as laser heads could replace the 3D printing head easily, increasing the usability and functional scope of the printer.

3. DESIGNS

3.1 Design Iteration 1- Cam Operated Movable Hot end

This design explores the possibility of Dual Extruder with one movable and one fixed hot end.

So the basic working principle is that when nozzle B prints, nozzle A will be 3mm above the printing level and when nozzle A has to be used, the bed will move 3 mm down and then nozzle A will move down by 6mm i.e. 3mm below the nozzle B level. Again when nozzle B has to be used, nozzle A will go up 6mm, bed will move up 3mm and printing resumes with nozzle B.

The nozzle (along with the hot end) can be moved by using different types of mechanisms such as gears, pneumatics, cam and follower, wedges and levers and many more. The one used in this design is by using a barrel cam. The hot end is connected to two Teflon rollers which roll inside the slot of the cam along the cam profile (as seen in the figure). So when the cam is rotated, the roller rolls up and down along the cam slot, hence moving the hot end up and down.

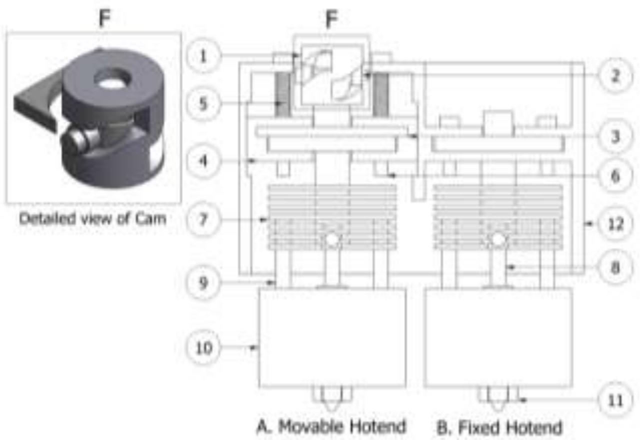

Fig. 1. Drawing of a Cam operated movable Hot end

1. Barrel Cam 2. Teflon roller 3. Follower plate connected to hot end 4. Main Slider 5. Spring 6. Semi-threaded bolt 7. Heat Sink 8. Heat Break 9. Heat Sink tube 10. Heater block 11. Brass Nozzle 12. Main body

The entire assembly majorly has 2 subassemblies: A. Movable hot end & B. Fixed hot end. The fixed hot end just slides into a slot made in the main body where it is firmly held by two bolts. This arrangement facilitates easy replacement of the entire hot end assembly. Just by removing the bolts, the hot end can be slid out and replaced by another hot end.

For the movable hot end, the heat sink is connected to a follower plate via two semi-threaded bolts. The follower plate holds the Teflon rollers at its end. This entire assembly of follower plate and hot end is able to slide in and out the main slider, thus facilitating easy replacement of hot end. The slider slides up and down along a slot in the main body, guided by the semi-threaded bolts. Two springs are placed in between the main body and main slider to ensure smooth movement of slider and the hot end. The Teflon rollers are designed to roll along the slots of the Barrel Cam. As the cam is rotated by an actuator, the rollers roll up and down along the cam slot, thereby moving the entire hot end up and down. The Barrel cam is designed for a rise and fall of 3mm from the level of nozzle B.

Fig. 2. 3D model of Cam operated movable hot end

Advantages of the mechanism:

1) Only one nozzle is to be moved, so it takes less time to switch between materials.
2) The weight of the entire mechanism is less as compared to one which lifts both the nozzles.
3) It takes up less space as compared to a mechanism with both movable nozzles.
4) The hot end can be changed easily.
5) A mixed combination of direct and Bowden extruder can be used.

Disadvantages:

1) Manufacturing of such a small and intricate cam is difficult.
2) Servo motor moving the cam has to be very accurate, precise and reliable which can be quite expensive.
3) Printing time is wasted in cooling of the hot ends in between the prints so as to ensure that heat is not transferred to the idle nozzle and dripping of material is avoided.
4) Use of direct extruders on both hot ends will take up a lot of space.

3.2 Design Iteration 2- Dual Hot end lifting mechanism

The aim of this mechanism is to accurately lift the non-printing head vertically upwards as it might scratch the printing surface. The design shown below consists of a simple mechanism used for head lifting in dual extruder system. The mechanism is designed in such a way that when nozzle A is printing, nozzle B should move 3mm upwards from the printing surface and vice-versa. It is one of the simplest designs powered by using a servo motor. The entire design is integrated by using a hub which is responsible for pushing the head axially upwards whereas the downward motion is achieved by using a spring.

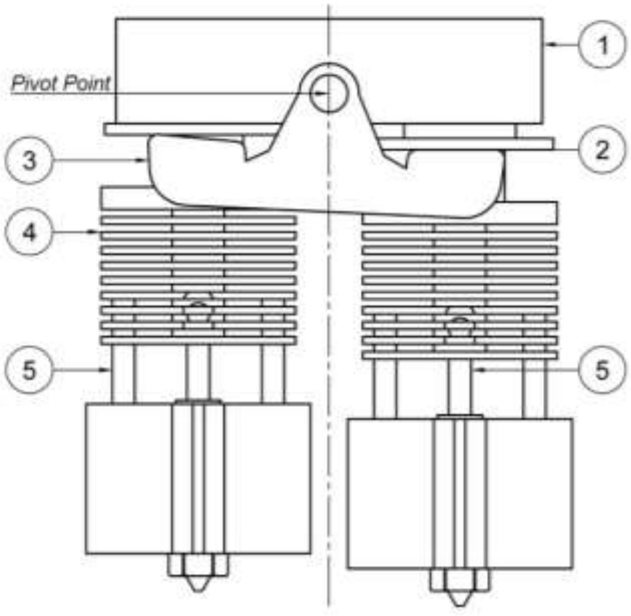

Fig. 3. Drawing of a Dual Hot end lifting mechanism

1.Spring Casing 2. Nylon Bush 3. Hub
4. Heat Sink 5. Heat Break

During the printing process the printer receives the command to use the secondary head whenever there is need to use the other loaded filament / support filament. This triggers the servo motor which is located at the back side of the printing head. The motor is coupled with the hub which is pivoted as shown in the figure and it can swivel in both the directions. The hub is responsible to press the printing head upwards against the spring. As the hub rotates, it pushes the collar of one of the nylon bush forcing it to move upwards and at the same time the nylon bush on the other side is lowered due to spring force. The mechanism is designed in such a way that the upward and downward motion of the printing head will always take place in a straight line hence maintaining the angle of the printing head. Other factors friction, weight, wear and tear and reliability are also considered while selecting the material for mechanism. The printing heads and coupled with nylon bushes by using a 3mm grub screw. The springs are fixed by inserting the spring wire inside casing surface. The other end of the spring is grounded and it rests on the printing head. The springs maintain a constant downward pressure on the hub which results in accurate lowering of the head. The spring is designed in such a way that the spring force does not exceed the motor torque.

Fig. 4. 3D model of a Dual Hot end lifting mechanism

Advantages:

1) Simple assembly and easy maintenance.
2) Easy replacement of Hot end.
3) High accuracy and reliability.
4) A mixed combination of direct and Bowden extrusion can be used.

Disadvantages:

1) The servo motor which is responsible for rotating the hub must be small, precise and accurate. This increases the cost.
2) Direct extrusion from both the nozzles decreases printing space of the X-axis.
3) Some amount of heat is transferred from the printing nozzle to the idle nozzle and hence dripping of material takes place.

3.3 Design Iteration 3 (Final) – Multiple Printing Heads

This design eliminated the dual extruders integrated into a single head assembly and divided multiple extruders into separate printing heads (as seem in the image above), each one with its own filament preloaded.

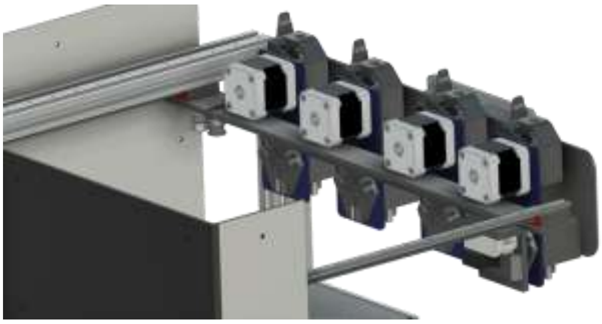

Fig. 5. Multiple Printing heads assembled onto the printer

So the entire design is divided in two parts: Carriage side and Docking side.

The docking side is where all the printing heads are placed (docked) when they are not being used. Whenever a head (the filament in it) is required, the carriage (mounted on the XY axis of the printer) will pick up the printing head from the dock, perform the print and place the head back in its position on the docking side.

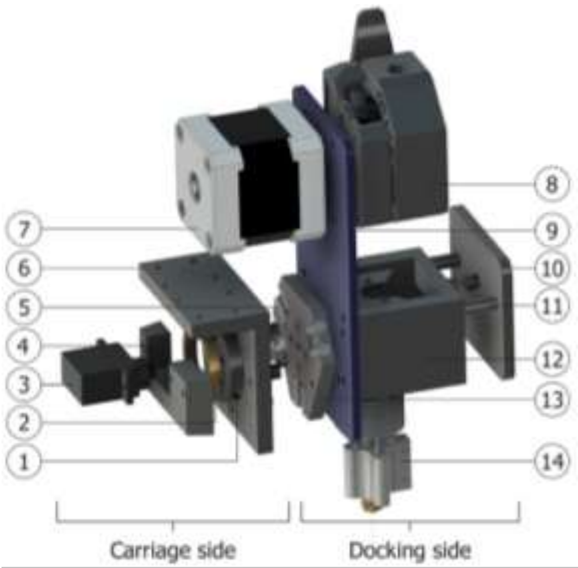

Fig. 6. Exploded view of printing head

1. Disc with magnets 2. Brass ring 3. Servo motor 4. Servo motor mount 5. Steel balls 6. Carriage block 7. Stepper motor 8. Direct Extruder 9. Sheet metal plate 10. Docking plate 11. Docking pins 12. Hot end holder 13. Rod plate 14. Hot end

So the main challenges were to pick up the printing head in the exact same location and orientation each time with high accuracy and precision, holding the head rigidly on the carriage while printing and placing the head back in its original position. After doing a thorough research on electromagnets, pneumatic sucker, locking mechanisms and pin locators, we finally came across Kinematic Coupling.

3.3.1 Kinematic Coupling

Kinematic couplings (KC's) are precision-machined mechanical contacts used to precisely locate components with respect to each other. Traditional KC's place a triangular arrangement of three hemispheres on one component into three corresponding 'vee-grooves' on a mating component, deterministically constraining all six degrees of freedom of motion. Given deterministic locating, analytical relations give the contact forces, contact stresses, and contact deflections for a given coupling geometry.

It works on the basic principle that when a component is to be constrained, the constraint points should be exactly equal to the number of degrees of freedom to be constrained. So in order to perfectly locate and hold the printing head, in total 6 degrees of freedom (3 linear and 3 rotational DoF) need to be constrained. These 6 contact points can be distributed in a number of ways. Two most common types of kinematic couplings are:

1) Kelvin Coupling

In this, a plate consisting of three spherical surfaces rests on another plate with a concave tetrahedron, a V-shaped groove and a flat surface. The tetrahedron provides 3 points of contact, the V-groove provides 2 points of contact and the flat part provides 1 point to the 3 spherical surfaces i.e. in total 6 points of contact constraining all the degrees of freedom. But this design is suitable only for light loads and it is difficult to manufacture.

2) Maxwell Coupling

In this, a plate with 3 spherical surfaces rests on another plate with 3 V-shaped grooves oriented to center the part. While mating, the 3 spheres sit onto the grooves and each groove provides 2 points of contact, therefore in total 6 points. This design is symmetric and therefore easy to manufacture. It is also suitable for high loads and the distribution of load is better than kelvin coupling.

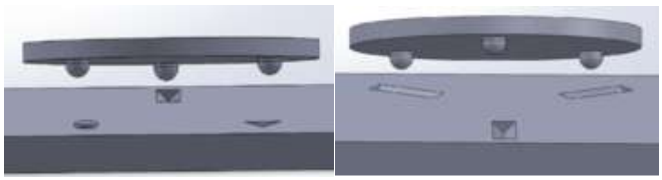

Fig. 7. Kelvin Coupling and Maxwell Coupling

The stability of a kinematic coupling interface is maximized when the coupling ball and groove centerlines, the normal to the planes containing pairs of contact force vectors, intersect at the centroid of the coupling triangle. In other words, the centerlines bisect the angles of the coupling triangle, and intersect at a point called the coupling centroid. For static stability, the planes containing the pairs of contact force vectors must form a triangle. Stiffness of a kinematic coupling is also related to the coupling layout. Stiffness is equal in all directions when all the contact force vectors intersect the coupling plane at 45-degree angles. Coupling stiffness can be adjusted by changing the interior angles of the coupling triangle. A number of experiments show that the optimal groove angle for most repeatability is 60 degrees.

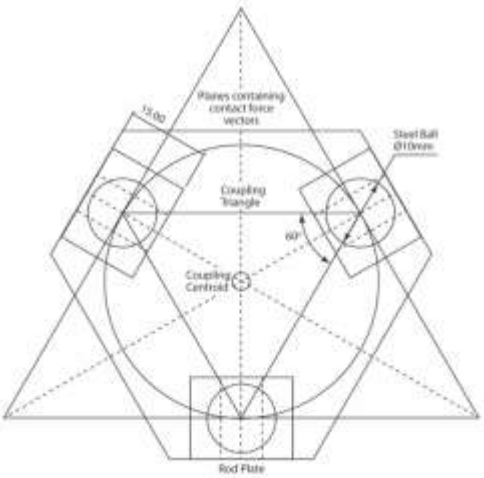

Fig. 8. Kinematic Coupling Geometry

Because of its better load distribution and good manufacturability, Maxwell kinematic coupling has been used in this design. Instead of V-grooves, 3 sets of two circular rods each, are used due to which the coupling is less costly and much more easily manufactured, as machining of grooves is avoided and two rods are equally effective and provide the required angle between the tangents at the point of contact. For the spherical surfaces, small spheres with tapped holes on one end are used.

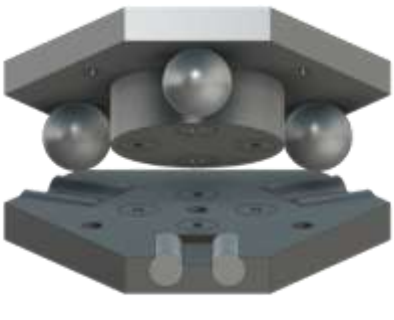

Fig. 9. Kinematic Coupling customized for a 3D printer

As per the standard components available in the market, circular rods of diameter 5mm and length 15mm and spheres of 10mm diameter with M4 threads up to a depth of 4mm are used. So as seen in the images, the coupling is divided into two parts: Rod plate and Ball plate. The rod plate is fixed onto the printing head, that is on the docking side and the Ball plate is fixed to the carriage of the printer. Both the plates are fixed onto their respective surfaces via 3 M3 bolts on each plate. When both the plates are assembled, they ensure precise and accurate alignment of the printing head, each time.

Fig. 10. Rod Plate & Ball Plate

1. Steel Rods, 2. Neodymium magnets
3. Disc carrying magnets 4. Steel Balls

So the problem of accurate locating with high repeatability is solved. Now how can the carriage hold the printing head while printing? So the most practical solution is to use strong permanent magnets. As seen in Fig. 10, both the plates have 4 Neodymium magnets fixed in them. The magnets are so arranged such that those on rod plate have poles opposite to those on the ball plate. So as the carriage approaches the printing head, the coupling aligns the head onto the carriage, the magnets attract and hold on to each other. So as the carriage moves backwards, the head is pulled out of the docking pins and printing is carried out without any hindrances. Selection of magnets:
Total weight of printing head = 600g

Available grade of disc shaped neodymium magnets – N35
Since the weight acts in the downward direction, the strength of magnet in shear direction has to be considered, which is around 25% of the pull force between two magnets.

So the strength of magnet in shear direction should be greater than 600 g and considering a FOS of 1.5, pull force between the magnets should be around (600 x 1.5 / 0.25) 3600 g.

Accordingly, 4 magnets of N35 grade with diameter of 7mm and thickness of 3mm were selected. Pull force for each magnet is 2.12lb (960 g), so a total of 3840 g for 4 magnets. So 4 magnets each on rod plate and ball plate of kinematic coupling with poles opposite to each other.

The printing head (on docking side) holds all the components required for printing. All the components are bolted to a sheet metal plate. There is the hot end assembly bolted to a hot end holder and extruder on one side of the plate with the extruder motor (Nema 17) and rod plate of the kinematic coupling on other side. Two docking pins, fixed to printer body, hold the printing head by two holes in the hot end holder. There is also a small neodymium magnet on the front side of printing head and in between the two docking pins to ensure proper docking and holding of printing head. So as the carriage approaches the printing head, the coupling ensures proper alignment of the head and the magnets hold the head firmly onto the carriage.

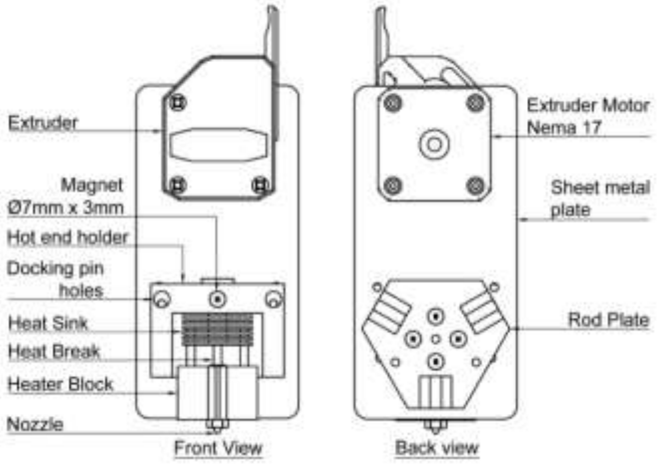

Fig. 11. Drawing of Printing head

So the problems of accurate and precise alignment and holding the printing head firmly have been solved. So finally, how do we separate the rod plate from the ball plate i.e. the printing head from the carriage when other filament is to be used? Since these are permanent magnets, they have to be pulled apart, in which case some mechanism has to be designed which holds onto the head after it is docked but also releases it when it has to be used. Since the force of magnets is weaker in shear direction as compared to pull force, this property is used in order to eliminate all the complexity discussed above. The 4 magnets on the ball plate (carriage side) are fixed on a rotating disc connected to a servo motor. The magnets are arranged in such a manner that the poles of consecutive magnets are opposite to each other. Similar arrangement is made on the rod plate. In the normal state, magnets on carriage and docking side have opposite poles, thereby attracting each other. So when the disc rotates by 90 degrees, the poles of magnets on carriage side and docking side become same and they tend to repel each other. So the printing head is easily separated from the carriage and it can freely move towards another printing head.

These small modifications in the carriage block solves our issue. So now the disc with magnets rotates in a brass ring which is fixed inside the carriage block. The servo motor to rotate the disc is mounted on the back side of carriage block with the disc coming out in the front. Since the disc has already been separated from the ball plate of the kinematic coupling, instead of using the entire plate, the steel balls are directly mounted at the front of the carriage block. Thus reducing the size and weight of the block. Lastly this entire block is mounted on the X-Y carriage of the printer, ready to be moved in any direction.

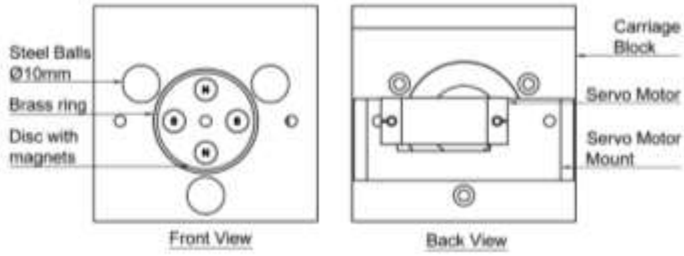

Fig. 12. Drawing of Carriage block

So in short, the carriage moves towards the desired printing head, the coupling ensures proper alignment of the head onto the carriage, the magnets ensure that the head is held firmly and the printer is ready to print. When another printing head is required, the carriage moves the head back to its position, pushes the head onto the docking pins, where a magnet holds it and simultaneously the servo motor rotates the disc, due to which the magnets on carriage and printing head repel each other, disengaging the head. The carriage then moves back, leaving the printing head on the docking pins, ready to be picked up some other time.

Advantages:

1) Number of filaments (extruders) is only limited by the size of the printer. Huge printers can accommodate many printing heads.
2) There is no extra weight (except the servo motor) on the carriage, as the printing heads are fixed to the main body.
3) Scope of use of this mechanism is wide because other heads such as laser heads can be used easily without any major changes.
4) Changing of a non-functional hot end and extruder assembly is quite easy.
5) Each material has its own dedicated nozzle and can even have a different type of extruder (direct or Bowden).
6) The printing nozzle is not affected by other nozzles, hence avoiding oozing and interference.

Disadvantages:

1) The initial cost of the machine would be quite high due to the multiple printing heads, but totally worth it.
2) The weight of the entire machine is increased.
3) Maintenance and repair might be a little tedious.

4. FUTURE SCOPE

1) Integration of connections of all the electronic components on the printing head such as Heater, Thermistor, Main cooling fan, Part cooling fan, Extruder motor, Bed level sensor, etc. onto a

common PCB to facilitate easy replacement of the entire head.

2) Integration of Extruder and Hot end assembly into a single unit to reduce weight and size.
3) Designing of different heads such as Laser cutting head, CNC carving head, PCB engraving head, etc compatible with the current design.

5. CONCLUSION

Multi-material extrusion is one of the most important discoveries in the world of FDM 3D printing as it has opened doors for new possibilities in 3D printing. Due to numerous benefits of multi-material extrusion, it is necessary to use it effectively and efficiently. In this paper, we have also discussed various alternatives for multi-material extrusion and the challenges faced because of them. There are many techniques through which multi-material extrusion can be achieved. Effective techniques like 'Cam Operated Movable Hot end' and 'Dual Hot End Lifting Mechanism' are demonstrated in this paper. Finally, the method of printing by using 'Multiple Printing Heads', being a more efficient and accurate technique, has been explained, along with the design of the entire mechanism.

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