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DESIGN, MANUFACTURING AND PROBLEM ANALYSIS OF AN ENTIRELY FDM 3D PRINTED LINEAR PNEUMATIC ACTUATOR

Urgency of the research. *Currently, manufacturing of pneumatic components is reserved only to well-equipped manufacturing plants and machine shops. The ability to reliably manufacture pneumatic components on a FDM 3D printer would enable the creation of low-cost custom-made pneumatic actuators with novel properties. This, in turn, could increase the speed and lower the cost of development of prototypes that use pressure air as their power source.*

Target setting. *Today cost-effective 3D printers can be found both in manufacturing plants and small machine shops and hobbyist workshops. Hawing the possibility to make reliable pneumatic components like pneumatic actuators on such machines could be beneficial and lead to opening new applications for them.*

Actual scientific researches and issues analysis. *Currently most research on using additive manufacturing to construct a pneumatic actuator focuses mainly on bellows type actuators. Research on 3d printing of classical pneumatic actuators is scarce and often presents a rough overview of the design process and immediately presenting a functional prototype without focusing and studying the design hurdles thoroughly.*

Uninvestigated parts of general matters defining. *Parts for firm pneumatic actuators manufactured by FDM 3D printing exhibit properties that have detrimental effects on the optimal working of such actuators. The question is on the magnitude of these effects whether these effects can be tolerated and how to design such a firm pneumatic actuator without the need to postprocess all the components.*

The research objective. *The aim of these research was to manufacture an early prototype of full plastic 3d printed not postprocessed linear actuators and make a preliminary analysis of encountered problems therefore pointing the way for further research in this field.*

The statement of basic materials. *The analysis consists of an attempt to manufacture a simple prototype of full plastic 3d printed linear actuators without the use of postprocessing techniques and establishing a baseline for further research.*

Conclusions. *In this paper the design of three iterations of FDM 3D printed pneumatic cylinders are presented. The problems arising from not using any postprocessing on either of the parts and using only 3d printed parts for the construction is also discussed. In the final chapter the design hurdles for the design and manufacturing of such an actuator are presented..*

Keywords: *actuator; pneumatics; 3D printing.*

Fig.: 9. Table: 4. References: 7.

Introduction. Material additive manufacturing technologies, commonly referred to as 3D printing technologies have been a part of manufacturing since the 1980. In the past 20 years thanks to the increasing computing power of low-cost microcontrollers, decreasing cost of manufacturing and the expiration of many patents on 3D printing technologies, 3D printing is being more and more popular with engineers and makers alike. 3D printing technologies allow to manufacture prototypes faster and often much cheaper than using traditional manufacturing methods. Apart from that, 3D printed parts can have geometry difficult or even impossible to achieve using other methods. Currently, the cheapest form of 3D printing is FDM (fusion deposition manufacturing) 3D printing, where the lower end 3D printers are easily accessible by common people.

On the other hand, 3D printed parts, in general, suffer from coarse surface finish, anisotropy in physical properties and, depending on the technology applied, lower dimensional accuracy.

This is one reason why parts requiring smooth surface finish and dimensional accuracy are still being predominantly manufactured using standard manufacturing techniques.

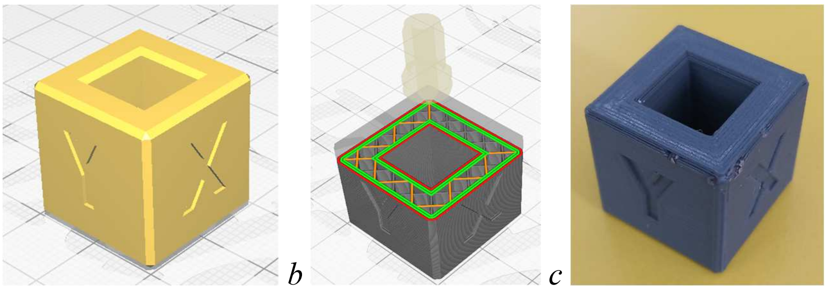
One such field on which little literature can be found is 3d printing classical pneumatic and hydraulic linear actuators. Usually research focuses more on developing and using of bellows type actuators. These actuators work on the principle of a flexible airtight container. If pressure air is pumped inside of this container, the container, depending on its geometry, deforms. An example of this can be found in [1] where a soft bellows type actuator attached to rigid links and variable stiffness joints simulates a grasping finger. True firm linear pneumatic cylinder type actuators manufactured using FDM 3D printing can be found in [2] and [3] where linear actuators made using FDM 3D printing are presented. Here, some parts, namely, the piston rod, friction rings and gaskets are not made by FDM 3D printing because the authors concluded that properties not achievable by FDM 3D printing are needed. The actuator was applied to construct a pneumatic linear servo actuator and a jumping robot. In 4 a design for a completely printed single part multimaterial piston and seal assembly for a full plastic linear hydraulic micro actuator for use in medical robots is presented. In this example the 3D printing technology of PolyJet was used. In all of these examples, components that needed to have special properties, e.g. smooth surface finish, high strength etc., were either not made using 3D printing, or were postprocessed.

The question asked in this article is whether it is possible to manufacture a pneumatic cylinder using only FDM 3D printing without postprocessing any of its parts and what are the challenges that need to be overcome before such an actuator can be used in an application.

We address this question by manufacturing three complete prototypes of pneumatic cylinders and analysing the most prevalent problems encountered.

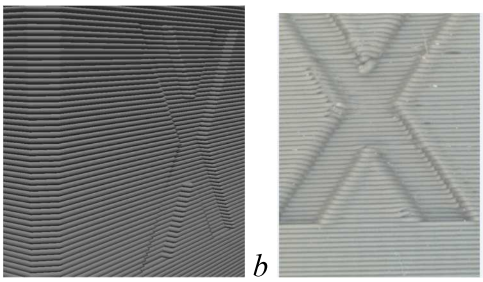
Manufacturing process. The manufacturing technology for the pneumatic cylinders was chosen to be FDM 3D printing. As mentioned above, this is the most affordable and widespread 3D printing technology, which still allows for the manufacturing of detailed and strong parts.

This technology functions by first discretising (slicing) the 3d model of the object into separate horizontal layers which are manufactured by the 3D printer on top of each other (figure 1 and 2). Each layer is in turn made from extruded plastic filament drawn across a layer and fused together to form the layer. Every layer has a spot where the start of the print path meets the end of the print path. This spot is called the seam and corresponds to a spot of decreased surface finish.



a *b* *c*

Fig. 1. Production cycle of a FDM 3D printed part:
a – 3D model; b – sliced model with toolpaths; c – finished part



a *b*

Fig. 2. Closeup on the structure of a 3D printed part:
a – theoretical a.k.a. within slicing software; b – real

As one can see from the figures above, the final part will have different tribological and strength properties along the layer lines compared to the direction normal to the layer lines. The strength of PLA parts along the layer lines according to [5] is around 50 MPa. Strength normal to the layer lines can be much lower, the difference is heavily influenced by the settings of the manufacturing process.

One other issue is that the parts manufactured using FDM 3D printing are not necessarily airtight as pores are created within the volume of the material during manufacturing (see figure 3).

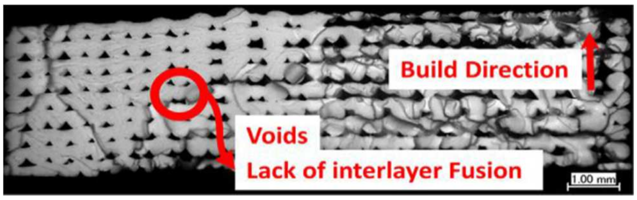


Fig. 3. Micro fractographs of 3D printed samples using FDM. Different raster orientations plays and important role in mechanical behavior of parts [7]

Basic construction of industrial grade pneumatic linear actuator. Linear pneumatic actuators are widely used, mainly in manufacturing plants. These actuators provide a good ratio of power to weight whilst being much cheaper and easier to integrate than other types linear actuators [7].

The basic construction of a linear pneumatic actuator can be seen in figure 4.

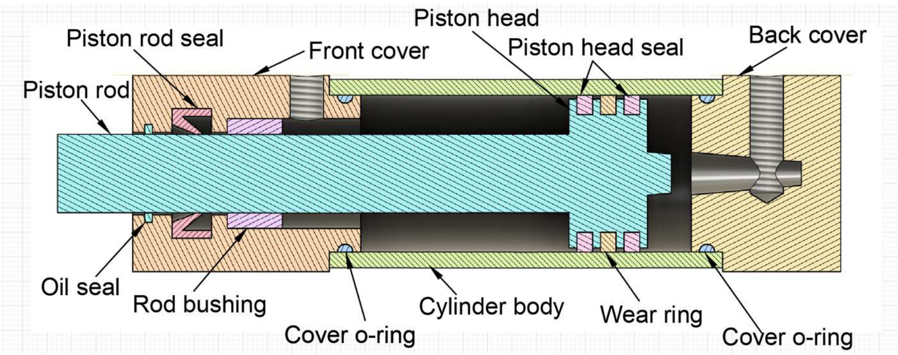


Fig. 4. Schematic sketch of a basic pneumatic linear actuator

The inner working of such an actuator is simple. Adding pressurised liquid or gas to one side of the piston head produces a pushing force acting on the piston head.

There are two sets of components in this assembly. There are the structural components: Back and front cover, cylinder body and rod bushing forming the cylinder body assembly and piston rod, piston head and wear ring forming the piston rod assembly. These provide structural integrity and eliminate unwanted degrees of freedom for movable parts of the actuator.

The other set of components are the sealing components: piston rod seal, piston head seals, oil seal and the two cover o-rings. These components provide sealing from the pressure medium leaking from one side of the piston head to the other and from inside of the actuator out, which would reduce the actuators efficiency.

One very important detail to point out is that, although the wear ring and rod bushing facilitate low friction movement for the rod assembly relative to the cylinder body assembly, these two assemblies, in ideal case, should, through the movement of the piston assembly, not touch. The piston rod assembly and actuator body assembly are connected through the piston rod seal and piston head seal. This fact can be easily seen on the commercial pneumatic linear actuator SMC CD85E10-50S-B (see figure 5) where there is noticeable play in radial direction between the piston rod assembly and cylinder body assembly.

Fig. 5. Linear pneumatic actuator SMC CD85E10-50S-B

Design and manufacturing of linear actuator prototypes. Three iterations of the pneumatic linear actuator were designed and manufactured. The basic design of the prototypes is based on the design of the SMC CD85E10-50S-B.

The design of the prototype was subjected to the following prerequisites:

a) The whole actuator including the seals is going to be 3d printed except the inlet fittings

b) The maximum pressure for testing the designs must, for safety reasons, not exceed 3bar

c) The default layer height for the structural printed parts is chosen to be 0.2 mm for faster printing

d) No surface of the actuator is going to be subjected to postprocessing and no lubrication is going to be used.

The main parameters used for0 3D printing can be found in table.1:

Table 1

Basic print settings used for manufacturing of linear pneumatic actuators

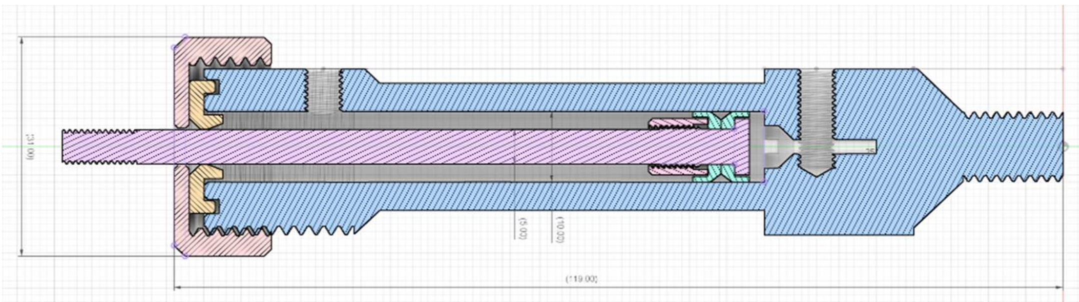
Parameter	value
Nozzle diameter	0.4mm
Layer height	0.2mm
Number of top/bottom layers	5
Perimeters	7
Extruder print temperature	205 °C
Print speed	60 mm/s
Cooling	100%

The machine used to manufacture the testing cylinder was chosen to be the Creality Ender 3. This is a very popular and cheap machine able to produce parts with satisfactory surface finish and physical properties without the need to modify the machine.

The material for manufacturing of structural components was chosen to be 3DFactory luminous red PLA and for the seals FIBER3D TPU black. These materials were on stock and are generally easily available.

Taking the basic design of an industrial grade design as a template, three consecutive iterative prototypes of linear actuators were made. Because 3D printing offers more freedom in the design of a part, the basic design of an industrial grade design was adapted to utilize the advantages and conform to the limitations of FDM 3D printing.

The cross sections of all three prototypes can be seen on figures 6 to 8.



a

b

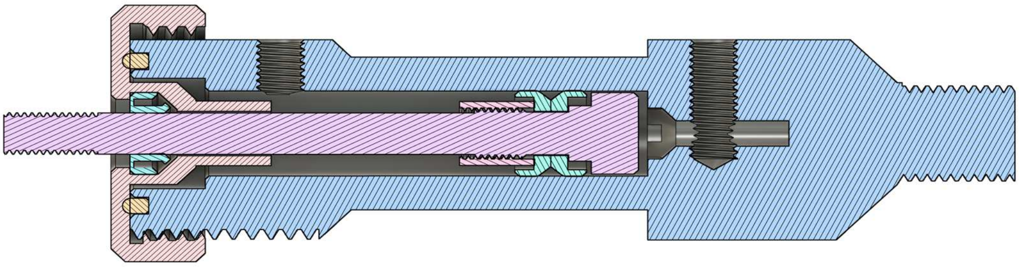
Fig. 6. First iteration of a 3D printed linear actuator (a),
finished parts of the first iteration of a 3D printed linear actuator (b)

As can be seen on figure 6 the overall construction is simpler than the example cylinder. The back cover is fused with the actuator body, the front cover is a screw on cap whose front part functions as the rod bushing. There is no wear ring and the rod seal, and the front o-ring seal is also fused into a single sealing cap. The piston head seals have a cup shape and are pressed against each other by a tightening nut.

This first iteration was functional allowing the piston to extend if pressurised to 2 bars. Unfortunately, this version suffered from high amounts of pressure air leaking through both the piston rings and front sealing cap. This issue was exasperated by the missing wear ring and loose tolerances allowing the rod to move radially opening a path around the seals.

The second iteration shown on figure 7, has a redesigned front cap acting again as the rod bushing and the rod has a widened back section taking on the role of the wear ring. Also, the front cap seal and front rod seal are two separate parts now. The diameter of the front rod seals was increased to decrease pressure air blow through. The body and piston were shortened, to decrease the material and time needed for manufacturing.

The back tread of the actuator body got damaged during testing resulting in the threaded section breaking in half. This resulted in pressure air escaping through the porous material of the cylinder. Also, the increase in the diameter of the seals slightly decreased pressure air escape. Unfortunately, due to the increased contact force between the seals and the rough actuator body of the bore the piston was not able to move at 3 bar of inlet pressure.

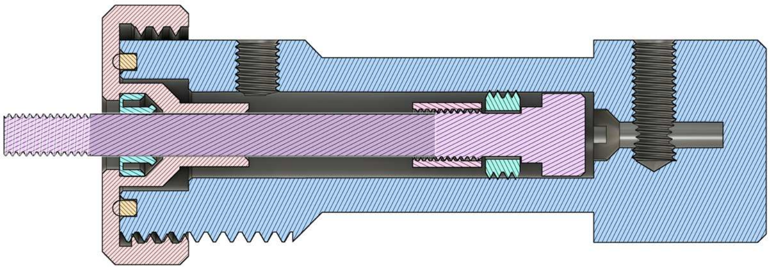


a

b

Fig. 7. Second iteration of a 3D printed linear actuator and finished parts of the second iteration of a 3D printed linear actuator

The final prototype is shown in picture 8. In this design the cylinder body was again simplified, and tolerances were adjusted. Also, a different design of the piston seal was implemented, this time using a laminar shape. The new seal design decreased the friction forces between the seal and bore, but the air leakage was audibly higher, nonetheless movement was achieved. Replacing the new piston seals with the seals from the first version showed the best results.



a

b

Fig. 8. Third iteration of a 3D printed linear actuator and Finished parts of the Third iteration of a 3D printed linear actuator

In table 2 one can see the extension force exerted by all three prototypes at a pressure of 3bar. Because the printing parameters were for all three prototypes the same, the variation of extension force is mainly due to seal design and random factors arising through the manufacturing process. The thick halfcup seal's diameter was too large leading to substantial binding through the tests and not producing reliable results.

Table 2

Extension force at 3bar

cylinder prototype no.	seal	extension force [N]	theorethical/messured force [%]
1	halfcup	13	55,1
1	thick halfcup	n/a	n/a
1	lamelar	8,8	37,3
2	halfcup	11	46,6
2	thick halfcup	n/a	n/a
2	lamelar	9,6	40,7
3	halfcup	12	50,8
3	thick halfcup	n/a	n/a
3	lamelar	9,8	41,5

The static friction forces and friction were measured for the first cylinder and for every seal (see table. 3).

Table 3

Extension force at 3bar

	static force (brake off force) [N]		
friction Ra	halfcup seal	lamelar seal	thick halfcup seal
1,136333333	10,2	1,22	40,2

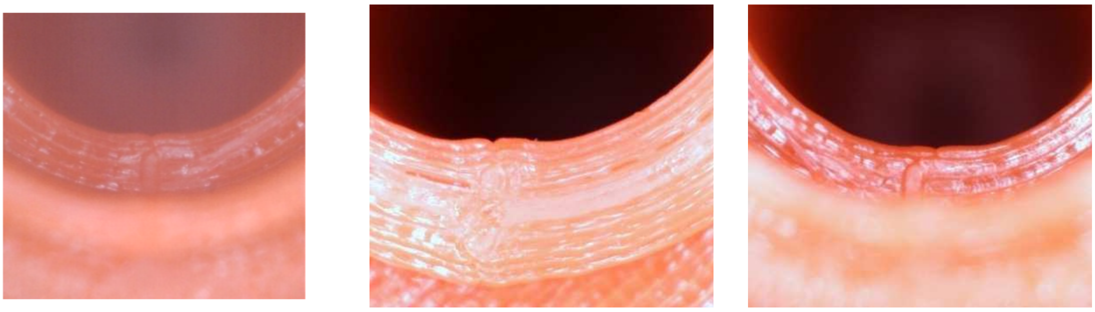
Design hurdles. As can be seen from the prototypes, there are significant hurdles to overcome in designing and manufacturing of a practical linear pneumatic actuator on a cheap desktop 3D printer. The main problems that need to be addressed are:

1. Surface friction control- surface roughness and material significantly influence the friction force between the surface cylinder body assembly and piston assembly
2. Seam quality control- the presence of a protruding seam negatively influences actuator performance (see figure 9 and table 4)
3. Tolerance control- improper dimensions of components effect seal blow through and friction forces
4. Seal design- 3D printing allows for novel seal design with unique properties
5. Material integrity control- both structural integrity at higher pressure and minimisation of pressure air escaping through the pores of the material of the cylinder need to be assured

Table 4

Seam height

Prototype no	Seam height [μm]
1	126
2	176
3	144



a *b* *c*

Fig. 9. Inner bore seam 50x magnification:
a – 1st prototype; b – 2nd prototype; c – 3rd prototype

Conclusions. In this paper the design of three prototypes of not postprocessed full plastic linear pneumatic actuators manufactured by FDM 3D printing and the topics that need to be addressed before these actuators can perform with satisfactory performance are presented. This paper is supposed to be a starting point for further research, pointing towards further work that needs to be done and giving basic information. Further topics for research can be, for example, on the ways to decrease the friction within the actuator, on reducing the negative effects of the seam on the performance of the actuator, on new seal designs, performance tests. This work will hopefully lead to the development of a new class of reliable actuators with properties only achievable using 3D printing manufacturing technologies.

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ПРОЄКТУВАННЯ, ВИГОТОВЛЕННЯ ТА АНАЛІЗ ПРОБЛЕМ ЛІНІЙНОГО ПНЕВМАТИЧНОГО ПРИВОДА, ПОВНІСТЮ ВИКОНАНОГО ЗА ТЕХНОЛОГІЄЮ 3D-ДРУКУ МЕТОДОМ ПОШАРОВОГО НАПЛАВЛЕННЯ

Актуальність теми дослідження. *Нині виробництво пневматичних компонентів доступне тільки в добре обладнаних виробничих підприємствах і механічних цехах. Виготовлення пневматичних компонентів для 3D-принтерів, працюючих на принципі пошарового наплавлення, дасть можливість створювати низьковартісні пневматичні приводи з новітніми властивостями. Це, у свою чергу, може збільшити швидкість та знизити вартість розробки прототипів, які використовують тиск повітря як джерело живлення.*

Постановка проблеми. *Сьогодні економічні 3D-принтери можна знайти як на виробничих підприємствах, так і в невеликих механічних цехах і майстернях для любителів. Виготовлення надійних пневматичних компонентів, таких як пневматичні приводи, на даних машинах може бути вигідним і привести до відкриття нових можливостей їх застосування.*

Аналіз останніх досліджень і публікацій. *На сьогодні більшість досліджень щодо адитивного виробництва для конструювання пневматичних приводів фокусуються переважно на приводах сильфонного типу. Дослідження 3D-надрукованих класичних пневматичних приводів є недостатніми і досить часто містять лише приблизний огляд процесів проєктування та презентують функціональні прототипи без наведення та ґрунтовного вивчення конструктивних перешкод.*

Виділення недосліджених частин загальної проблеми. *Компоненти фірмових пневматичних приводів, виготовлені за технологією 3D-друку методом пошарового наплавлення, проявляють властивості, які мають шкідливий вплив на оптимальну роботу таких приводів. Питання полягає в тому, чи величина цього впливу є допустимою, і яким чином спроєктувати приводи без потреби послідуючої обробки всіх компонентів.*

Постановка завдання. *Метою цих досліджень було виготовлення раннього прототипу цілком пластикових лінійних приводів, надрукованих на 3D-принтері, без послідуючої обробки, а також попередній аналіз проблем, що виникли, для пошуку шляхів подальших досліджень у цьому напрямку.*

Виклад основного матеріалу. *Стаття містить описання спроб виготовлення простого прототипу повністю пластикових лінійних приводів на 3D-принтері без використання методів послідуючої обробки та визначення підґрунтя для подальших досліджень.*

Висновки відповідно до статті. *У цій статті представлені моделі трьох ітерацій пневматичних циліндрів, надрукованих 3D-друком методом пошарового наплавлення. Обговорені проблеми, що виникають без використання жодної постобробки компонентів та при застосуванні у конструкції тільки надрукованих 3D-друком деталей. У заключній частині наведені конструктивні перешкоди для проектування та виробництва таких приводів.*

Ключові слова: *привід; пневматика; 3D-друк.*

Рис.: 9. Табл.: 4. Бібл.: 7.

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