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A Mobile Robot Gripper for Cooperative 3D Printing

Jason Steck, Rolando Morales-Ortega*, Jacob Currence*, Wenchao Zhou**

**The AM^3 Lab, Department of Mechanical Engineering, University of Arkansas at Fayetteville Fayetteville, AR, United States of America; Corresponding email: zhouw@uark.edu*

Abstract

Cooperative 3D printing is an emerging technology that aims to overcome several limitations of contemporary 3D printing (e.g., print size, cost, complexity) by allowing multiple mobile 3D printers (or printhead-carrying mobile robots) to work simultaneously on a single print job. In particular, one challenge of 3D printing is the inability to incorporate pre-manufactured components in a structure without human intervention. In this paper, we present a mobile robot gripper that can work with other mobile 3D printers to pick and place pre-manufactured components into a 3D printed structure during the printing process. First, we designed a simple gripper using a rack and pinion actuator that can be driven by a single stepper motor like a regular extrusion printhead. Next, a mobile robot gripper is developed with the designed gripper mechanism. Finally, we tested the mobile robot gripper for picking and placing objects using G-code commands. Results show the mobile robot gripper can successfully pick and place pre-manufactured components into a 3D printed structure. This development will potentially enable autonomous hybrid manufacturing that combines 3D printing and traditional manufacturing to improve the quality and capability for manufacturing complex products.

Keywords: Additive manufacturing; cooperative 3D printing; robot gripper; hybrid production

1. Introduction

Over the past three decades, 3D printing has presented a vast array of manufacturing possibilities, ranging from rapid prototyping in product design [1, 2], to novel methods of producing tissues and organs for biomedical applications [3-5]. Although this progress has been substantial, many challenges to modern commercial 3D printers remain, including size constraints of the build envelope, speed of production, strength of the resulting structures, and the inability to incorporate pre-manufactured components within a 3D printed structure without manual assembly [6]. The vast majority of commercially available 3D printers use a single print head confined within a build chamber, thus exhibiting these limitations. Cooperative 3D printing is an emerging technology that aims to overcome many of these challenges by allowing multiple mobile 3D printers, or printhead-carrying mobile robots, to work simultaneously on a single print job. By using a mobile 3D printer, an arbitrary X-Y build envelope is enabled. In addition, the removal of the geometric constraints allows for the cooperation of multiple mobile 3D printers, since the printed structure is exposed to the surrounding build platform. Furthermore, with multiple active extruders working simultaneously on a print, the manufacturing speed is greatly improved.

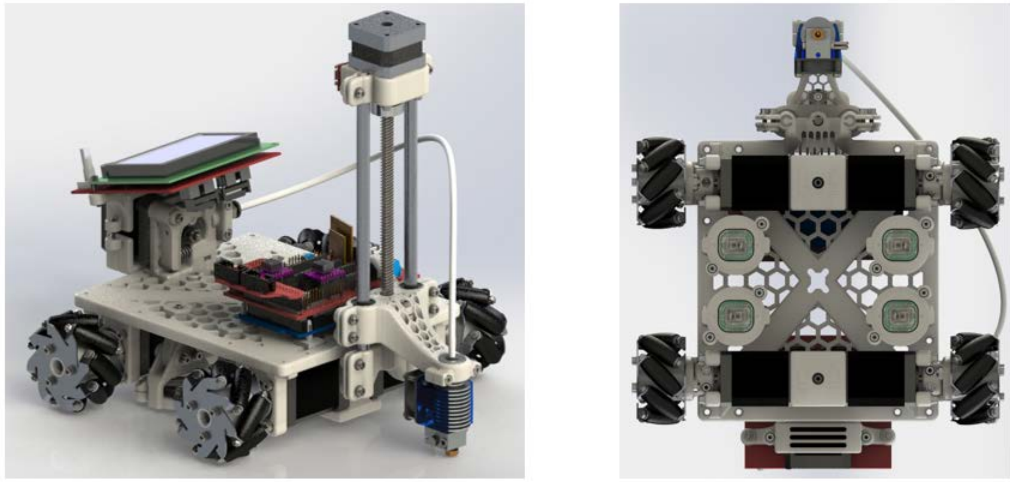
There is a compelling need within the additive manufacturing (AM) community for 3D printers that can incorporate pre-manufactured components during the 3D printing process [7-10]. Incorporation of pre-manufactured components bridges the gap between traditional manufacturing and 3D printing and allows the use of sophisticated parts that cannot currently be made using fused deposition modeling (FDM) or other AM processes, such as circuit boards, semiconductors, and various other electronic elements. Installing these within a 3D printed structure would allow for the autonomous construction of various electromechanical devices, which would enable a wide range of applications. Prior research has reported manually inserting components into a designed cavity within the printed structure [7-9] and embedding various materials or solid conductors for various electrical functionalities [10]. However, no methods have been developed which allow for incorporation of complex components during the printing process without some degree of human intervention.

In our prior research, we developed a mobile 3D printer for cooperative 3D printing. In this paper, we present a mobile robot gripper, utilizing the same motion components and controls as the mobile 3D printer, to expand the capability of the cooperative 3D printing platform. A pick-and-place printhead is designed to replace the FDM printhead, enabling pick-and-placing pre-manufactured components inside a 3D printed structure for assembly. This device utilizes a single degree-of-freedom (DOF) rack and pinion linear actuating mechanism, which is controlled using a custom Arduino firmware (initially designed for operating a mobile 3D printer). The mobile robot gripper is then used to assemble a simple 3D printed case for a commercially available LED name tag, demonstrating its ability to accurately place pre-manufactured components within a 3D printed structure.

The paper is organized as follows. In section 2, the requirements and design of a gripper printhead compatible with the existing mobile 3D printer are established. Section 3 presents geometric considerations of the gripper design, followed by a force analysis and finite element simulation of the gripper assembly in operation. The prototype mobile robot gripper is then assembled and tested by completing a test demonstration. The results of this test are discussed in section 4, along with a presentation of data validating its completion. Conclusions are given in section 5.

2. Design

Our objective is to design a mobile robot gripper that can work cooperatively with mobile 3D printers to pick and place pre-manufactured components during the 3D printing process. Recently, a mobile robot equipped with a FDM printhead has been developed in the AM^3 Lab at the University of Arkansas for cooperative 3D printing, as shown in Fig. 1. Mecanum wheels [11-17] were used to provide omnidirectional motion within the x-y plane. A Z-stage and printhead similar to a regular FDM 3D printer were installed on the mobile platform for 3D printing of plastic filaments.



(a) (b)

Figure 1. A mobile 3D printer: (a) isometric view; (b) bottom view.

In this paper, we will design a “gripper printhead” to fit on the same mobile platform, thus creating a mobile gripper robot. This mobile gripper robot is then used to assemble, and assist in the manufacture of, 3D printed electromechanical devices and components. To achieve this goal, a series of engineering requirements were established prior to beginning the design process:

1. Load: The gripper must be able to grasp objects with masses up to 0.5 kg.
2. Size: The gripper must be capable of grasping objects of various sizes, with one dimension up to 100 mm. This range, in addition to the stated load requirement, encompasses a majority of electrical components, including CPUs, stepper motors, and many circuit boards.
3. Single DOF actuation: The gripper should be actuated using a single stepper motor to ensure that its operation is compatible with existing 3D printer commands.
4. Reliability: The gripper must not allow for movement of the object after it is initially grasped. For example, in a number of recently developed single DOF gripper mechanisms, such as compliant passively adaptive grippers [18, 19] or universal grippers based on the jamming of granular material [20], there is potential for the object to shift within the robot’s grasp. This invalidates the position information previously known to the robot, thus decreasing accuracy of placing the object at the destination (i.e., once the gripper completes its gripping motion, any subsequent movement of the object is unrecorded).
5. Modular design: The gripper printhead must be modularly compatible with the existing mobile 3D printer platform. For this to be accomplished, it must use the same Z-stage assembly to raise and lower the printhead. In addition, the rear-mounted stepper motor should remain installed on the mobile robot gripper. Leaving this motor installed alleviates concerns of the pick and place printhead offsetting the device’s center of gravity, and improves the traction of each mecanum wheel. By using these components, it is possible to easily transform a mobile 3D printer into a mobile gripper robot.

2.1 Gripper Mechanism: Rack and Pinion

Through consideration of each design requirement, a two-fingered gripper which utilizes a rack and pinion linear actuating mechanism is designed. Fig. 2 provides a schematic of the gripper mechanism, and Fig. 3 shows a gripper assembly mounted on the mobile platform. The centrally located pinion actuates each gripper arm in opposite directions, until each gripper pad meets at the middle plane. The pinion is supported by the surface created by each gripper arm, as seen in Fig. 2b. The top and bottom sections of the housing utilize a top-down snap-fit assembly, which further reduces the total number of components and removes the need for any fasteners.

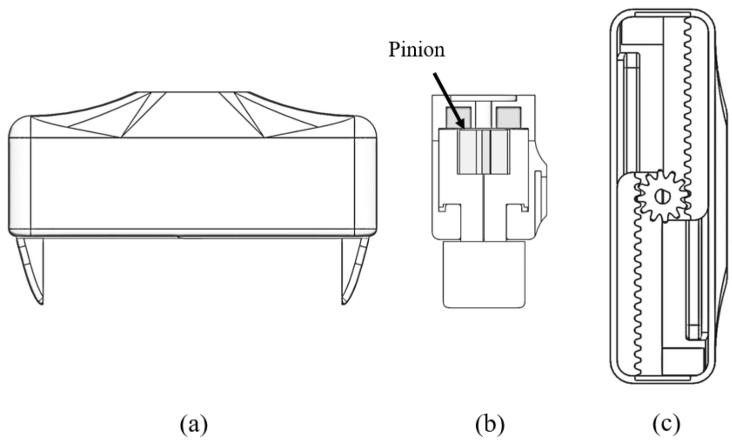


Figure 2. Design of a rack and pinion gripper: (a) front view; (b) cross section; (c) top view.

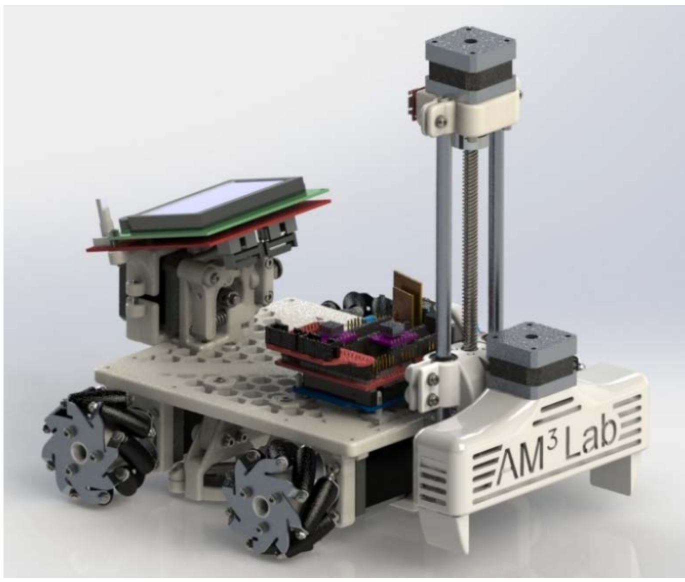


Figure 3. Concept design of a mobile robot gripper.

3. Design Analysis

3.1 Geometric Considerations

When applied to 3D printing, the linear movement of each arm provides a few benefits:

1. Precise gripping location: Because each arm moves only in the horizontal direction, the vertical location of the object being grasped can be accurately known based on the initial conditions, which alleviates vertical positioning error that may be introduced with other gripping mechanisms [18-20]. Also, because the gripper arms always meet in the center, the horizontal position of the object can be obtained from the position of the robot.
2. Weight balancing: The gripper arms always meet coplanar with the robot's center of mass. Meeting in the center ensures that the weight distribution on the robot will not be shifted with different sizes of components that are to be picked up.
3. Self-correction: The flat gripper pads will ensure that the gripping surface of the objects is always normal to the gripper arm surfaces. Slightly inaccurate motions or placement will not affect the positioning accuracy of the object. Fig. 4 provides an example illustrating these features.

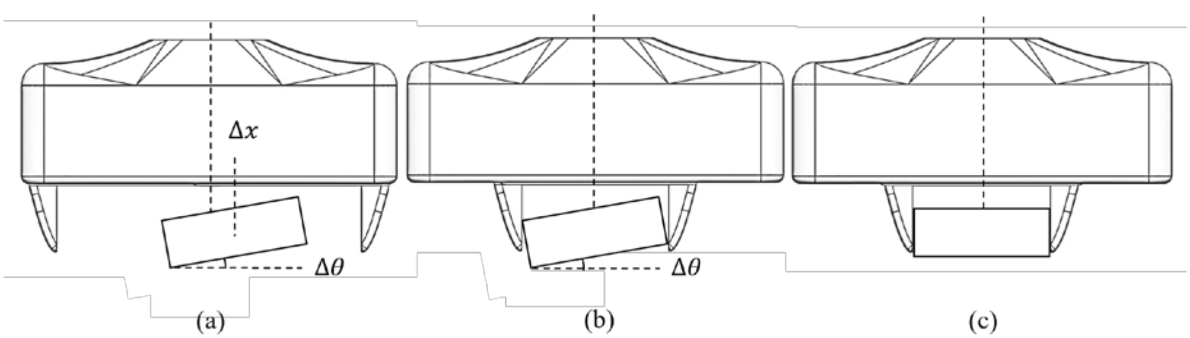


Figure 4. (a) Initial conditions of an object; (b) gripping of the object and self-correction of horizontal displacement error; (c) self-correction of the angular displacement error.

3.2 Stress Analysis and Structural Dimensions

3.2.1 Problem Statement

With the fundamental design of the gripper established, the size of the stepper motor and the pitch diameter of the pinion must be determined. Then, the grip strength and structural integrity and the gripper may be analyzed using finite element analysis (FEA) with the determined input torque and pitch diameter.

3.2.2 Force Analysis

The required input torque and pitch diameter to raise a given object was calculated through a force analysis of the gripper assembly. A free-body diagram of the gripper assembly is provided in Fig. 5, where d is the pinion pitch diameter, W_t is the tangential force applied by the pinion on the gripper arms, T is the input torque, m is the mass of the object, and μ_s is the coefficient of static friction. The following steps solve for the pitch diameter as a function of the input torque, mass of the object, and coefficient of static friction.

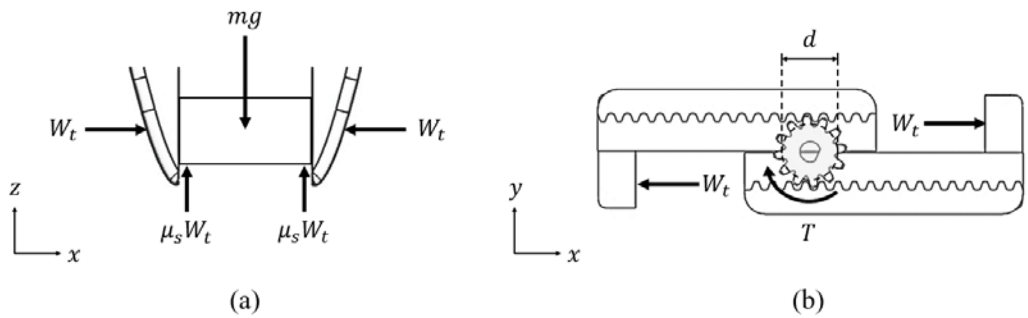


Figure 5. Free-body diagram of the gripper assembly: (a) front view; (b) top view.

Applying static equilibrium to Fig. 5(a) and summing the forces in the z direction, a relationship between the force of gravity on the object, *mg*, and the force applied by the pinion, W_t, is generated. Solved explicitly for W_t, this analysis results in Equation 1:

$$W_t = \frac{mg}{2\mu_s} \tag{1}$$

This force is then related to the applied torque, *T*, through Equation 2, where the torque is doubled due to the pinion driving both gripper arms simultaneously, and *r* is defined as the pitch radius of the pinion:

$$T = 2rW_t = dW_t \tag{2}$$

The pitch diameter required to raise an object of a given mass, input torque, and coefficient of static friction can then be calculated by:

$$d = \frac{2T\mu_s}{mg} \tag{3}$$

3.2.3 Design Parameters and Solution

The motor was chosen to be a 3.5 V, 1 A, NEMA 14 bipolar stepper motor, which has a rated holding torque of 12.5 N*cm. Silicone rubber pads were installed on each gripper arm, which have an approximate static coefficient of friction of 0.6 against a steel counterface [21]. The pinion was then designed as a spur gear with a pressure angle of 20 degrees and a pitch of 20 teeth/in. Finally, an object with a mass of 0.5 kg was chosen to determine the maximum pitch diameter to accomplish the previously established requirements. Equation 3 is now used to solve for the pitch diameter of the pinion.

This analysis yields that the pitch diameter of the pinion is to be 3.058 cm. In order to accommodate for inaccuracies in this estimate, the final pitch diameter is chosen to be 1 cm. Consequently, this decision results in a factor of safety of 3.058 when grasping a 0.5 kg object, which provides a theoretical limit for holding objects up to 1.529 kg. Here it is assumed that no friction occurs between each component of the assembly. This safety factor provides sufficient room to account for the possible friction reduction, the additional forces due to rapid acceleration of the robot, and other disturbances.

3.3 Load Simulation

3.3.1 Parameters and Material Properties

A FEA stress simulation was then performed to evaluate the mechanical integrity of the proposed design by simulating the gripper being used to grasp the largest predicted object. The two z-axis axle bores are set as the zero displacement boundary conditions, and the force exerted by the gripper is applied to the inner face of both gripper arms. A force of 12.5 N force on each arm was chosen to simulate the gripper holding a 1.529 kg object. Each part was 3D printed using ABS plastic, and the material properties used in this simulation are listed in Table 1 [22]. A flat print orientation was used, such that the applied forces are coplanar with the printed layers. The face width of the pinion was increased by a multiple of two from comparable catalog gears, thereby increasing the strength of this critical component.

Table 1: 3D printed ABS material properties printed flat at a [0/90] degree orientation [22].

Poisson's Ratio	0.37 ± 0.04
Young's Modulus (MPa)	2020 ± 60
Yield Strength (MPa)	32.0 ± 0.8
Ultimate Strength (MPa)	33.5 ± 0.5
Shear Modulus (MPa)	770 ± 40
Yield Strength (shear) (MPa)	21.5 ± 2.0
Ultimate Strength (shear) (MPa)	29.1 ± 0.3

3.3.2 Simulation Results

The results of an FEA simulation on the gripper assembly is shown in Fig. 6. Results show that the greatest von Mises stress of 1.46 MPa occurs on the gripper arm, which is significantly less than the yield strength of 3D printed ABS and gives a safety factor of 21.91. In addition, the largest deformation also occurs at the tip of the gripper arms, with a displacement of 0.02687 mm. This displacement is well within the accuracy of regular 3D printers (~100 µm), and is thus considered insignificant.

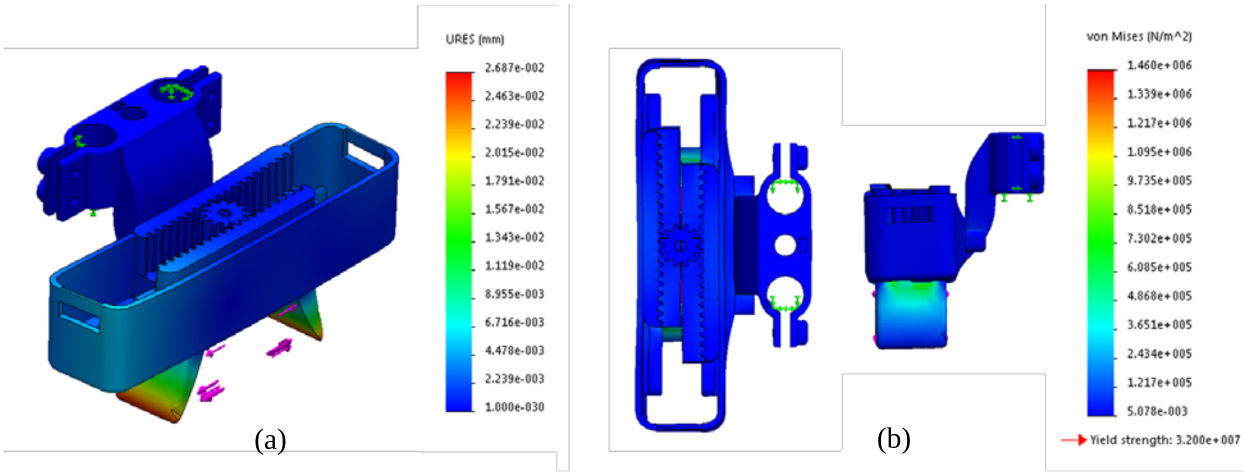


Figure 6. Results of the FEA simulation on gripper mechanism: (a) displacement; (b) von Mises stress.

3. Control

The mobile robot gripper is controlled using G-code commands, similar to a FDM 3D printer. The pick and place printhead is operated in the same way as an extruder, using the linear move "G1 Xnnn Ynnn Znnn Ennn Fnnn Snnn" to accomplish the pick and place operation. Each parameter is defined according to [23]:

- Xnnn The position to move to on the X axis
- Ynnn The position to move to on the Y axis
- Znnn The position to move to on the Z axis
- Ennn The amount to extrude between the starting point and ending point
- Fnnn The feedrate per minute of the move between the starting point and ending point (if supplied)
- Snnn Flag to check if an endstop was hit *(S1 to check, S0 to ignore, S2 see note, default is S0)*

The G1 command may use any combination of these input parameters, and each move will occur simultaneously once the command is sent. If the moves must be sequential, then individual G1 commands may be sent for each move. For example, the command "G1 Xnnn Ynnn" will move the robot simultaneously in both the x and y directions, but not in any order. For controlling the mobile gripper robot, all movements are conducted in relative positioning mode, since the mobile robot does not possess a physical origin from which to base its absolute position. In addition, the Fnnn command may be used to adjust the speed at which the move is completed, which allows for deviation between coarse and fine movements.

The G1 command is translated by the firmware of the robot to move a certain number of steps for each stepper motor corresponding to the distance specified in the G-code command. In our current robot design, this relationship is 34 steps/mm for x-y movement and 2000 steps/mm for z. That is, displacements in x or y are input directly using the "G1 X Y" command, and the robot firmware sends corresponding commands to the four mecanum wheels to move the robot.

Similarly, z-axis movement of the gripper assembly is controlled using the “G1 Z” command, which rotates the vertical threaded rod using the top mounted stepper motor. The Z axis is zeroed by the gripper assembly activating an endstop at the apex of its range of motion. Finally, the gripper arms are modelled as the filament extruder, thus allowing use of the positive and negative “G1 E” commands to open and close the gripper. Since the relation between steps and distance is calibrated for the filament extruder, a further calibration for the gripper motion is necessary.

3.1 Pick Command

In order to include pre-manufactured components within a 3D printed structure, the mobile gripper robot must first be able to accurately pick up an object. Schematics of this task is provided in Fig. 7, where the input parameters are defined by their physical dimensions.

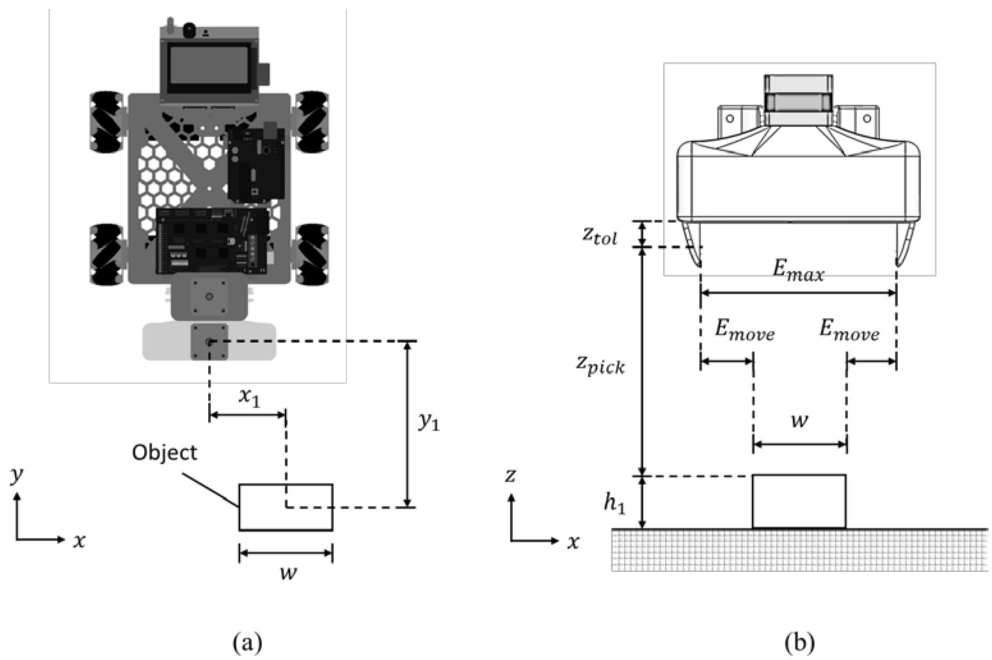


Figure 7. Illustration of the pick command: (a) x-y view; (b) x-z view.

As stated previously, the relationship between input and output is defined within the robot firmware for x, y, and z move commands. However, since the stepper motor controlling the gripper is modelled as an extruder and the extruder has a different driving gear from the gripper, the distance input specified in the G1 command doesn’t move the gripper the specified distance, but a distance linearly proportional to the input distance as shown in Equation 4, where *I* is the input distance in the G1 command, O is the distance of movement of the gripper, and *C* is a proportionality constant.

$$O = CI \tag{4}$$

The value of *C* for motion of the gripper was then calculated by measuring that one gripper arm moves 8.695 cm when assigned an input of 20 cm. This calibration results in a proportionality constant *C* of 0.4348, which will be used in subsequent testing of the device.

In order to pick up an object, the input parameters for the pick command must be obtained. Fig. 7 shows the required movements in the x-y and x-z planes. The X and Y parameters can be obtained based on the location of the object as shown in Fig. 7(a). The Z parameter z_{pick}, is the distance the gripper needs to move in Z direction, which can be calculated by Equation 5.

$$z_{pick} = z_{current} - h_1 - z_{tol} \tag{5}$$

where $z_{current}$ is the current Z position of the gripper, h_1 is the height of the object, and z_{tol} is a safety tolerance. The E parameter determines the distance the gripper arm should move, which must ensure accurate grasp of the object with enough pressure to provide sufficient friction. To do so, the width of the object is used to calculate the movement of the gripper arms, E_{move}, with Equation 4 and Equation 6.

$$E_{move} = \frac{1}{2}(E_{max} - w) \tag{6}$$

With all the parameters known, picking up the object is then controlled using two G1 commands. The first command moves the robot to position the gripper, and the second command simply closes the gripper, thus grasping the object.

1. G1 X1 Y1 Z_{pick} E_{max}; //moving to the picking location while opening the gripper to the max
2. G1 E_{move}; //closing the gripper

3.2 Place Command

For the place command, the robot must raise the object, move to the destination, place the object, and exit. Fig. 8 shows the required movements in the x-y plane and the x-z plane.

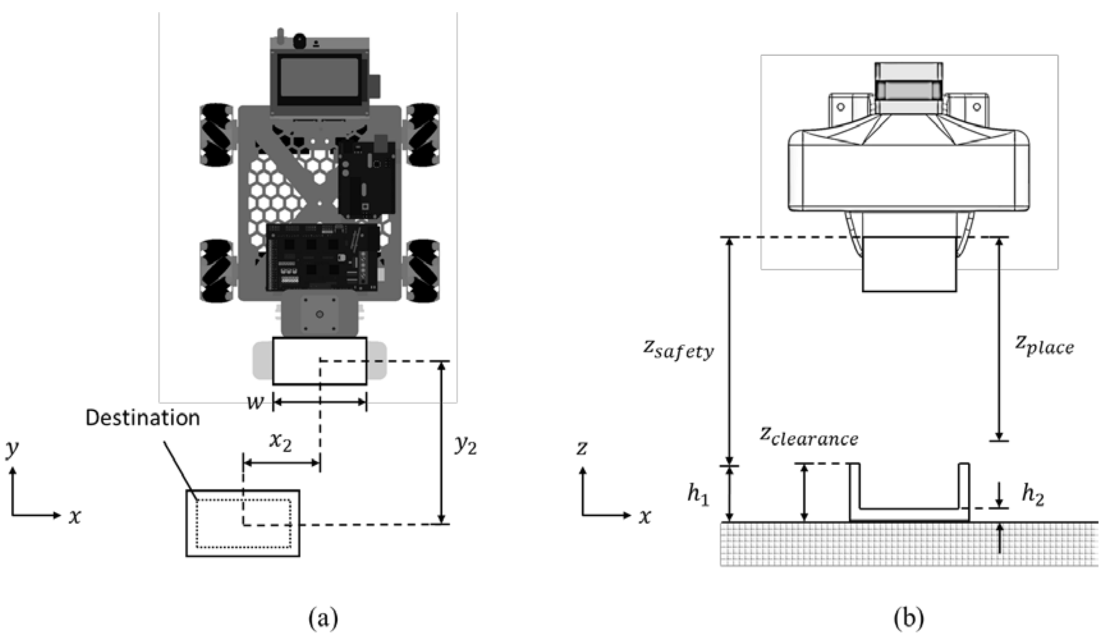


Figure 8. Illustration of the place command: (a) x-y view; (b) x-z view.

In order to avoid a collision during the placement of the object, the gripper first moves to a height above the tallest point between the object and the destination. In this study, z_{safety} is defined to be 2.5 cm higher than this tallest point, and is calculated using Equation 7.

$$z_{safety} = z_{clearance} + 2.5\ cm \tag{7}$$

Then, the robot moves the distances x_2 and y_2 defined in Fig. 8(a), positioning the object above the destination. The gripper is then moved to place the object, and must account for the height of the destination, h_2, by using Equation 8.

$$z_{place} = z_{safety} - h_2 \tag{8}$$

Finally, the object is released, and the gripper robot exits from the assembly. In total, these actions correspond to the following four G-code commands:

1. G1 X2 Y2 Z_{safety}; //move from object to destination while moving object to safety height
2. G1 Z_{place}; //move object from safety height to destination height
3. G1 E_{max}; //release the object
4. G1 X_{home} Y_{home} Z_{home}; //move robot to home positions, defined as the negative sum of each prior movement

4. Results

4.1 Prototyping

The gripper design was manufactured with ABS using an uPrint SE Plus 3D printer, with a 0.01 inch tolerance on each surface experiencing sliding contact. Fig. 9 shows the final prototype of the gripper assembly. Note that two silicone rubber pads have been installed on each gripper arm using an adhesive, and that no fasteners were used in the assembly.

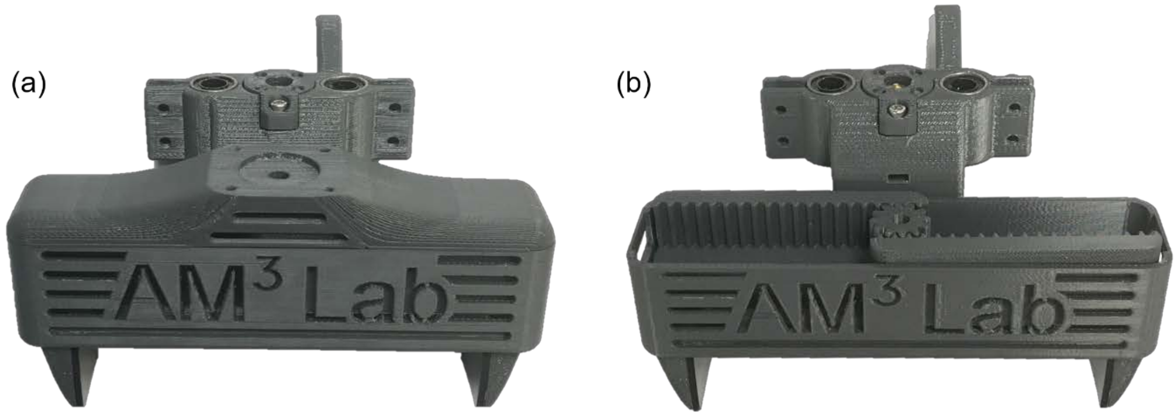


Figure 9. (a) Photo of final gripper prototype assembly; (b) photo of the rack and pinion mechanism installed within the gripper prototype.

The gripper prototype was then mounted onto the mobile robot (Fig. 1). Since the gripper assembly utilizes the same mounting bracket and the same control wiring for the filament extruder, installation was straight-forward and had little room for error. The final prototype of the mobile gripper robot is shown in Fig. 10, where the NEMA 14 stepper motor has been installed on the top of the gripper housing.

Figure 10. Image of final mobile gripper robot prototype.

4.2 Testing

The mobile gripper robot was tested by demonstrating its capability in placing a pre-manufactured LED name tag within a 3D printed case, followed by securing the LED name tag inside the case with a cover. Photos of each component are shown in Fig. 11, and the two steps are schematized in Fig. 12. Each step contains corresponding pick and place commands, and the input parameters of each step are compiled in Table 2.

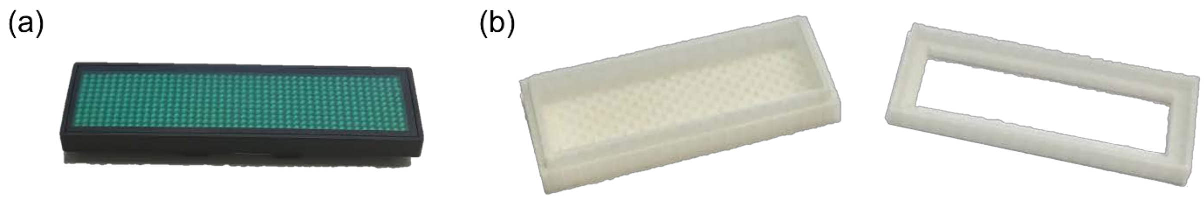


Figure 11. Image of the (a) LED name tag and (b) case to be assembled.

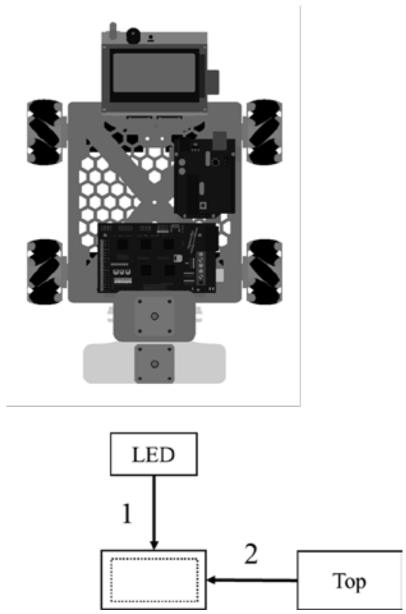


Figure 12. Diagram of the initial conditions of the test case.

Table 2: Input parameters for the test case.

	Step 1: Pick and Place LED		**Step 2: Pick and Place Cover**	
	Parameter	**Value**	**Parameter**	**Value**
Pick Command	x_1	0	x_1	200 mm
	y_1	0	y_1	0
	w	70 mm	w	90 mm
	E_{move}	15 mm	E_{move}	5 mm

	z_{pick}	95 mm	z_{pick}	40 mm
	h_1	12 mm	h_1	15 mm
Place Command	x_2	0	x_2	-200 mm
	y_2	300 mm	y_2	0
	z_{safety}	40 mm	z_{safety}	40 mm
	h_2	5 mm	h_2	15 mm
	z_{place}	35 mm	z_{place}	25 mm

The test was carried out by setting each component on a flat wooden surface in the orientation depicted in Fig. 12. The rubber mecanum wheels adhere well to this surface, thereby minimizing the chance for slipping to occur. The test case was run successfully, and a series of snapshots outlining this experiment are provided in Fig. 13, followed by the finished product shown in Fig. 14.

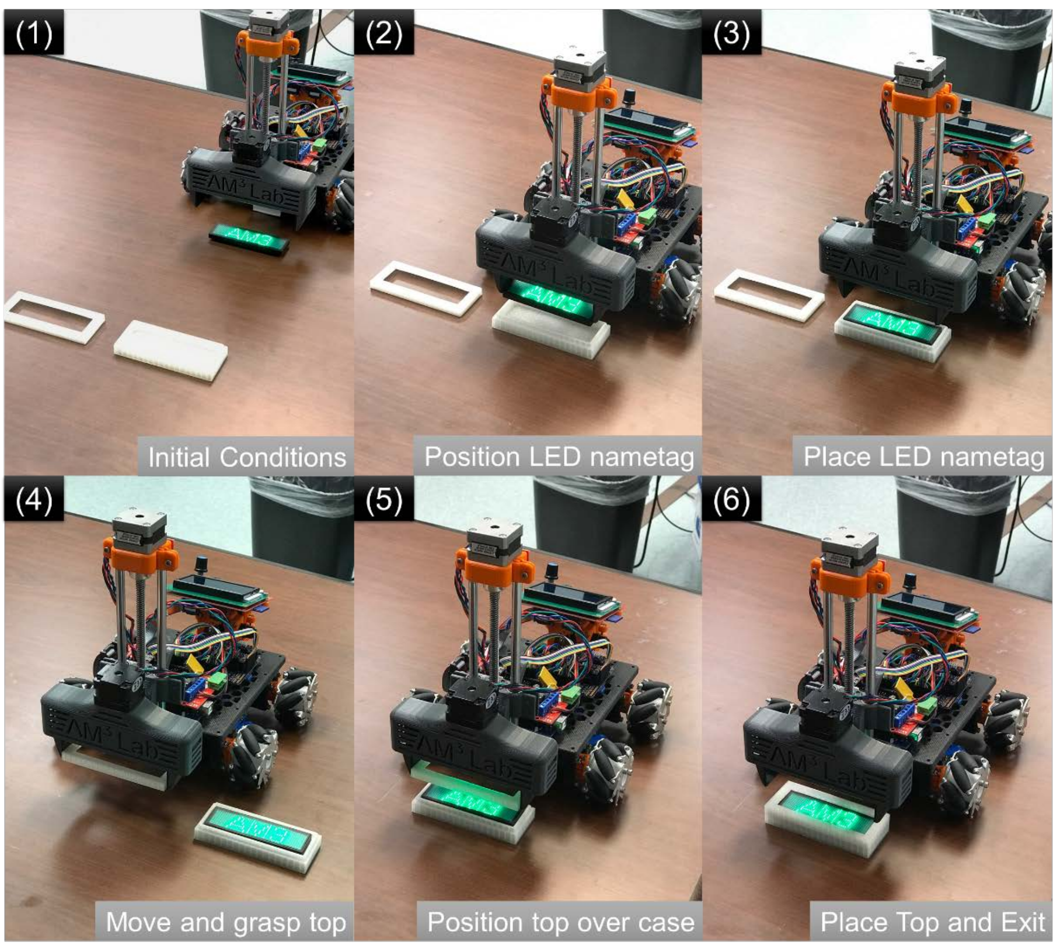


Figure 13. Mobile gripper robot placing an LED name tag into a 3D printed case, followed by assembling the case with the LED name tag inside. Each snapshot follows chronologically from the previous.

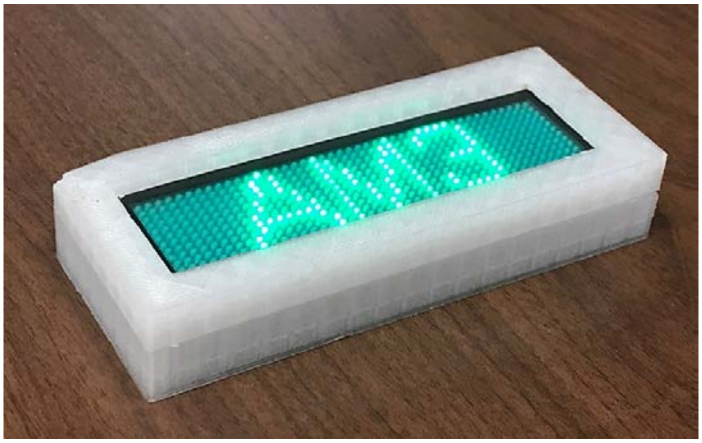


Figure 14. Assembled LED name tag and case.

During the assembly process, the mobile robot gripper was characterized for its electromechanical performance by plotting the current drawn as a function of time, as shown in Fig. 15. Each movement coincides with a shift in the current delivered to the entire robot, representing when the stepper motor responsible for each movement was activated. This analysis validates that each action was completed as illustrated in Fig. 13, in addition to demonstrating the rate at which each move was completed. It was observed that the mobile robot gripper draws ~1.40 A when no motors are running (i.e., standby), and the current jumps to ~1.91 A when the z-axis stepper motor is activated. In the same fashion, the current drawn increases to ~2.55 A when the gripper is actuated, and to ~2.60 A for any x-y movement. Since the voltage is held constant at 12 V, the current is directly proportional to the power consumed by the robot. Overall, the test took 47.5 s, measured as the time between the two standby regions.

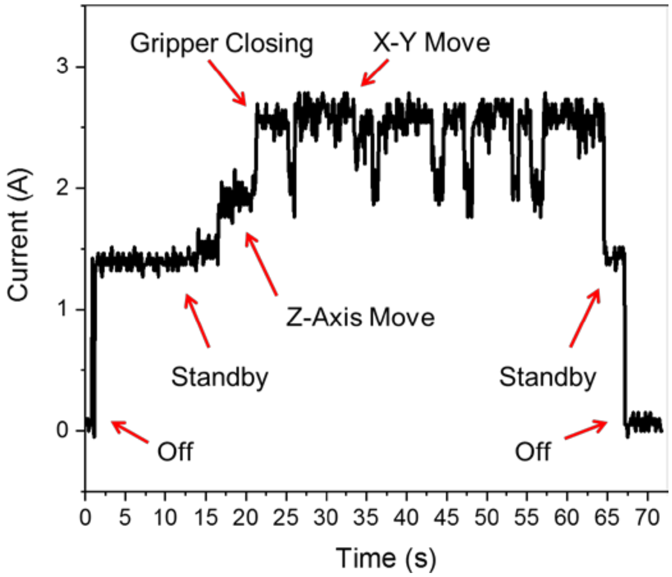


Figure 15. Plot of the current drawn as a function of time for the gripper picking up and placing the LED name tag and assembling the case.

It is clear that by using a mobile robot gripper, incorporation of pre-manufactured components within a 3D printed structure is possible. This leaves the opportunity to employ the mobile robot gripper in tandem with cooperative mobile 3D printers. Doing so would allow autonomous manufacturing of sophisticated products, not previously possible with FDM alone. For example, the case assembled here may be printed alongside the mobile robot gripper, such that one printer prints the bottom, the gripper places the LED name tag, and another printer finishes the top of the case. This would result in a 'unibody' 3D printed case around the LED screen, without requiring intermittent human assembly.

5. Conclusions

This paper was set out to provide a method for incorporating pre-manufactured components within a 3D printed structure using cooperative 3D printing. First, an existing omnidirectional mobile 3D printer was adapted into a mobile robot gripper, inheriting its advantage of an arbitrary x-y build envelope. A number of requirements were established for a gripper compatible with cooperative 3D printing, and a gripper with a linear rack and pinion actuating mechanism is designed. This design was then evaluated through a force analysis and FEA simulation. Next, the control mechanism for the mobile robot gripper was established by using G-code commands and modeling the gripper as a filament extruder. The gripper prototype was tested by demonstrating the assembly of an LED nametag and case, and by measuring current consumption throughout the assembly process. It was shown that by using the mobile robot gripper, the placement of pre-manufactured components within a 3D printed structure is possible, in addition to assembling a part with multiple components. The significance of this design lies in its potential to be implemented with cooperative 3D printing, which aims to solve a number of the current issues of 3D printing (e.g., size constraints, build speed, and using pre-manufactured components). Cooperative 3D printing with the mobile robot gripper would allow the autonomous manufacture of 3D printed electromechanical devices, using components not currently possible with 3D printing alone (e.g., semiconductors, motors, batteries). Therefore, the mobile robot gripper presented here may now be used in the future development of cooperative 3D printing, and thus holds the promise of advancing 3D printing as a competitive digital manufacturing method.

6. Acknowledgements

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7. References

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