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Study of 3D-printed robot with mobility

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Abstract. In recent years, 3-dimensional (3D) printers have successfully fabricated parts. The purpose of this study is to propose a 3D-printed robot that anyone can fabricate easily at a low cost employing a home-use 3D printer. To achieve this purpose, this study focuses on efficiently utilizing parts manufactured using a 3D printer and the mechanism of a robot comprising these parts. Although numerous studies have been conducted on 3D-printed robots, we propose the use of a fused deposition modeling (FDM)-type 3D printer to manufacture a robot at low production costs. The proposed robot does not require an assembling process as it is created by a single process using a 3D printer. On the basis of the above-stated design criteria, a wheeled robot was manufactured through a single 3D printing process. However, the circuit, sensor, and motor require a separate installation process. The study successfully concludes that anyone can reproduce an integrated robot form in approximately 300 USD using a low-price 3D printer made for ordinary home use. Therefore, a significant number of innovative mechanical robot's prototypes can be manufactured using this open-source technology. In addition, it is expected that the effectiveness of the fabricated robot can be practically ascertained.

1. Introduction

A robot is a machine consisting of huge parts that autonomously perform work on behalf of human beings. In this paper, the word robot refers to a machine that can move by itself and has power as well as programmable circuits. Although robots have changed considerably in shape and performance with time, there are certain aspects about them that remain unchanged. A considerable amount of time is required to design and manufacture a robot. In addition, it is necessary to be a technician with specific knowledge and skill to assemble a robot. A technician learns to assemble several parts independently and thereafter trains extensively to improve these skills over time.

However, with the recent advances in technology, the earlier expensive hardware and software are now available at low costs. Moreover, there is also an increase in opportunities for non-professional individuals who do not have any significant expertise in these fields.

Although the 3D printer was put into practical use in the 1980s, the machine itself was expensive and required advanced control at the time; therefore, its use was not widespread. In 2009, the patent for the fused deposition modeling (FDM) technique expired; this allowed the popularization of 3D printers. Nowadays, the number of people involved in manufacturing is on the rise. Similar to the FDM patent, the patent for selective laser sintering (SLS) expired in 2014. The SLS technique has a higher printing accuracy than the FDM technique. However, compared to the FDM method, it is currently difficult for ordinary people to use this method owing to its complexity in terms of materials and systems.

Therefore, there is an increase in the number of studies on the use of FDM-type 3D printers and other types of 3D printers; for example, printing of surgical instruments in outer space at a significant distance from the earth [1], 3D bio-printing [2, 3, 4], fabrication of robots using 3D printers [5, 6, 7, 8], etc.

In addition to the aforementioned fields, a significant number of studies are being conducted on the integration of robots [9, 10], particularly on the design of robots using 3D printing solids and liquids [10]. The robots are designed with a 3D CAD software and are manufactured through 3D printing in a single process. These robots can operate immediately after their removal from the 3D printer by attaching the necessary circuit components such as sensors and actuators. These robots can be operated using bellow actuators based the expansion-contraction mechanism for their six legs.

In the above-stated case, all the parts, excluding the electronic parts such as circuits and actuators, were manufactured using a 3D printer in a single process. As a result, the assembly process, which is usually an indispensable process in robot production, is no longer required. As mentioned above, not every individual can assemble a robot; by removing this process completely, this study aims to change the production process of robots significantly.

However, the study faces a problem that 3D printing of robots is extremely expensive. Moreover, the 3D printer must be remodeled to print the robot. The printer originally uses only three materials to make the robot; however, this process requires the remodeling of the printer so that eight materials can be used simultaneously. The study also aims to make this robot production process easily accessible to common people.

Therefore, this study uses an inexpensive and easily available FDM-type 3D printer, namely Da Vinci Jr 1.0 (by XYZ printing). This 3D printer ensures ease in the design and evaluation of the robot for non-professional individuals; furthermore, it ensures that a single-process 3D printing technique successfully manufactures the desired robot.

2. **Concept of 3D printing of robots**

Recently, there has been an increase in 3D-printer users as well as an increase in the manufacturing processes that use 3D printers. In the academic field, it is common practice to use expensive 3D printers. These printers make rapid prototyping difficult. To differentiate our research from the existing robot making techniques, we have focused on ensuring that our technique has a low cost and is easy to use. The following subsections state the purpose of this study.

2.1. Single-process manufacture of robot using 3D printing

The primary purpose of this study is as follows: "A robot that anyone can make using an inexpensive 3D printer". Currently, it is considered impossible to design, produce, and operate a robot using a single process. Therefore, the robot is manufactured with a 3D printer only. As the robot is a single- process 3D-printed robot, the production time can be devoted to other processes. Consequently, this makes robot manufacturing an easy process. Moreover, many innovative 3D prototypes can be created using inexpensive materials for ordinary household use at low production costs. The aforementioned reasons differentiate our research from previous studies in the same field.

2.2. Design criteria for mechanical parts

Our objective is to develop a 3D-printed robot through a single process using a 3D printer. In comparison to previous studies, our research methodology has improved precision, the number of nozzles of the printer is different, and the injected resin material is different. Therefore, we require a new method in 3D projection for manufacturing through a single process. This study focuses on the rotating axis, which is an important element of our robot. Therefore, an additional design criterion of our research was to create a rotation axis through a single process in 3D printing. As a result, these design criteria will enable widespread usage in the creation of different 3D-printed robots through a single process.

2.3. Evaluation of experiment on application of 3D printing robot with one process

The functioning of the robot, manufactured by a single-process 3D printing technique, requires appropriate evaluation through experiments. The experiments are designed to examine the effectiveness and mechanism of the 3D-printed robot.

The accomplishment of the above-stated objectives will enable the successful production of a robot simply through the activation of a 3D printer. In addition, as 3D printers are commonly used commercially, anyone would be able to produce the robot at an extremely low cost, thereby making this technology an open-source technology.

This will enable an increased number of studies and prototype developments, which in turn will help determine the effectiveness of the aforementioned technique in the design and manufacture of a 3D-printed robot through a single process.

3. Evaluation experiment of 3D printed mechanical part

3.1. Experimental setup

The study uses an inexpensive FDM-type 3D printer. Therefore, there is a difference between the sizes of the CAD drawing and the actual product. In order to overcome this drawback, it is required to determine the optimum axle diameter of wheel, inner diameter of wheel, and their clearance through experimentation. Hence, we conducted the following two basic experiments.

First, we test multiple printing conditions through experimentation. Therefore, only the driving unit of the 3D-printed robot is printed with a single process under various conditions. The same sizes are used for the clearance optimization experiments and the supporter angle optimization experiments (refer figure 1). The supporter is the support material used for printing the axle. The ratio of the motor shaft (high-speed shaft) to the axle diameter (low-speed shaft) is 1: 2. The least count of the measuring scale used in the experiment is 1 mm.

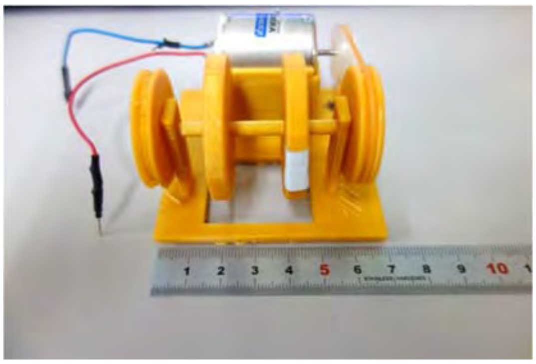

Figure 1. Experimental set up model

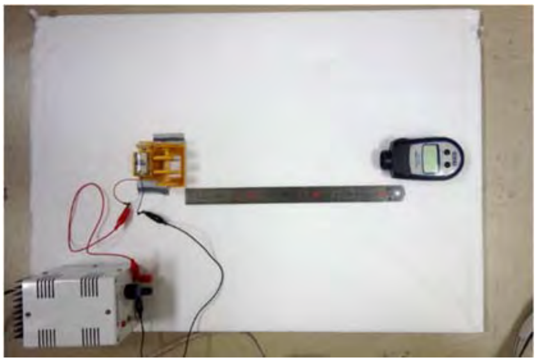

Figure 2. Experimental set up situation

The regulated power supply (3 V) is connected to the motor of the above-stated model. Thereafter, a reflective seal is placed on the wheel and the tachometer (TMS 792 D) is set 300 mm away from the model. The number of revolutions (rpm) of the wheel was measured 10 times every 2s; thereafter, the average rpm value was calculated (refer figure 2).

3.1.1. Clearance of Axle diameter and inner diameter

The inner diameter was set at 5 mm on the basis of the results of the preliminary experiments. The optimum clearance was obtained by changing the axle diameter.

In figure 3, the red circle depicts the axle diameter and the blue circle depicts the inner diameter. The term clearance refers to the difference between the radii of the aforementioned circles. The clearance was set at 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, and 0.5 mm for this experiment.

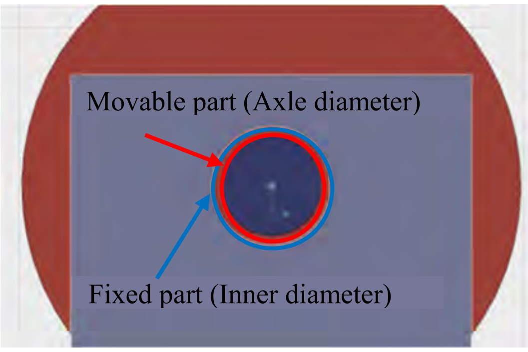

Figure 3. Axle cross section

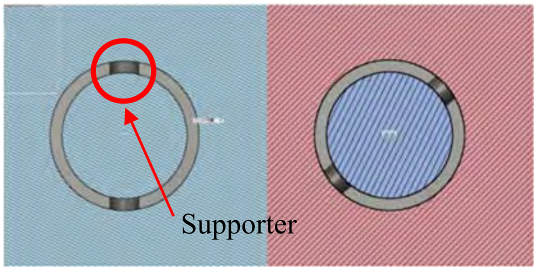

Figure 4. Attachment angle of supporter

3.1.2. Attachment angle of supporter. The attachment angle varied from 0° to 90°; 0° was assumed as the vertical direction (refer figure 4). In figure 4, the angle of the supporter on the left-hand-side figure is 0° and that on the right-hand-side figure is 50°. This experiment aims to determine the optimum attachment angle of the supporter.

3.2. Clearance and supporter of drive unit

3.2.1. Clearance of axle diameter and inner diameter. Table 1 presents the results of the initial clearance optimization experiments. When the clearance value was set to 0.1 mm and 0.2 mm, the clearance was lost ("Clearance" is the gap between axle diameter of wheel and inner diameter of wheel.). Hence, the movable part and the fixed part adhere to each other and the wheels were unable to rotate.
The experimental results indicate that the most stable rotational speed is at a clearance of 0.4 mm.

Table 1. Results of clearance optimization experiment

Clearance(mm)	0.1	0.2	0.3	0.4	0.5
Axle diameter(mm)			4.4	4.2	4.0
Inner diameter(mm)			5.0	5.0	5.0
Adhesion	Exist	Exist	None	None	None
pulley on motor side(mm)	30	30	30	30	30
pulley on wheel side(mm)	15	15	15	15	15
Maximum value(rpm)			3612.8	3814.0	3526.8
Minimum value(rpm)			3167.4	3187.2	3382.4
Average value(rpm)			3515.7	3618.2	3452.4

3.2.2. Attachment angle of supporter. On the basis of the experimental results described in subsection 3.2.1, the axle diameter of the robot used in the experiment was set at 4.2 mm and the inner diameter was set at 5 mm. The experimental model was created by varying the angle of the supporter with 10° steps from 0° to 90°. The experimental results of the rotational speed of the model and the supporter attachment angle are displayed in figure 5.

It can be observed from the above results that the attachment angle of the supporter changed insignificantly between 20°–90°. Therefore, by setting the supporter attachment angle at 0°, the rotational speed is increased by 1.4–2 times when compared to other angles.

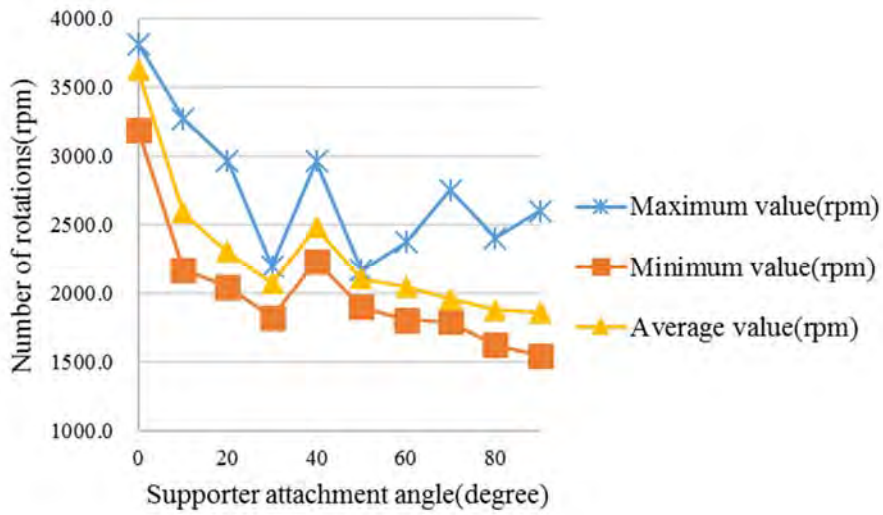

Figure 5. Optimization experiment of supporter mounting angle

3.3. Consideration on gap and support of driving part

A clearance of 0.4 mm was observed to be the optimal clearance. Although no adhesion was observed at a 0.3 mm clearance, the axle diameter was thermally deformed owing to the small value of clearance and the high frictional force applied to the axle diameter.

At a 0.5 mm clearance, the axle diameter blurred on rotation owing to the large inhibiting rotation. Furthermore, the axel rotated at a 0.3 mm clearance; however, the friction significantly hindered the rotation. In comparison, a 0.4 mm clearance offered the most stable rotational speed with respect to blurring and rotational friction of the axle. Therefore, the optimum design clearance of the axle was 0.4 mm.

This experiment also aims to optimize the mounting angle of the supporter. At 10° and 0°, the supporter gave high rotational speeds. However, when the supporter was attached at an angle higher than 10°, the rotational speed was significantly decreased. This is because while designing the supporter in the horizontal direction, the axle diameter is in a floating state; hence, the computer automatically produces a support at the time of printing. In other words, the two patterns of support created for the axle diameter resulted in large friction.

4. Single-process 3D printing of robot

4.1. Experimental conditions

In order to investigate the performance of the 3D-printed robot manufactured in a single process, the following experiment was conducted.

First, the robot was printed using a 3D printer. Second, a rubber field with x: 600 mm and y: 800 mm was prepared. Thereafter, the robot was placed at three different positions of x: 100 mm, x: 300 mm, x: 500 mm. Subsequently, the laser pointer that was installed in the middle of the field was moved to the left and right of the optical sensor attached to the robot, and the target point was set 400 mm away. The robot was required to make a turn after arriving at the target point. Finally, the trajectory and the time taken to reach the target were measured and evaluated as an example of the behavioral performance of the robot.

4.2. Driving experiment and performance analysis

The single-process 3D-printed robot measures 100 mm in width (W), 100 mm in length (D), and 90 mm in height (H), as shown in figure 6. The mass of the main body is 95 g and that of the circuitry and other components is 182 g. Furthermore, the printing cost of the robot is 3.5 USD. The time taken to print the robot is approximately 19 h.

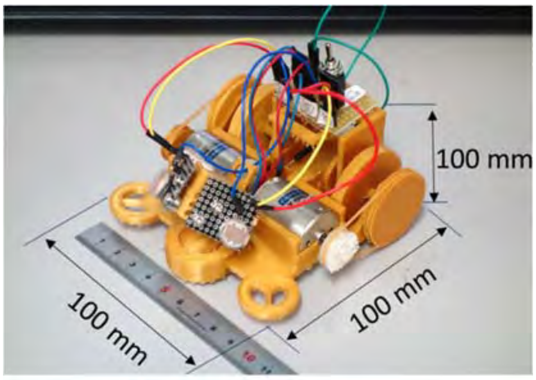

Figure 6. 3D printing robot with one process

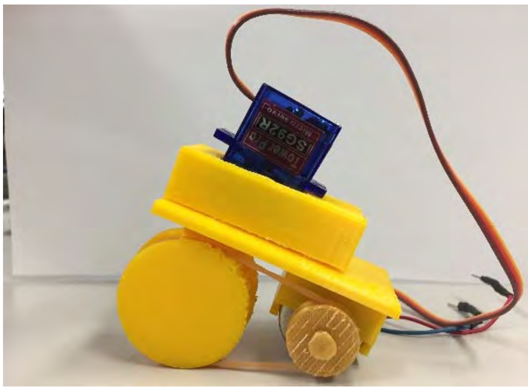

Figure 7. Steering mechanism

Figure 7 displays the steering mechanism of the robot; it consists of a servomotor and a DC motor. The single-process 3D-printed robot is similar to a two-wheel drive robot. However, there are a significant number of improvements.

The two-wheel drive robot was manufactured in a single process by 3D printing. Table 2 compares the number of man-hours required for assembling the robot from scratch with the man-hours required to create this robot. The table shows that the assembling process itself requires nine steps.

Table 2. Comparison of number of steps in the assembly process

	Number of steps for assembling 3D printed robot	Number of steps for assembling the robot from scratch
Assembly steps of body	0	9
Mounting of belt	1	1
Installation of circuit parts	3	3
Mounting of Motor	2	2
Total	6	15

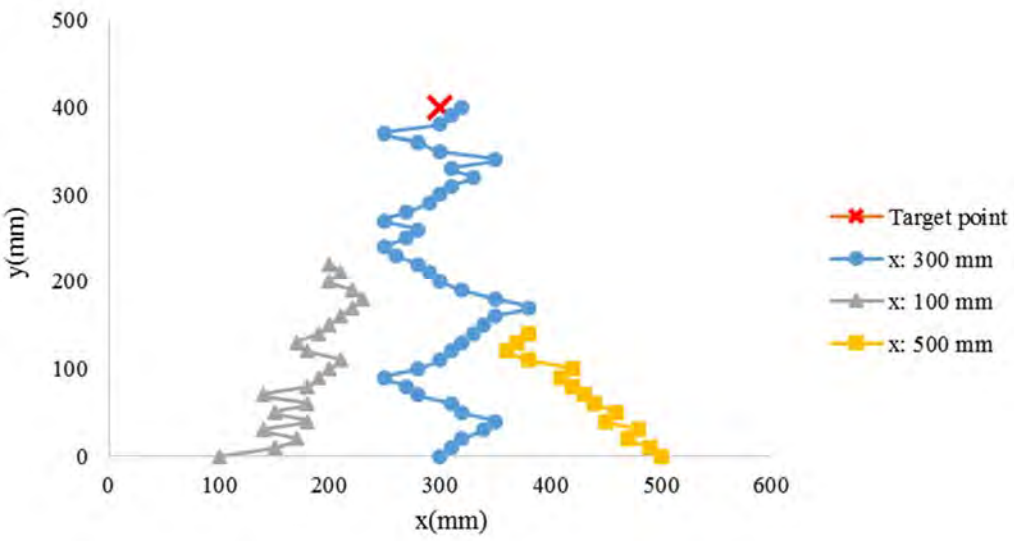

Figure 8. Robot orbit

The robot took 1 min and 10 s to travel from the 300-mm point to the target. However, the robot starting from the points x:100 mm and x: 500 mm was stopped at approximately 200 mm in the y-axis direction from the starting point and was unable to reach the target (figure 8).

4.3. Discussion

The aforementioned robot has a low production cost of 3.5 USD, which is suitable for mass production. Considering that the process can be repeated and the robot can be duplicated within a day makes the robot extremely suitable for mass production.

In this experiment, the basic experimental robot, which could only move forward in a straight line, was mounted with two wheels and a moving mechanism to enable it to perform the functions of turning and direction change. Consequently, the robot started from the point x: 300 mm and reached the destination. As the sensor received the light of the laser pointer, the robot was able to move forward while turning left and right.

Further, when the robot started from the points x: 100 mm and x: 500 mm, it did not reach the target point; however, it was able to approach the target.

The above-stated observations ascertain that it is possible for a 3D-printed robot, manufactured by a single process, to complete a simple task. Furthermore, it was unable to reach the target as the sensor ceased to recognize the laser beam because the light beam stopped reaching the sensors midway.

5. Conclusion

In this study, a robot was manufactured as a single piece using the modeling accuracy of a 3D printer. Therefore, we successfully proved that the proposed robot manufacturing technique does not require assembling work. This new manufacturing technique uses a less costly printer than the other 3D-printed robot in a single process conducted in a previous study.

The objectives described in section 2 were achieved as follows:

1. The experimental cost was reduced by using the Da Vinci Jr 1.0 printer, which can be easily obtained for approximately 500 USD. Therefore, we succeeded in manufacturing a working model of a two-wheeled 3D-printed robot using a single printing process.
2. While we modeled a wheeled robot with a single 3D-printing process, we focused on the axis of rotation of the robot and investigated the design rules required to obtain the maximum ease of rotation of the axis through basic experiments. Consequently, the robot cannot be driven by a gear mechanism and a simple driving method such as a pulley-drive is the preferred. The optimum dimensions for the axle diameter and inner diameter were 4 mm and 5 mm, respectively. The optimum clearance between the axle diameter and inner diameter was set at 0.4 mm. The support material, when forming the axle diameter, should be designed to be cylindrical with a diameter of 1 mm in the vertical direction.
3. In the experiments based on the above-mentioned design criteria, we created an active two-wheeled robot whose driving mechanism was a pulley, and we evaluated it with a simple operation. We examined the effectiveness of single-process 3D printing for producing a robot. The robot successfully reached the target position in approximately 1 min and 10 s and was able to move forward in a straight line until the signal was lost. In addition, we confirmed that the robot could approach the target point successfully from three different starting points. Therefore, although we considered only one sample robot, we discovered that the 3D-printed robot is effective in performing simple tasks.

In conclusion, it is necessary to select appropriate circuits, sensors, and motors to successfully create a wheeled robot based on the design criteria used in this study for manufacturing a 3D–printed robot through a single process.

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