A Project Based Learning Study Through Student Design of a Low-cost, Open Source, Easy-to-use, and Easy-to-build Ventilator

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ABSTRACT

This work presents a project based learning (PBL) study, through student design and fabrication of a low-cost, open source, easy-to-build, and easy-to-use bag valve mask (BVM) ventilator, to potentially serve COVID-19 patients during the incubation period. A new learning outcomes framework, i.e., Profiles of Learning for Undergraduate Success, was adopted as the pedagogical model, with a focus on problem solver and innovator. Using the reciprocating motion system, the ventilator is capable to provide an air supply with adjustable breath frequencies. 3D printing is used to fabricate customized components. In parallel to the mechanical assembly of the ventilator, a CAD model was developed to understand the motion mechanisms in the ventilator, which can further help optimize the system. The design files are available at GitHub for open access. The project is to serve as a backup to handle any surge of patients who may need breathing assistance in hospitals across the nation. The feedback from the participating students is very positive. The success of this PBL based project using the profiles of learning for undergraduate success shows its promise and it can be extended to other student learning experiences.

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1. Introduction

Project-based learning (PBL) has been used as a student-centered pedagogy that allows students to learn knowledge through solving real-world problems. Ref. [1] provides a review of PBL in terms of a quasi-experimental pretest-posttest design with some baseline equivalence established, to link between PBL instruction and positive student outcomes. Ref. [2] shows a study of using PBL for the application of research methodology skills for better learning, by encouraging an all-inclusive approach in teaching and learning rather than an individualized tailored approach. In Ref. [3], A PBL study was carried out for the dentistry students. PBL was spread over five days. Pre- and post-test questions along with different questionnaires were designed for the students.

In this work, we apply the PBL approach for a group of undergraduate students to research design and developing a mechanical ventilator, in response to the Covid-19 pandemic. A ventilator is a device that assists or replaces spontaneous breathing. Conventional commercial intensive care unit (ICU)-grade ventilators are designed and equipped with different modes of ventilation that can help to supply higher concentrations of O_2 than that delivered by a mask or other devices, and CO_2 can be expelled from the lungs. It also provides positive end-expiratory pressure (PEEP) to hold alveolar open preventing them from collapse at the end of expiration [4]. With earlier peaks of the pandemic, many hospitals ran out of ventilators, and many companies stopped their normal production and diverted their resources. The resource diversion has still led to low availability. Mechanical ventilation is important to ensure patients' condition improves enough for them to breathe on their own, therefore our mechanical ventilation design can help in these critical situations.

In this work, the ProtoVent was developed as a low-cost, open source, easy-to-build, and easy-to-use ventilator to serve COVID-19 patients during the incubation period. Specifically, the goals of the ProtoVent are: (1) minimize cost and difficulty of setting up by utilizing ready-made items, and (2) increase performance of the mechanical ventilator by equipping it with a controller. Current commercial ventilators are typically large and relatively heavy [5]. In comparison, the ProtoVent was designed to fit in small spaces of already crowded hospital rooms, light, and easy to operate to help patients faced with breathing difficulties during their incubation period. The result is an inexpensive, 3D-printable, open source mechanical ventilator that can vary in speed, assist patients with breathing difficulties, and serve as a backup to handle any surge of patients in hospitals across the world.

2. Profiles of learning for undergraduate success

In this project, we adopt a new pedagogical model, i.e., Profiles of Learning for Undergraduate Success, developed by the university in 2019 [6]. It is designed to equip all undergraduate students with the key skills and abilities they need to succeed in the workplace and become significant contributors to their communities. The skills and abilities are grouped under four characteristics: communicator, problem solver, innovator, and community contributor [6].

The Profiles of Learning for Undergraduate Success was designed with the idea of providing a foundation as students progress through the academic programs, choose out-of-class experiences, and prepare for the student future. The Profiles will offer the students a unique education that incorporates campus values such as engaged learning, civic engagement, diversity, global learning, and other initiatives for which the campus is nationally recognized, including innovation, service learning, and civic engagement. It will also give the students the opportunities to develop knowledge and skills that positively impact the students' engagement and well-being throughout their future careers. Additionally, it will enhance the students learning both inside and outside of the classroom as well as through internships, student employment, research, study abroad, club leadership, theatre and performance, community-based projects, and many other opportunities on and near campus. Finally, it will prepare the students with the knowledge and skills that employers seek when recruiting future employees, not just for the student's first job, but for the student's entire career [6].

2.1 Communicator

Communicators convey their ideas effectively and ethically in oral, written, and visual forms across multiple settings, using face-to-face and mediated channels. Communicators are mindful of themselves and others, observe, read thoughtfully, listen actively, ask questions, create messages with an awareness of diverse audiences, and collaborate with others and across cultures to build relationships [6].

2.2 Problem solver

Problem solvers work individually and with others to collect, analyze, evaluate, and synthesize information to implement innovative solutions to challenging local and global problems [6].

2.3 Innovator

Innovators build on experiences and disciplinary expertise to approach new situations and circumstances in original ways, are willing to take risks with ideas, and pose solutions. Innovators are original in their thoughts and ask others to view a situation or practice in a new way. Innovators are good decision makers, can create a plan to achieve their goals, and can carry out that plan to its completion. Innovators use their knowledge and skills to address complex problems to make a difference in the civic life of communities and to address the world's most pressing and enduring issues [6].

2.4 Community Contributor

Community contributors are active and valued on the campus and in communities locally and globally. They are personally responsible, self-aware, civically engaged, and look outward to understand the needs of society and their environment. They are socially responsible, ethically oriented, and actively engaged in the work of building strong and inclusive communities, both local and global [6].

Each Profile will provide students with various opportunities to deepen disciplinary understanding, participate in engaged learning, and refine what it means to be a well-rounded, well-educated person prepared for lifelong learning and success [6].

In this project, the assessment objective is to understand how students are satisfied with the above four elements.

3. Design and fabrication of the ventilator

The ProtoVent combines design elements from existing DC motor actuator systems into an easily printed, assembled, and installed device. Specifically, it is lightweight, a single controller is driven, capable of volume adjustment, inexpensive, open source, and designed for ease of fabrication, installation, and operation by the average user. The ProtoVent consists of 3D printed components and stored bought hardware. The ProtoVent consists of four main parts, i.e., reciprocating motion system, bag valve mask, base components, and auxiliary components, as detailed below.

3.1. Reciprocating motion system

Automating the ventilator so that continual operator intervention is not needed for safe, the desired operation, the ventilator required the following three components: A source of input energy to drive the device; a means of converting input energy into output energy in the form of pressure, and flow to regulate the timing and size of breaths; and a means of monitoring the output performance of the device and the condition of the patient.

The reciprocating motion system consists of a small 12V 5A linear actuator with a DC gear motor (Figure 1), a controller (Figure 2), and a power supply unit (Figure 3). The controller is used to actuate the mechanism that will push a soft pad onto the self-inflating bag. Using the reciprocating motion system, the ventilator is capable to provide an air supply with adjustable breath frequencies.

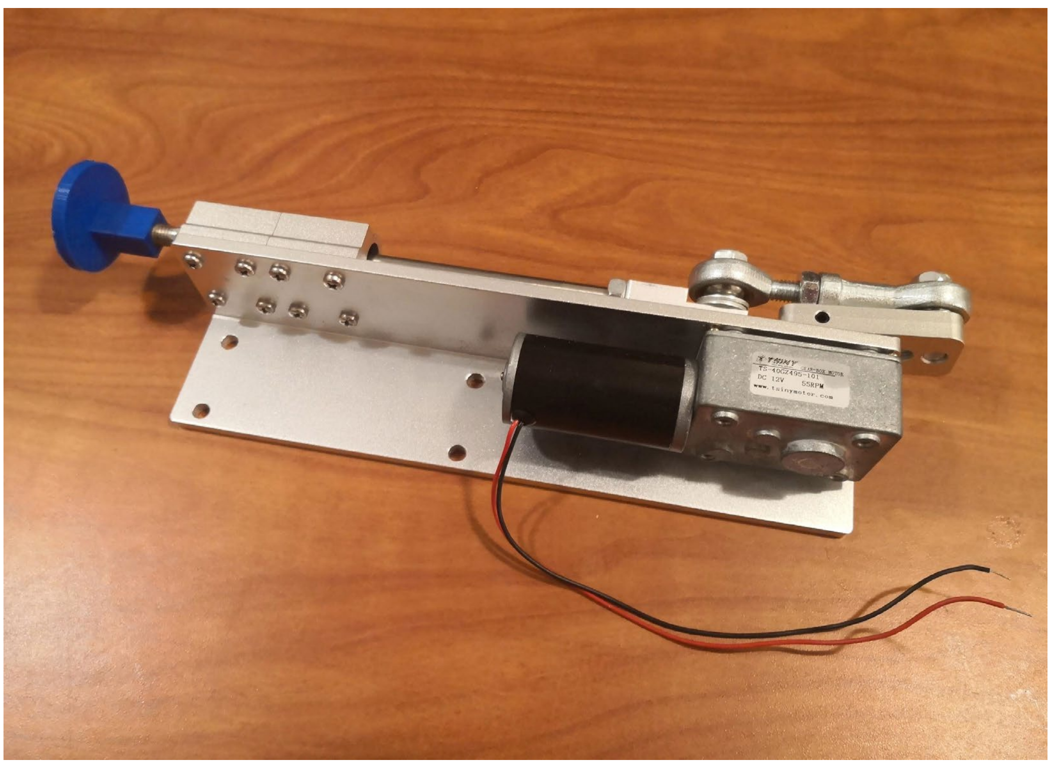


Figure 1: Linear actuator with DC Gear Motor and soft 3D printed pad (blue color)

Figure 2: Controller

Figure 3: Power supply unit

3.2. Bag valve mask (BVM) with a self-inflating bag

The bag valve mask (BVM) with the self-inflating bag for the ProtoVent is shown in Figure 4. It is a Ventlab V-Care Small Adult Resuscitator VN 5000 series. The volume of the bag is 1500 mL and its tidal volume is 1500 mL. The prototype was built to accommodate different sizes of bags for adults, children, and infants.

Figure 4: Bag valve mask with a self-inflating bag

3.3. Base components

The base frame (Figure 5) used to support the DC motor system was made of a ½ × 2 × 4 birch hardwood. The bag support was made of a 3D printed part with PLA plastic.

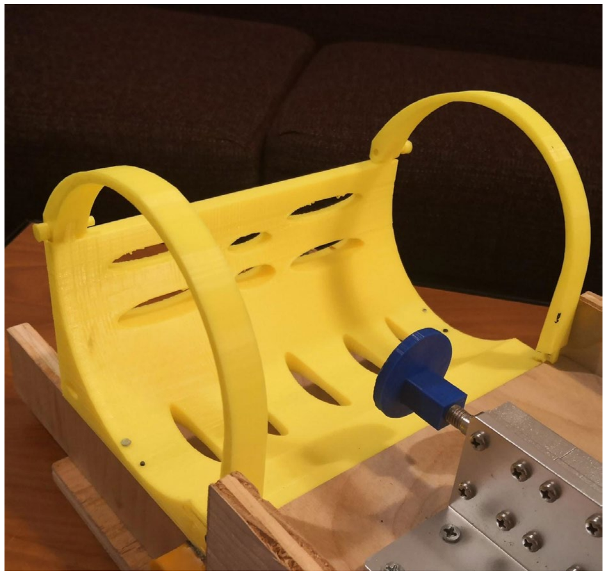


Figure 5: Bag support with 3D printed curved locks (yellow color)

3.4. Auxiliary components

Several essential components were 3D printed to help support the base and improve functionality. First, there is a soft pad used at the tip of the actuator to softly hit the bag (Figure 6). Second, two side adjustable locks were placed on the sides of the frame (Figure 7). Their purpose is to allow the bag support to be adjusted closer or away from the base hardwood support.

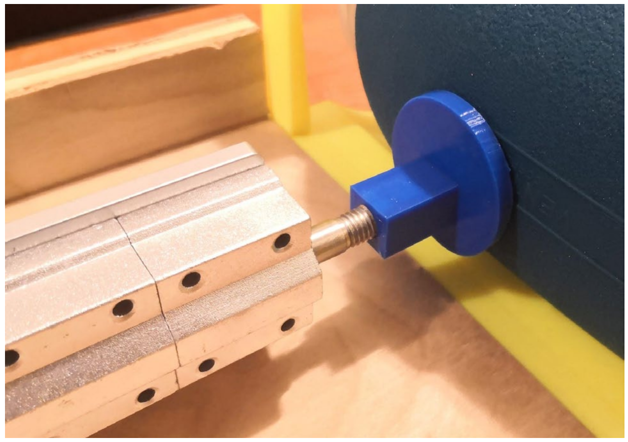


Figure 6: 3D printed soft pad (blue color)

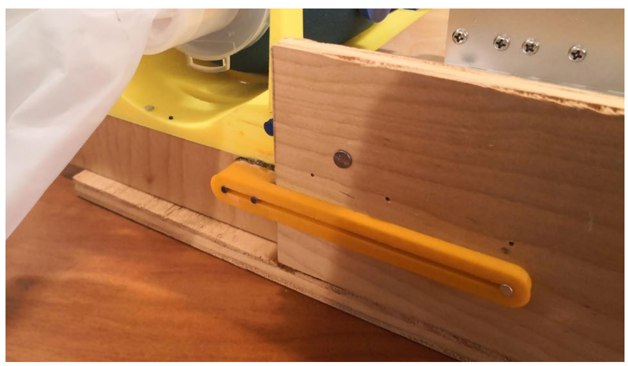


Figure 7: Side adjustable lock (orange color)

4. CAD model of the ventilator design

In parallel to the actual ventilator, a CAD model is developed to understand the motion in the ventilator. The model is capable to simulate the reciprocating motion observed in the actual system. Figure 8 shows the complete CAD model of the ventilator model using SolidWorks.

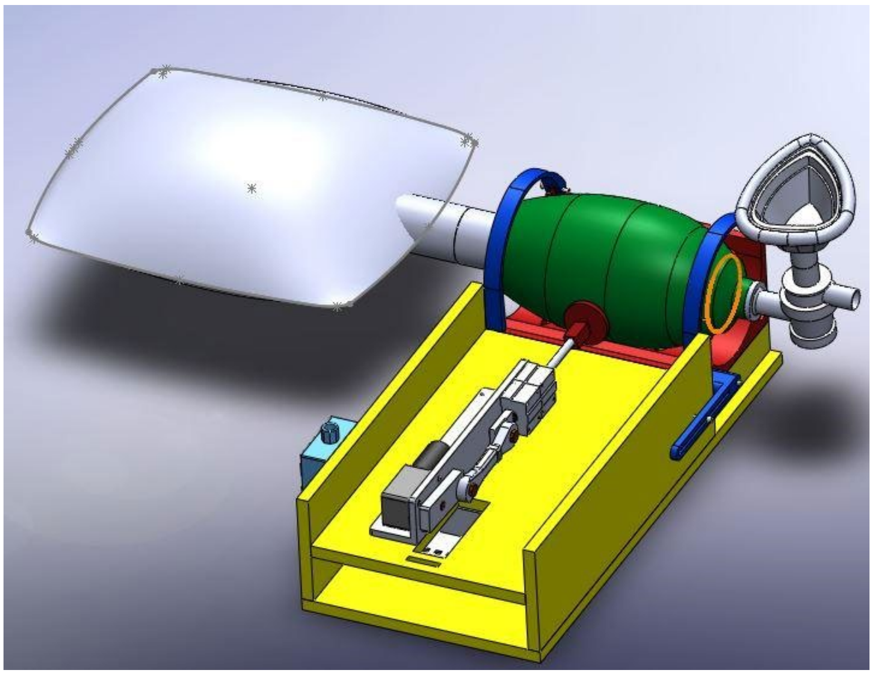
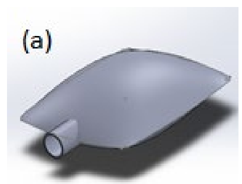
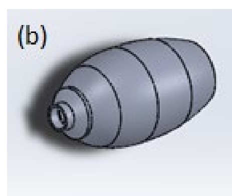
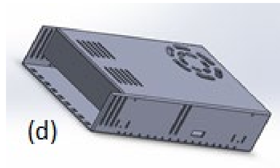
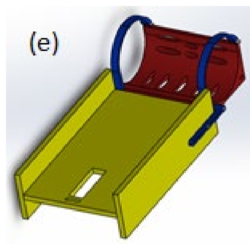
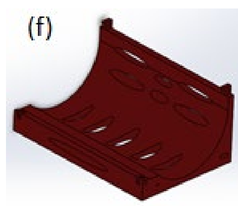
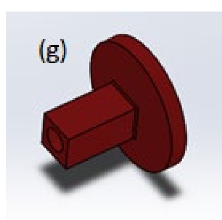


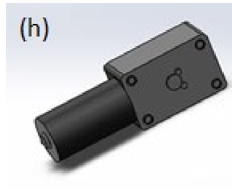
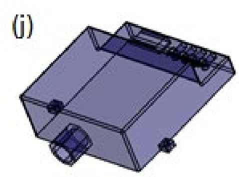
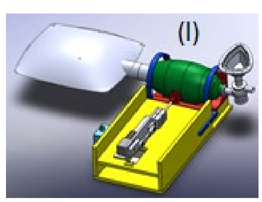
Figure 8: CAD model of the ventilator model

For this open source project, all the design files including those used for 3D printing can be found at GitHub site. Table 1 below contains a summary of the main design files obtained with SolidWorks.

Table 1: Design files summary

Design file name and description	Figures	Location of the file (removed for blinded review)
Freeform_revised.SLDPRT Reservoir bag		
bag_revised.SLDPRT Self-inflating bag		
mask_revised.SLDPRT Face mask		

MURI_ASSEMBLY1.SLDASM* Power supply unit		
Base assembly.SLDASM* Base and support		
bag_support.SLDPRT Bag support		
soft pad.sldprt Soft pad		

DC_motor.sldprt DC motor		
Part6.sldprt Curved lock		
Controller.SLDPRT Controller		
Part7.sldprt Side adjustable lock		
Ventilator assembly.SLDASM* Entire ventilator assembly		

*Additional files are needed to run the assembly file (see GitHub link)

5. Bill of materials

Typical commercial level mechanical ventilators cost between $10,000 and $200,000 each. Some of the least expensive units can be obtained between $500 and $50,000. There are currently open source projects that aim to offer affordable ventilators such as ventilators made by the University of Minnesota, and Rice University. The University of Minnesota designed a low-cost ventilator for $150, obtained the FDA approval, and will sell it for approximately $1,000 per device [7]. Also, Rice University designed a low-cost ventilator for $300, in what was a reasonable amount, and the goal for Rice University's ventilator would be to be affordable enough to low-income regions. Rice University is still waiting for the FDA approval, and the selling price has not been determined yet [8].

To address the issue of cost and to make an efficient, easy-to-build ventilator system available to health care facilities, our ProtoVent prototype is about a total cost of material of less than $200. The bill of materials in our design is given in Table 2.

The reason for the low cost was because of a combination of 3D printed elements and market available supplies. Additional upgrade components to optimize the system such as an embedded control system, interface screen, a variable speed, different structural material (such as plastic) will increase the cost beyond $300.

Table 2: Bill of materials

No.	Name	Price ($)	Quantity	Total ($)	Source
1	DC Motor power supply	16	1	16	Online purchase
2	Motor Controller	24	1	24	Online purchase
3	DC Motor with reducer	14	1	14	Online purchase
4	Airbags and accessories	24	2	48	Online purchase
5	Birch hardwood	12	1	12	Hardware store
6	Plastic	NA	NA	<$20	3D printed

7	Glue, Screw, etc...	NA	NA	<$20	Hardware store

6. Building of the ventilator

The general assembly instructions of the ventilator are provided in this section. Tools or equipment required for assembly includes a hand or circular saw, sets of screwdrivers, sets of screws and nails, drill and bits, and access to a plastic 3D printer.

The ventilator is positioned in a horizontal dimension and below are steps/instructions on how this ventilator was mounted. Before going into the setup stage, it needs to be stated that the team tried to make this ventilator a convertible system, i.e., a ventilator that can be positioned in a horizontal or vertical orientation. This could not fully be achieved because the material used for the base of the ventilator is not strong enough to support the weight of the motor. Nevertheless, if a stronger material is used then it will be possible to convert this ventilator to accommodate for both positions. This is the reasoning behind having a square cut closer to the edge (see Figure 9 below). The idea of having variability is to accommodate space or unique position choices in a hospital room. Below are the steps for mounting/setting this ventilator up.

1. Measuring and cutting the wooden base to accommodate all the motion of the crankshaft. A second cut was made closer to the edge to mount the ventilator in a vertical position using a hook attached to the wall.
2. Insert the nuts and drilling holes to hold all the parts to the wooden base as shown in Figure 9
3. Designing and 3D printing the ventilator bag base, with all the support tools that go with it.

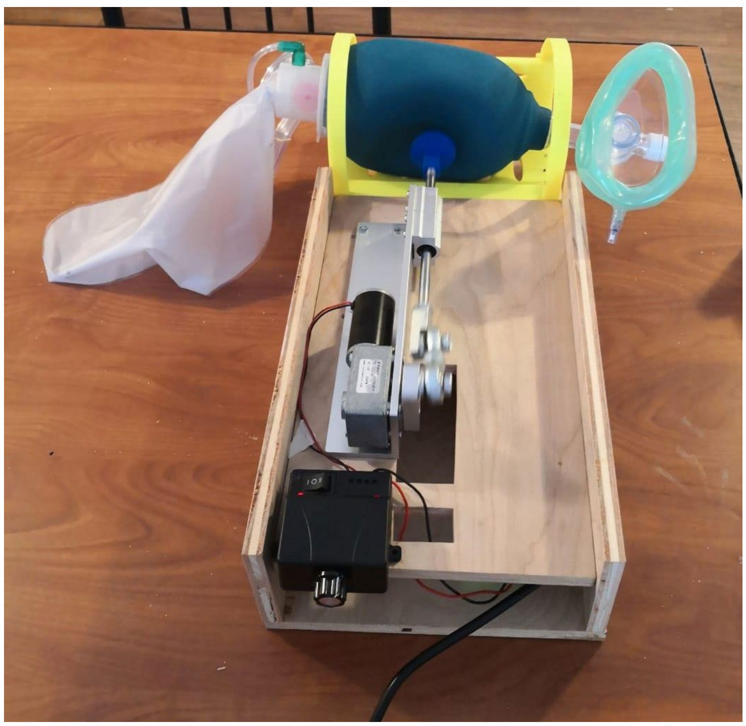


Figure 9: Assembled ProtoVent ventilator with the mounting base

7. Operation of the ventilator

The main operation instructions are as follows: (i) connect the power supply plug to a power outlet, (ii) turn on the controller, (iii) set desirable speed to the desired rate depending on the medical factor of the patient, and (iv) monitor and regulate the ventilator as development occurs. With the controller, the ventilator is capable to provide a desirable air supply.

8. Operational testing

The four steps of the reciprocating motion applied to the bag in the ProtoVent are shown in Figure 10. The speed of the DC motor is controlled using the attached controller. The speed was set at a medium rate (180° nob rotation) and the DC motor will rotate 360° before pushing the bag. It shows that the ProtoVent has successfully applied pressure on the bag.

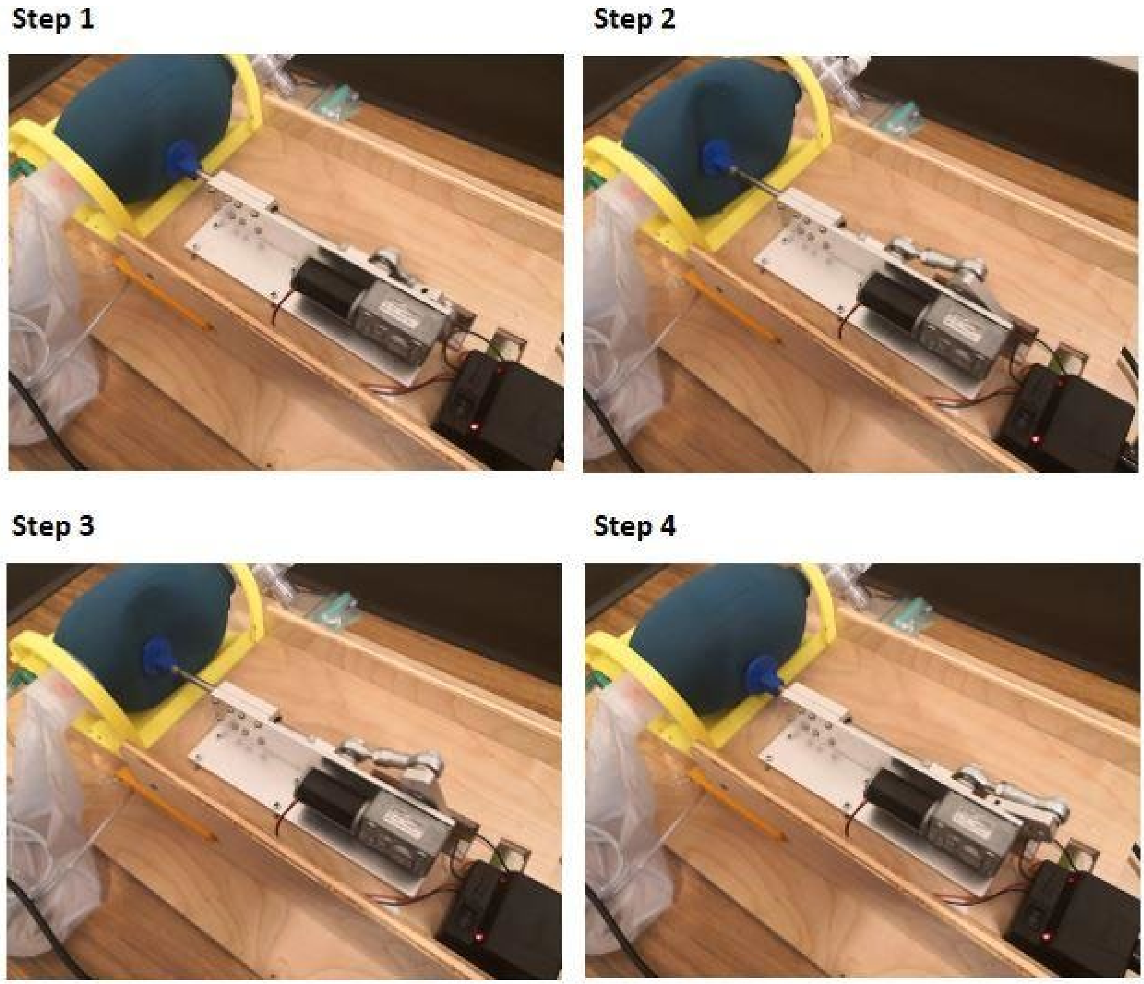


Figure 10: Four steps of the reciprocating motion applied on the bag

9. Feedbacks from participating students based on profiles of learning

In general, the students' feedbacks are very positive. Below are a few examples from the participating students based on the selected Profiles of Learning elements.

Student #1: Problem Solver: "All through the entire process of this research we used critical thinking skills to solve the problems that we encounter. We constantly collaborating with one another to any issue that arise". Innovator: "All through this project we constantly overcome any challenges across our path, because of our passion and dedication we make sure get to the root of the problem and provide adequate solution to it, and that is the key to our success in this project."

Student #2: Problem Solver: "We utilized critical thinking skills to solve the problems faced along the way. Collaborating with others helped to generate creative solutions to tackle challenges when working on our ventilator project." Innovator: "I proposed some interesting design ideas to suit the requirements set by our mentor, and the solutions proposed were implemented in our project."

Student #3: Problem Solver: "Throughout the entire process we were using our critical thinking skills to solve the problems we faced along the way. We were constantly collaborating with one another to achieve solutions, and we preserved when the challenges kept coming with the initial design intent". Innovator: "I was constantly overcoming challenges sent our way and investigating when problems arise in order to find the root cause."

In this project, the assessment objective is to understand how students are satisfied with the above four elements. Given the feedback from the participating students, the two of the four Profiles of Learning elements [6], i.e., Problem Solver and Innovator, were 100% strongly agreed by all the participating students.

Ideally, more quantitative data analysis will be better to draw comprehensive conclusions. Due to time constraint, we won't be able to achieve it this time, but will definitely be included in future work.

10. Conclusions and future improvements

In this study, a low-cost, open source, easy-to-use, and easy-to-build ventilator has been successfully demonstrated by a group of students through the PBL approach with the pedagogical model - profiles of learning for undergraduate success. The major conclusions are summarized as follows:

1. Using the reciprocating motion system, the ventilator is capable to provide an air supply with adjustable breath frequencies.
2. All the open source design files including those used for 3D printing can be found at GitHub site.
3. Using 3D printing, customized components can be produced and used in the ventilator
4. A CAD model is developed to understand the motion in the ventilator. The model is capable to simulate the reciprocating motion observed in the actual system.
5. The cost of the ProtoVent ventilator is less than $200, making it affordable to most users.
6. The feedback from the participating students is very positive. The success of this PBL based project using the profiles of learning for undergraduate success shows its promise and it can be extended to other student learning experiences.

Although the successful demonstration of the ProtoVent's functionality, it is noted that it can only provide mandatory breathing with breathing rate control managed on a time-based frequency. This may be uncomfortable for patients who only need partial assistance breathing and can lead to side effects such as inflammation and barotrauma [9]. Complex breathing patterns will need variable pressure and volume control. Further studies on the project for a complete ventilator may focus on (i) testing the physical prototype for ranges of volumes, pressures, and breathing rates, (ii) developing a solid physical and computer control system to handle complex breathing conditions and side effects that basic bag squeezing cannot achieve, and (iii) collecting additional assessment data regarding students' learning experience. The student feedbacks were included in Section 9. We were not able to conduct a quantitative data analysis due to time constraints. We have added the data analysis in future work.

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