Design of Machines and Structures, Vol. 12, No. 1 (2022), pp. 38–46.
https://doi.org/10.32972/dms.2022.004

3D PRINTED PLANETARY GEARBOX FOR ROBOTIC ARM JOINTS

FILIP HRDLIČKA

University of West Bohemia, Department of Machine Design
Univerzitní 22, 301 00 Plzeň
ficeriov@kks.zcu.cz
https://orcid.org/0000-0003-2815-0062

Abstract: 3D printing technology has become very popular in last several years as a cheap way how to make different parts. 3D printing is as a perfect tool for prototyping of various, mostly difficult, structures which is the reason why it is more and more use in mechanical design. This article is focused on assessment if 3D printing technology can be used for creating light, durable and cheap variation of classic metal or moulded plastic gearboxes for electric motors which can be used for low cost robotic arms. For this purpose was in CAD software designed a small two-stage planetary gearbox with identical stages. All parts of gearbox were printed by FDM 3D printer with most common printing material PLA. The gearbox has been tested on noise, durability, resistance and maximum load on lever to find out where can be potential of 3D printed gearboxes.

Keywords: *3D printing, Gearbox, Robotic arm, Stepper motor*

1. INTRODUCTION

Robotic arms nowadays mostly using electric motors for propulsion of each their joint. Every electric motor need to be connected with joints of a robotic arm by some kind of propulsion which transfer revolutions and torque, because revolutions of the electric motors are high and torque low. These propulsions can be divided into two categories, distant propulsion and direct propulsion.

Distant propulsion means that the motor is placed before the joint which is propelled. For transmission and transfer torque and revolutions are mostly used timing belts. Mostly is the motor close to the previous joint what helps decrease load of previous motor thus increase maximum manipulating weight of the robotic arm. Next advantages of this solution are low weight and low number of parts. Disadvantages of this solution are requirements to belt tensioning and more frequent maintenance.

Direct propulsion, as the name suggests, means that the motor is placed directly in the joint which is propelled and for transfer torque and revolutions are used different kinds of gearboxes. Gearboxes which are mostly used are planetary gearboxes, harmonic gearboxes, cycloidal gearboxes, gearboxes with worm gears or gearboxes with spur gears. Advantages of gearboxes are small dimensions and closed system so they do not need so frequent maintenance. Disadvantage of direct propulsions is high weight placed on the joint what means that the more far from center of gravity of the robotic arm is this propulsion placed, the more maximum manipulating weigh of the robotic arm is decreasing. Another disadvantage is high price of these gearboxes in comparison with timing belts.

This article deals with design, production, tests and comparison of a prototype 3D printed planetary gearbox as a potential alternative to metal gearboxes for small robotic arms.

2. DESIGN OF THE PLANETARY GEARBOX

As a final design was chosen a planetary gearbox concept which combine properties of compact dimensions and simple way to print [1]. For initial design of composition was used online software Planetary Gear Simulator [2] which is fast and easy tool for calculation of number of gears, number of their teeth and transmitting ratio of planetary gearbox. The gearbox is designed as two-stage with similar revolutions transfer ratio 5 : 1 per to stage. Total ratio of the gearbox is 25 : 1 for revolutions. Every stage of the gearbox has 1 sun gear, 3 planet gears and 1 ring gear. The sun gears are input periphery and the planetary gears attached in carriers are output periphery. The ring gears are rigid. All gears are made with a double-helical gearing. The double-helical gearing was chosen due to its useful ability self-centering – do not produce axial forces on the gearbox. This gearbox was designed for stepper motor NEMA 17HS4401 [3].

Whole gearbox was designed in the CAD software Autodesk Inventor 2019 which contains gears design utility. This utility can generate external or internal spur or helical gears with involute gearing. Input values are a module, axis distance, number of teeth, width of gears and angle of teeth. To get the gears for the planetary gearbox is necessary to generate two gear pairs with helical gearing, one with external gears and second one with internal and external gear *(Figure 1)*. These gears are mirrored around the lateral plane which creates double-helical gearing. Final dimensions of the gears are listed in the *Table 1*.

Table 1

Final dimensions of gears

		Sun gears	Planetary gears	Ring gears
Number of teeth	z [–]	15	22	60
Module	m [mm]	0.75	0.75	0.75
Tip circle	d_a [mm]	13.219	18.655	45.475
Pith circle	d [mm]	11.647	17.082	46.587
Root circle	d_f [mm]	10.020	15.456	48.7
Module correction	[–]	0.1656	0.1656	0.1582
Width	t [mm]	10	10	5

As shown in *Table 1*, the ring gears have only a half width as other gears, this difference has a reason. All gears have double-helical gearing and that means that during assembling they cannot be simply inserted. From this reason are the ring gears divided into half so they can be slid on the planetary gears from sides.

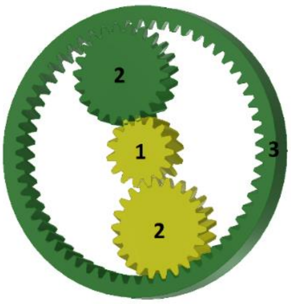

Figure 1. *The yellow pair represent the sun gear (1) and the planetary gear (2), the green pair represent the planetary (2) and the ring gear (3)*

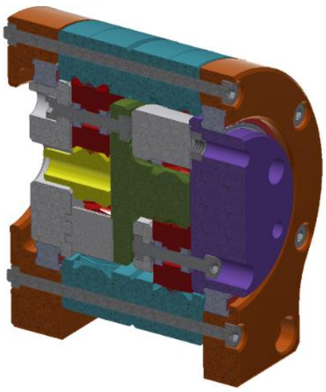

Figure 2. *Cut through the final model of the planetary gearbox*

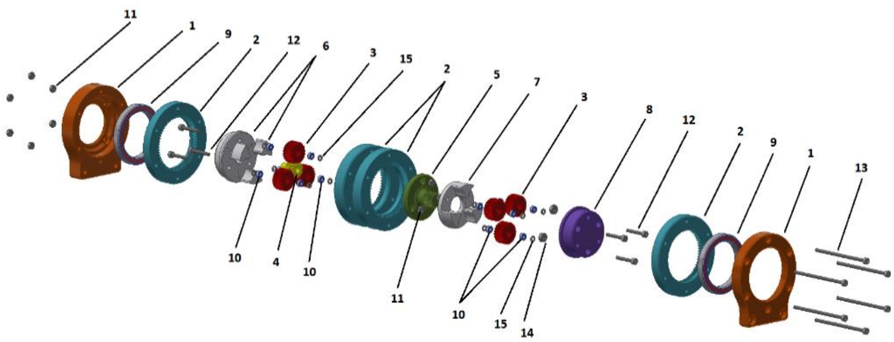

Figure 3. *Exploded view of the designed planetary gearbox*

The final model of gearbox *(Figure 2, Figure 3)* is assembled from parts: 1 – 2× covers with housing for bearings (9), 2 – 4× ring gears, 3 – 6× planet gears, 4–1× sun gear of first stage, 5 – 1× sun gear of second stage as a second part of carrier of first stage, 6 – 1× first part of carrier of first stage, 7 – 1× first part of carrier of second stage, 8 – 1× second part of carrier of second stage/output flange, 9 – 2× bearings 6808-2RS (40 × 52 × 8), 10 – 12× bearings MR63-2Z (3 × 6 × 2.5), 11 – 12× hex nuts M3 (DIN 934), 12 – 6× Hex socket bolts M3 × 20 (DIN 912), 13 – 6× hex socket bolts M3 × 60 (DIN 912), 14 – 3× hex nuts M4 (DIN 934), 15 – 12× 3D printed spacer rings (3.3 × 5 × 1).

Part no. 4 (sun gear) is input peripherals connected directly to chamfered shaft of the stepper motor. Part no. 8 (flange) is output peripherals with connection dimensions M4 3 × 120° on pitch circle 30 mm.

3. Production of the prototype

Production of gearbox consists from 3D printing of parts (gears, covers, etc.) and their assembly with bought parts (bearings, bolts, etc.).

3.1. 3D printing

For 3D print was used FDM 3D printer Artillery sidewinder X1, as printing material was used the most common material – PLA. All parts were exported into STL format and prepare for print in PrusaSlicer. Axis of all parts were oriented vertical to the pad of the 3D printer *(Figure 4)*. Before export into STL were all parts adjusted to tolerance of 3D printing. Tolerance of 3D printed parts is approximately –0.2 mm. Holes for bolts got +0.3 mm tolerance for guaranteed clearance, holes for nuts got +0.15 mm for overlap fit and holes for bearings got +0.1 mm for overlap fit.

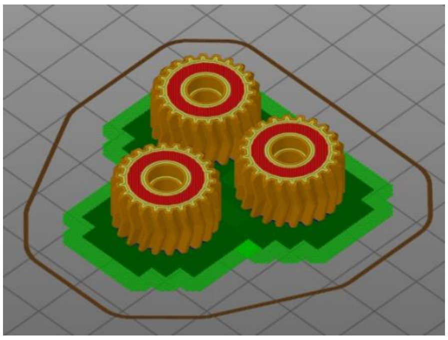

Figure 4. *The planetary gears prepared for print in PrusaSlicer*

Parameters of printing were focused to the best precision and details of printed parts. [4] The sun and the planetary gears were printed by 0.1 mm thick layer, 30% gyroid infill and with 2 layer thick raft which ensured accurate width of gears. The ring gears and all other parts were printed by 0.2 mm thick layer with 30% grid infill and without raft. Speeds of the 3D printer were 60 mm/s for perimeters, 15 mm/s for small perimeters, 30 mm/s for outside perimeters, 80 mm/s for infill, 30 mm/s for full fill, 20 mm/s for infill of thin walls, 20 mm/s for top 3 layers, 25 mm/s for first layer, 50 mm/s for bridges and 130 mm/s for rapid traverse.

3.2. Assembling the gearbox

Printed parts were assembled with bearings, nuts and bolts *(Figure 5)*. The final gearbox is 65.5 mm long, 78 mm high and 70 mm wide where 70 mm is outside diameter of the ring gears. Total weight is 249 g where 169.34 g represent printed parts. Total cost of the gearbox are 195.73 Kč – 7.67 EUR (exchange rate from 24. 11. 2021) where 67.56 Kč – 2.65 EUR represent cost spent on printing material. After assembly was measured backlash of the gearbox which is 0.57° (34’).

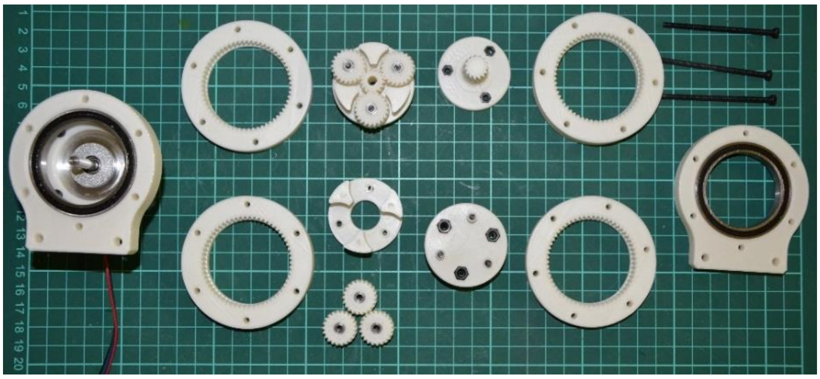

Figure 5. *Printed parts of the gearbox assembled with bearings and nuts*

4. TESTING OF THE GEARBOX

Tests were focused on four categories, noise, resistance, maximum load capacity and durability.

Noise was compared with noise of used stepper motor which was mentioned. At constant speed was measuring noise of the stepper motor without the gearbox, the motor with the gearbox without grease and the motor with the gearbox with grease. All these three measurements of sound pressure level were long one minute and made at a constant distance of 10 cm. From data was compute average level of noise. The first case had noise 48 dB(A). In the second case was measured average noise 63 dB(A) and the last case had average noise 59 dB(A).

Second test was focused on resistance of the gearbox. Subject of test was measuring temperature of the stepper motor and compare how much resistance of the gearbox affects it. Test compare three cases, motor without load (motor only), motor with the gearbox without grease and motor with the gearbox with grease. Temperature was measured for 6 hours in 10min. intervals for first hour. Between first and second hour in 15min. intervals and from second to sixth hour in 1 hour intervals.

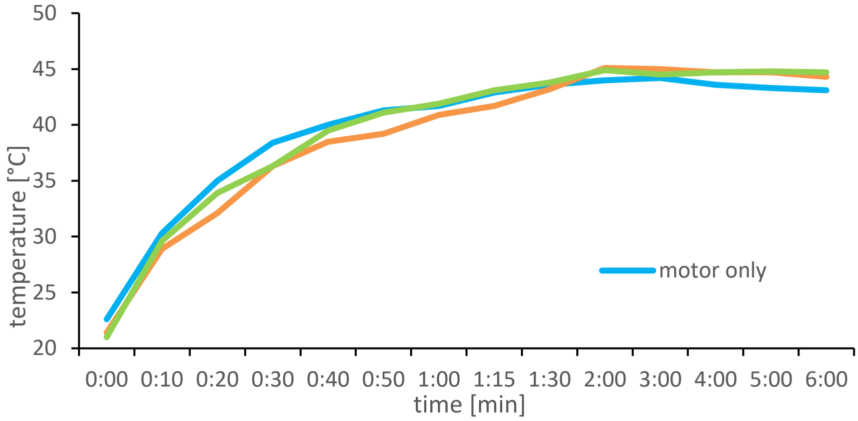

Figure 6. *Temperature of the motor in time*

As shown in *Figure 6*, temperature in all three cases raised up from room temperature (on average 21.5 °C) very quickly in first several minutes. After 2 hours of continuous run the temperature has stabilized between 44–45 °C. In the first case temperature after third hour started slightly decline to the final temperature 43.1 °C. It could be caused by changes temperature in the room during day. This test find out that resistance of the gearbox do not have any significant effects on connected motor. Third test was focused to find maximum load torque which is the planetary gearbox able to transfer. On the 3D printer was printed testing arm with hole distant 200 mm from the axis of the gearbox. In the hole was hooked up a bucket with load which was increased till the gearbox failed.

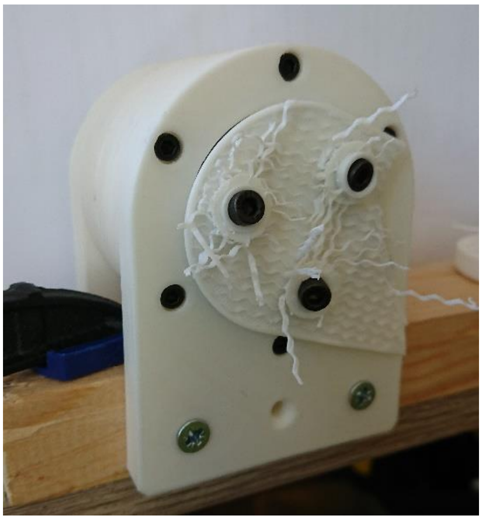

Figure 7. *Failed testing arm*

Figure 8. *Failed part of the gearbox – output flange*

Achieved load when the gearbox failed was 13.2 kg what represent torque moment 25.9 Nm. First symptoms, visible deformation and crackling sound, appears at 12.3 kg what represent torque moment 23.54 Nm. As shown in *Figure 7* and *Figure 8*, parts which were damaged during the test were testing arm and output flange of the gearbox. On output flange is obvious how torque twisted holes with bolts and also crack in place where is placed bearing. This happened due to sparse infill of this component. If the infill would be denser, would be this component able to transfer even bigger load.

Last test was focused on durability. During all tests input sun gear did over 300,000 revolutions, then was the gearbox disassembled and the sun gear checked how much was abraded. As shown in *Figure 9*, the sun gear has no visible symptoms of abrasion or damage.

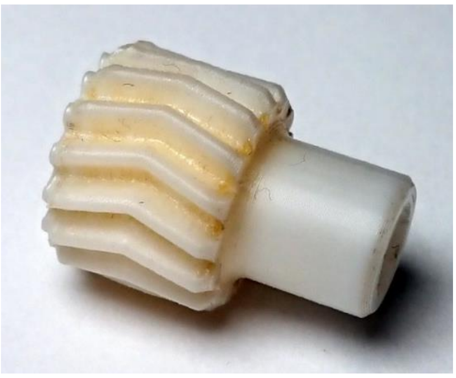

Figure 9. *The input sun gear after more than 300,000 revolutions*

5. COMPARISON

On the market we can find several types of gearboxes for stepper motors. To compare this 3D printed gearbox were chosen gearboxes with similar parameters – planetary layout, output torque and suitability for stepper motor NEMA 17HS4401. These parameters meets metal gearbox GP42-S2-21-SR from company Nanotec [5] and metal gearbox PLE17-G20 from company Stepperonline [6].

Table 2

Comparison of gearboxes

		GP42-S2-21-SR gearbox	PLE17-G20 gearbox	3D printed gearbox
Reduction ratio	[1]	20.64 : 1	20 : 1	25 : 1
Max. output torque	[Nm]	17.7	12	<23.54
Dimensions (W × H × L)	[mm]	42 × 42 × 50.9	42 × 42 × 67	70 × 78 × 65.5
Weight	[g]	380	382	249
Max. backlash	[°]	51	19	34
IP protection	[–]	IP54	IP54	–
Service life	[h]	10,000	20,000	–
Noise	[dB(A)]	–	<55	59
Price	[EUR]	109.3	46.49	7.67

Although 3D printed gearbox is bigger, do not have IP protection and we do not know its service life, *Table 2* shows, that for its small weight and especially low price, it can be good solution for undemanding applications like small robotic arms.

6. Conclusion

The goal of this article was create functional 3D printed planetary gearbox as cheap alternative to existing manufactured gearboxes for low cost robotic arms. Tests have shown that is possible with most common 3D print technology and printing material create light, cheap and durable gearbox which has potential works long time and with medium size torque. In any case there is still a lot of space how to improve the gearbox and reach better parameters. Big potential is both in the design and in the material where can be used material with better mechanical parameters as polypropylene or nylon. Can be also used another and still cheap 3D printing technology as SLA which has better resolution than FDM what can reduce size of whole gearbox.

References

[1] García, P. L. – Crispel, S. – Saerens, E. – Verstraten, T. – Lefeber, D. (2020). Compact Gearboxes for Modern Robotics: A Review. *Frontiers in Robotics and AI*, Vol. 7, Article 103, August 2020. https://doi.org/10.3389/frobt.2020.001

[2] *Planetary Gear Simulator*. http://www.thecatalystis.com/gears/ (2021/12/13).

[3] *NEMA 17HS4401 datasheet*. http://www.datasheetcafe.com/17hs4401-datasheet-stepper-motor/ (2021/12/13).

[4] Kumar, K. M. – Pandey, P. M. – Wimpenny, D. I. (2019). *3D Printing and Additive Manufacturing Technologies*. ISBN 978-981-13-0304-3, Springer Nature, Singapore, https://doi.org/10.1007/978-981-13-0305-0.

[5] *Nanotec*. https://en.nanotec.com/products/2802-gp42-s2-21-sr/ (2021/12/13).

[6] *Stepperonline*. https://www.omc-stepperonline.com/ple-series-planetary-gearbox/ple-series-planetary-gearbox-gear-ratio-20-1-backlash-20-arc-min-for-nema-17-stepper-motor.html?mfp=287-gear-ratio%5B20%5D/ (2021/12/13).