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Development of 3D Printable Part Library for Easy to Manufacture Components for Educational and Competitive Robotics

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Abstract

Educational and competitive robotics enable hands on learning and experimentation. Despite cost effective and ease of access of open source micro-controllers, drives and sensors, the structural components and brackets continue to be very expensive. Motivated by the Robotics for Everyone initiative, we are developing many easy-to-manufacture parts that will allow learners to easily 3D print parts for (1) Structural assembly of robot chassis (2) Sensor mounting (3) Electronic control mounting (4) Power supply (5) Various power drives. The ecosystem of the robotic components is developed around extrusion structures and tubular elements and 3D printing is used for building the parts for testing and qualifying. Fixtures for mounting cameras for advanced machine learning and computer vision experiments are provided.

Introduction

Contextual understanding, aided by relevant examples and extensive hands-on experimentation, plays a crucial role in comprehending intricate concepts within subjects like science and math [1-4]. Educational Robotics, is one of the versatile platforms that connects classroom learning with real-life systems. It provides unique ability to verify and validate ideas through experimentation. Ardito et al. and Sana et al. [5,6] reported successful utilization of robots as educational tools in teaching intricate concepts in geometry, including ratios, estimation, and geometry. Their studies also highlight the practical relevance of incorporating robots in classroom learning. Amico, Guastell, and Chella [7], claim that the integration of robots in learning experiences leads to improved comprehension of concepts and increased student engagement across different physics topics. Robots possess unique characteristics that set them apart from other machines, including multifunctionality, reconfigurability, and re-programmability [8]. For both learners and educators, reconfigurable equipment such as hobby and learning-grade robots have become a popular medium for learning and experimentation. Designing, constructing, and operating robots, therefore, require a diverse range of skills. Various aspects of robotics serve as instruments for conducting experiments in logical thinking, programming, and the principles of math and physics such as (but not limited to):

1. Robot navigation: Investigating the impact of acceleration, deceleration, velocity, and displacement relationships to achieve accurate and time-effective motion of a robot between two points in a 2D or 3D environment.
2. Wheelbase correlation: Exploring the relationship between wheelbase, motor rotation, mobile robot wheel diameter, and the total distance covered while steering around obstacles.
3. Lever systems and kinematics: Understanding the application of levers, gears, kinematic chains, and simple machines to control torque and force when lifting objects with a robot arm.
4. Load distribution and center of gravity: Examining the principle of load distribution and the concept of the center of gravity when a robot traverses inclines and declines.

The rising prominence of educational and competitive robotics has served as a catalyst in the growth of multiple commercial kits such as LEGO, VEX, REV etc. However, it is common for proprietary commercial robotics kits to cost several hundred dollars each. This poses a significant barrier for students from impoverished regions who lack the necessary resources to establish and finance a team. Additionally, should a user wish to expand learning by expanding the scope of experiments and learning, related challenge is the dependency on specific manufacturers for computational platforms, actuation hardware (such as DC motors and servo motors), and structural components.

Competitive robotics is another avenue where many educational institutions and community teams come together to participate and learn. Most of the competitions such as FIRST, VEX, WRO etc. are based on a prescribed kit provided by specific supplier. In addition to the robotic kit, the competitions require a robotics field that changes every season. Another challenge in competitive robotics is the need for exorbitantly priced field setup kits. Across various seasons and challenges such as FIRST, VEX, and similar events, the core task for robots typically revolves around picking and placing objects, often involving stacking or launching. Given the similarity of these fundamental tasks, it would be possible to reuse and reconfigure the same field elements, significantly reducing team costs. Alternatively, teams could employ a minimal superset of field elements that can be utilized for a range of challenges over multiple years. However, most leagues mandate the acquisition of new field elements annually, which can cost $1,000 USD or more per year [9-14].

In contrast, many open source control and computation platforms like Arduino, Raspberry Pi, BBC Micro:Bit, BeagleBoard etc. are highly popular in the DIY community and offer comparable capabilities. Moreover, there exists a wide array of affordable control, sensing, communication, and display modules that can be used in conjunction with these open-source platforms. These cost-effective kits have potential to become the go-to choice for numerous underprivileged schools and communities seeking to engage in STEM activities or participate in robotics competitions. The usability of these systems stems from their extensive flexibility and programmability. They provide a wide range of computational capabilities, multiple input/output ports, and seamless integration with numerous open-source libraries and electronic hardware. However, the learning with theses platforms will be limited to exploration in electronics and working principle by building circuits on a breadboard. As a Robotics learning platform, the electronic perception systems, the electronic actuators, programmable modules, navigation hardware, other functional platforms and end effectors are needed to build Entire systems. For example, principle of obstacle detection using ultrasonic sensing can be done by building a circuit and programming microcontroller; however, to enhance the learning the sensor needs to be mounted on a programable mobile robotic platform, where ultrasonic sensor detects an obstacle and provides input to a microcontroller that in turn drives a motor controller for a Robot to move, stop, slow down, or turn. Multiple robotic platforms based on open source programmable modules are available from any vendors [15,16]. However, the robotic platforms are fixed in configuration, limited to navigational and sensing platforms. The platform cannot be expanded to test additional sensor and end effectors.

Availability of parts and pieces, that allow easy reconfiguration to attach multiple sensors, actuators, end effectors, navigational platforms – differentially driven, actively steered, omnidirectional, legged, vision-based control is needed for comprehensive learning and experimentation. With such hardware, a learner may begin with basic odometry-based navigation experiments and gradually progress to more intricate tasks, such as machine vision and machine learning, all using the same hardware. The hardware is also compatible with an effective mode of learning and progression [17,18].

The research presented in this paper is inspired by Robotics for Everyone (R4E) initiative that enables accessibility of low cost, reconfigurable platforms for a comprehensive, experimentation and be competition ready within educational robotics. This work is a continuation of design and development work by authors to provide low cost experimentation platforms. They had earlier proposed flat pattern enabled brackets that can be manufactured using laser cutters or CNC routers [4]. Additionally, where possible, the brackets are designed as 2D flat patterns for ease of manufacturing. Many complex brackets are built by assembling a set of brackets manufactured from 2D flat patterns. In this research, we are presenting our findings in regard to using 3D printing as a means to build multiple cost effective educational Robotic platforms. Each platform is built using a set of low-cost extrusions or tubular structures and brackets. The brackets can be arranged in different configurations to enable complex assembly of structural elements, functional elements as well as assembling sensing modules, power modules and multiple hobby grade microcontrollers. The repeatability of extrusion types, tubular members as well as brackets across various robotics kits ensures that a small number of parts suffice manufacturing of multiple robotic platforms and hence savings. The brackets can be 3D printed so that the learner does not have supplier limitations.

In the following sections of the paper, different architectures of robotic platform along with the design of brackets is described. We describe the features that are added to the 3D printable brackets for multiple use, ease of manufacturing and efficient material utilization. The paper concludes by outlining future work and proposing a mechanism for learners to access and share the available resources including 3D printable parts and programming library and codes.

Path of learning and advancement in educational Robotics

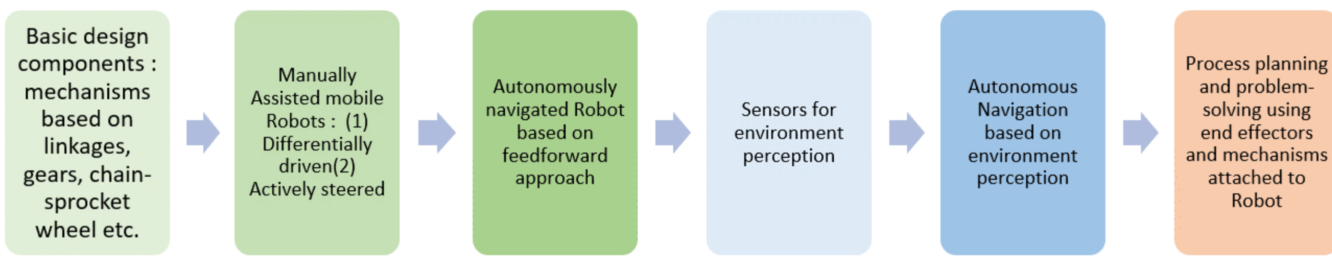


Figure 1 : Path of progression for learning with Robotic Platform

A common pathway for learning with educational robotics involves initially experimenting with physical systems and then identifying opportunities to introduce complexity, autonomy, and the need for programmability. This approach naturally establishes a context for logical thinking and programming. The design of the Robotic Platforms is driven by the same intent. As described in the Figure 1, the kit will allow building of a simple robot that can be controlled differentially for a feedforward odometry based path planning, then environmental perception using sensing is added to the robotic platform. End effectors are added to the robot to performing different tasks. Later, features to add vision systems and machine learning modules are added to the robot.

As described in Figure 2 , Figure 3 and Figure 4 we start with simple platforms such as differentially driven Robotic Platform and add additional modules as the learner ventures further into autonomy by adding Robot navigation. Additionally, the complexity of the robot is enhanced by adding additional end effectors, complex drives such as omnidirectional mobile modules and industrial architecture. The robots are built using 10mmX10mm extrusion and Metric 3mm (M3) hardware is used for the system assembly. The brackets for assembly of the extrusions, motors, sensors, microcontroller installation are 3D printed parts.

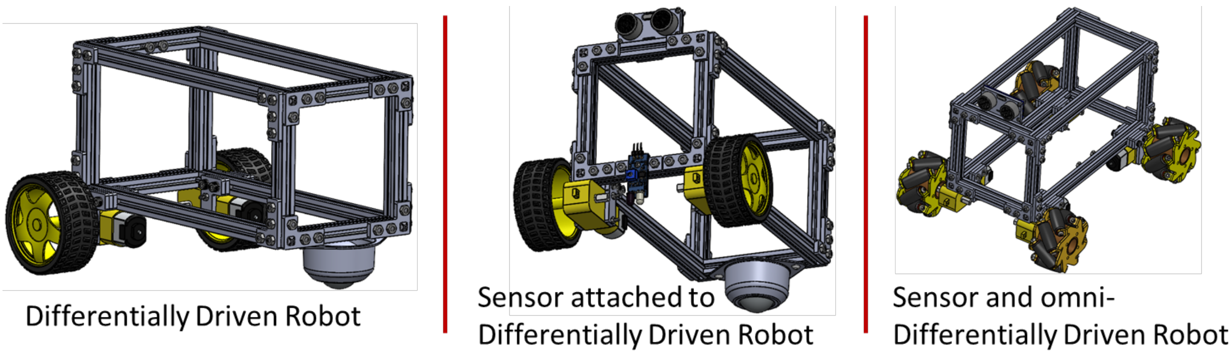


Figure 2 : Mobile Robots and increasing complexity (CAD Model)

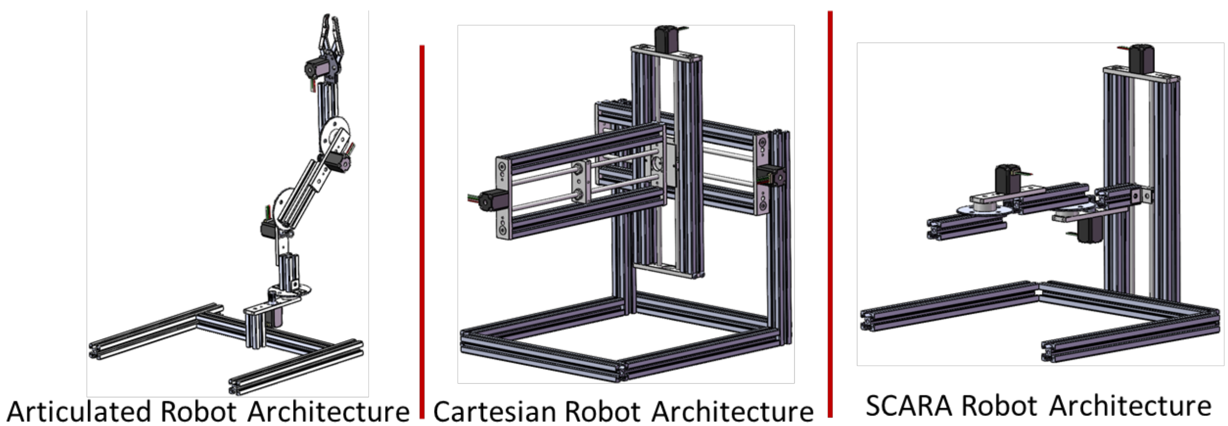


Figure 3 : Additional Industrial Robot Architectures built using 3D printed brackets and 10mmX10mm extrusions

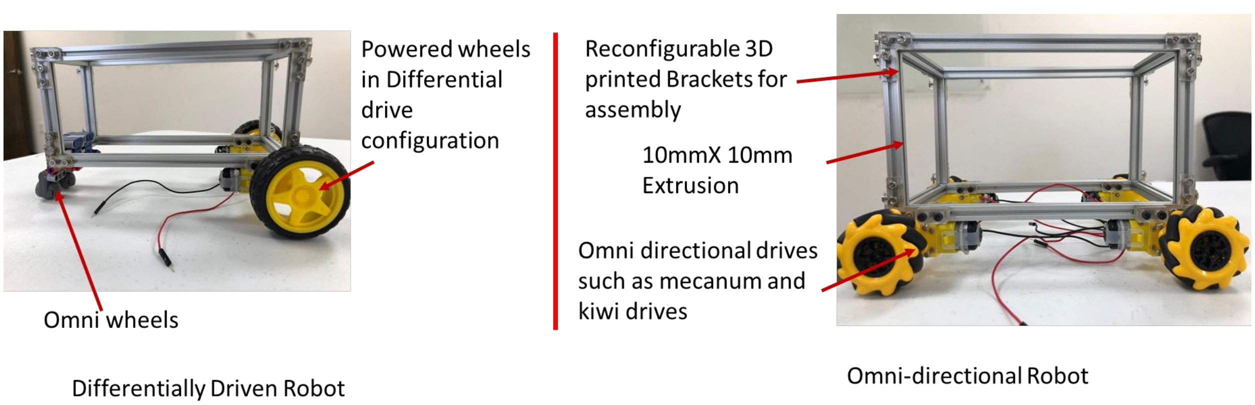


Figure 4 : Mobile Robots built using 3D printed brackets and 10mmX10mm extrusions

Design for Accessibility

During the development of the kit, we adhered to several key principles. These include:

Cost Consideration: The total cost including the structural elements and the brackets should not exceed 75 USD. This cost does not include the controller and sensors. To enable autonomous navigation of the robot following components should be added: ultrasonic sensors, IR reflective sensors, a controller, and a battery kit. The suggested cost for additional modules does not exceed 30 USD. Therefore, the total cost for an autonomous microcontroller-based Robot will not exceed 105USD. For advanced learning and experimenting in vision and machine learning a camera can be added and the microcontroller can be replaced with microcomputers such as Raspberry Pi. The total cost of a vision enables Robot (Including mobile robot platform, motors, camera and microcomputer) will not exceed 125USD.

Manufacturability: The parts can be produced using most personal desktop 3D printers and easily accessible machines. Both the structural features and assembly hardware features can be printed without requiring additional processing.

Interchangeability: The parts are designed to be interchangeable and compatible with a wide range of open-source controllers and modules.

Alternate designs using Flat Stock Material: Should an organization or individual wish to mass produce the parts, the 3D models can be manufactured by stacking a set of flat structures. The flat structures can be manufactured in a very cost-effective manner using laser cutter or CNC-mill. In cases where flat patterns are limiting, a combination of flat patterns is used to simulate 3D features. The authors wish to refer to their previous work on the same [4].

Reusability and Reconfigurability: As described in Figure 2 and Figure 3 the core framework for the mechanical hardware is built using 10mm x 10mm T-slot aluminum extrusions or tubular elements. To further enhance versatility, lightweight extrusions can be easily customized for different structural and functional purposes using a range of brackets.

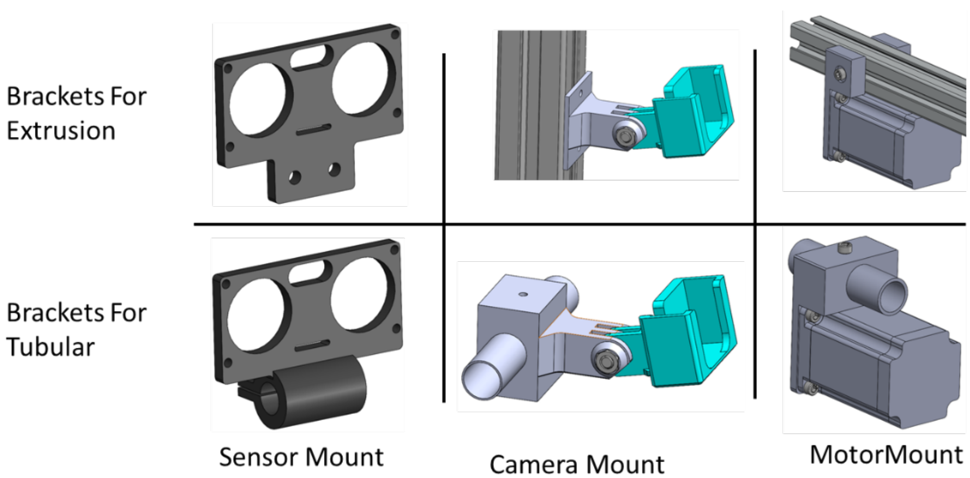


Figure 5 : CAD models for some brackets as designed for Extrusion vs Tubular framework

We extensively utilized computer-aided design (CAD) software to design and test a variety of attachments during the initial concept phase. Figure 5 showcases a selection of these designs, which can be 3D printed and assembled with the structural elements. A learner can download and 3D print these models from the Robotics for Everyone website [19]. We used Solidworks (Rev 2021) to design the parts. The CAD files are available in original Solidworks source format (SLDPRT for parts and SLDASM for assemblies). Where applicable, the flat patterns are provided in DXF format. The STL files are provided so that user can 3D print the files directly. For the CAD users other than Solidworks, STEP files are provided.

These extrusion framing elements feature continuous T-slots that allow for easy attachment of various types of fasteners. The rails have slots on all sides, providing maximum design flexibility. Unlike many other structural elements that require pre-drilled holes for assembly, T-slot aluminum framing allows for the insertion of T-nuts or bolts to create assembly features. This feature eliminates the need for fixed hole positions and enables assembly in almost any increment.

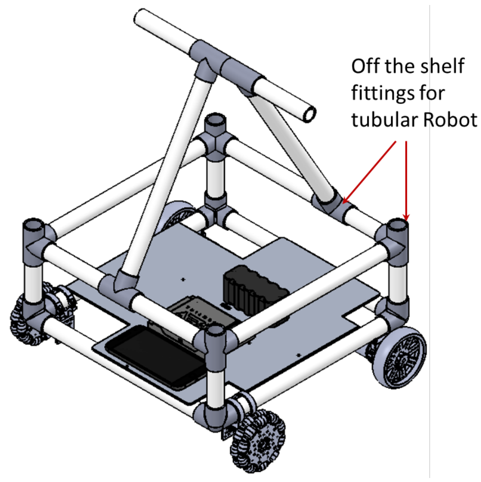


Figure 6 : Cost effective Robot built using tubular elements

Another readily available structural element is tubular structures. For an extensive set of experiments in educational robotics and compatibly with DIY (Do It Yourself) electronic parts we are providing robotic platforms for 1/8 tubing (Figure 6). The tubing is easily available for PVC, aluminum and steel. The tubing can be purchased for low cost in segments of 5ft incremental lengths. The tubing can be cut as needed. One advantage of the tubing is that many off the shelf fittings are easily available. Additionally, a library of 3D printable parts for structural-, sensor-, drive- brackets are provided (Figure 5). In addition to the structural assembly elements, we have also designed brackets specifically for mounting functional elements such as motors and sensors. In addition to the brackets for extrusion elements, the brackets for tubular element are available for download, allowing a learner to easily incorporate additional components into robotics projects.

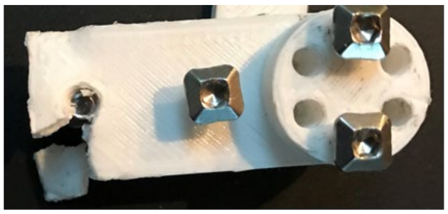
Considerations for 3D printable elements

The experimental robots must withstand static and dynamic loading. A learner may reconfigure the robot for multiple experiments, therefore the versatility of bracket design will reduce the part count and keep the overall manufacturing cost low. Additionally, each bracket should be designed for multiple cycles of assembly and disassembly.

The Metric 3mm (M3) hardware is used for the system assembly. Two types of holes are designed for system assembly (1) threaded (2) clearance. The holes that require threads for assembly, are manufactured for without thread with interference fit diameter. When a screw is assembled into the holes, the screw taps and creates a thread. Sensors that are based on reflection from the robot environment (e.g. floor), require accurate mounting. Additionally, vibration isolation is required for inertial and reflective sensors. To reduce the measurement errors, robot structure shall provide a stable datum to mount the sensors.

Table 1: Failure test for reassembly of parts

Parameter				
Nozzle Diameter (mm)	0.2	0.4	0.6	0.8
Printing speed (mm/s)	25	30	35	40
Repetetion at which part broke				
Sample 1	1	3	4	6
Sample 2	1	3	3	7
Sample 3	2	3	3	6
Sample 4	1	3	4	6
Sample 5	1	4	3	5
Functional Cycle (Speculated)	1	3	3	6



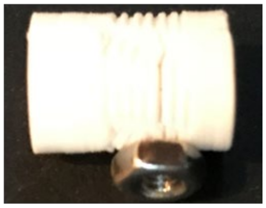


Figure 7 : Two types for damages seen due to multiple cycles of assembly

We manufactured the parts using different nozzles used within hobby grade Open-source desktop 3D printers. The manufacturing was done one Ender 3 pro (Fused Filament Fabrication) FFF machine with PLA+ filament. We performed basic test for fatigue and structural integrity. For the brackets that at are cantilevered, we add structural features such as ribs. A detailed analysis is not within the scope of the research presented in this paper. However, we are reporting some of the testing and findings based on basic manual assembly. We tested the designs for 10 reassembly cycle for structural thickness of 3mm. Each test was performed for approximately 5 similar parts. The speed of extrusion is adjusted for the nozzle size. For the parts manufactured with nozzle size 0.8mm or above, the assembly feature such as screw holes start to crack after 5 cycles of reassembly. The smaller nozzle diameters also take longer time to build. As a rule of thumb, we recommend using 0.4mm nozzle diameter for 3D printing. The learner may choose their own parameter based on the choice of their printer and material. Should significant reuse and reconfiguration of the 3D printed parts required learners may perform a quick experiment to determine the parameters amenable. Table 1 summarizes results of our experiments. Figure 7 describes two types of damages seen during the test. In some cases, the crack will lead to complete dislodging of a segment. Whereas in some other cases we saw crack develop. A partly cracked bracket may continue to function as needed as long as not a significant static or dynamic load is not applied. However, we strongly recommend that sensor brackets should be immediately substituted, since the position of sensor with respect to environmental features is critical for the robot to function. Additionally, we found that irrespective of the nozzle diameter, the threads introduced by assembling hardware in interference fit holes do not show any deterioration for thicknesses tested.

Our estimates of the price of filament material consumed for different brackets range from 0.15USD (United States Dollar) to 0.85 USD. The price estimate of the linear extrusion is approximately 0.11USD and 0.05USD for tubular structures. The cumulative price estimate for a complete navigational platform with electronic controls, drives and motors is approximately 45USD.

The part library is done for in-school learning and experimentation. The part library will enable complete learning and experimentation per path of progression described in Figure. For learners who wish to compete, the part library will allow building a robot that will meet FIRST, VEX, WRL, BEST and WRO form fit specifications for a fraction of cost (115 USD vs approximately 500USD). However, the robot will not be admissible for FIRST and VEX leagues due to league prescribed elements such as LEGO and VEX.

Test Cases for 3D printable parts

Figure 5 describes a representative set of parts from our CAD library as applicable for extrusion-based platform and tubular platform. The models are available in STL format to 3D print it as is. Additionally, the models are provided in STEP format should the user want to customize the models per specific needs. We are describing below a sample of parts that enable reconfigurability and multifunctionality.

Part manufacturing for reconfigurability and multifunctionality:

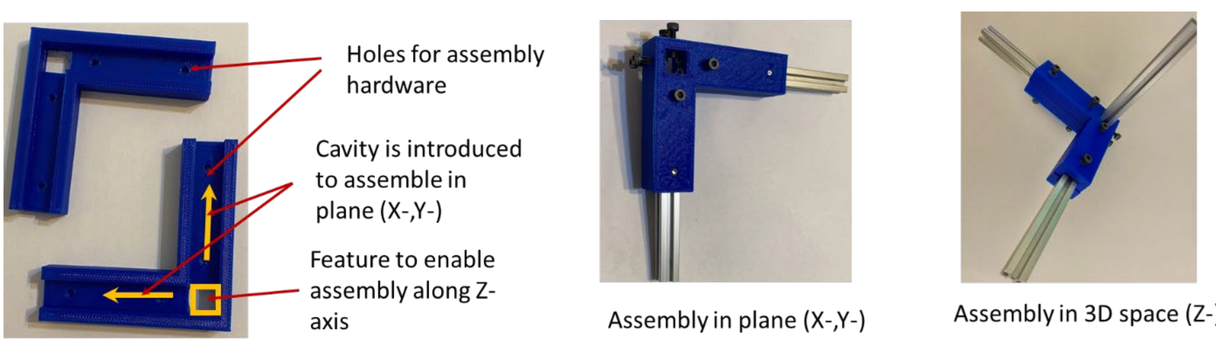


Figure 8 : Bracket for assembly in multiple configurations and reuse

Figure 8 describes a bracket used for connecting extrusion structure at 90 degrees. Additionally, the bracket has features being reconfigurable and multi-functionality. The bracket has a feature that will allow assembling a third extrusion to build a 3D frame.

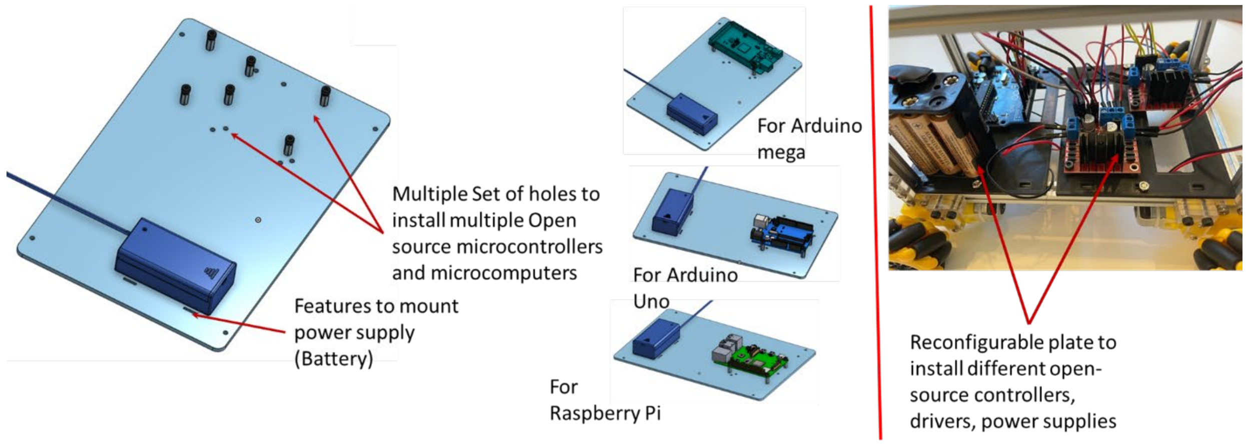


Figure 9 : A plate to enable installation of multiple Open source microcontrollers, computers, drivers and power supply

Similarly, as described in Figure 9 the mounting plate for the microcontrollers and battery is designed with assembly features to enable assembly of multiple open source microcontrollers (Ardunio Uno, Arduino Mega) and microcomputer such as Raspberry Pi on a common plate.

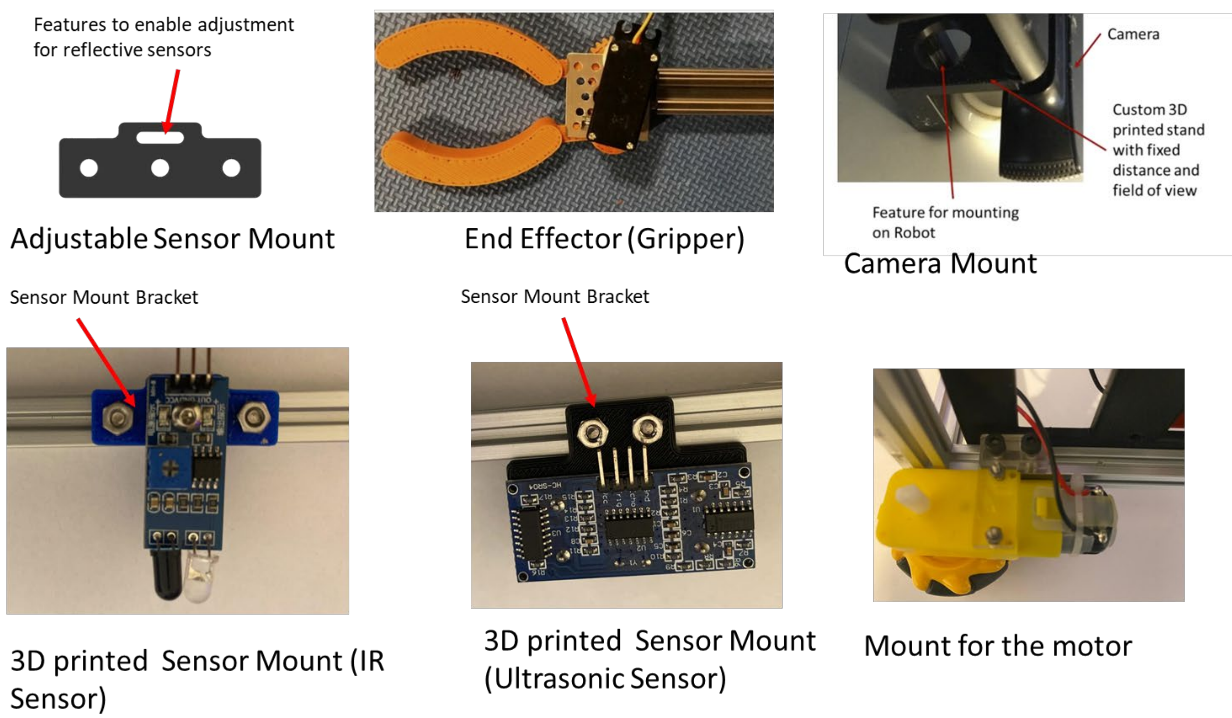


Figure 10 : Sample 3D printed parts used for building Robots

Figure 10 describes brackets for installing popular sensors for environment perception. The bracket allows installing the ultrasonic sensor in front as well as rear side of the robot. Additionally, using the same bracket sensor can be installed along the side to enable wall following. Reflective sensors are used for line following and similar environmental perception. The sensitivity of the sensor may vary due to manufacturing variation as well as the robot environment, therefore it is critical to have some adjustability to the distance of the sensing end effector to the surface. The bracket as described in Figure 10, enables installation of the sensor with the adjustability for height.

The limitation of material availability manifests in mixing two different type of structural platform for

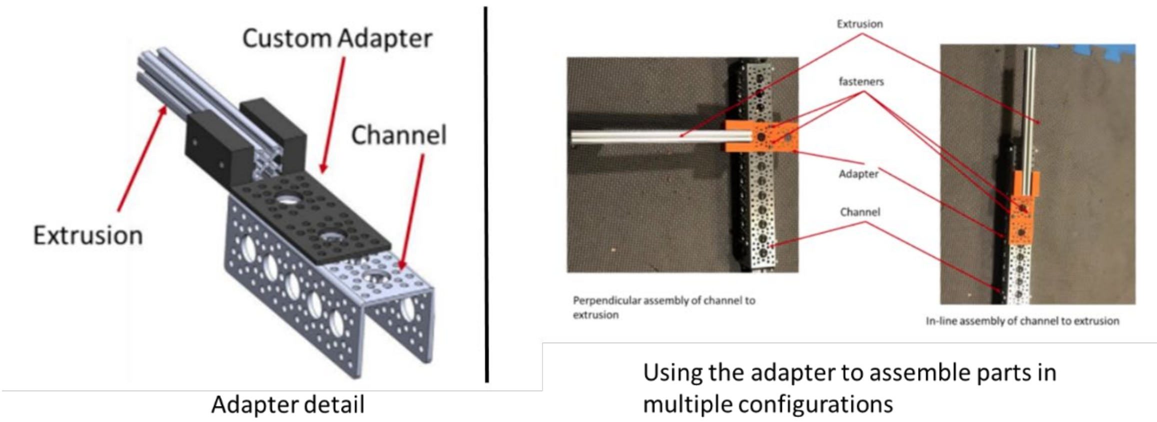


Figure 11 : Adapter for connecting the extrusion-based platform to other commercially available Robotics Platform

building robots. The learners may expand the capability of robot by interchanging components between extrusion and commercial platforms that use channels. In certain cases, a learner might choose to design and produce a robot using one kit, but opt to incorporate other subsystems, such as drives, from a different system. This decision could be driven by either the advantage of the form factor or the availability of specific components. Adaptive brackets may be used (Figure 11). A user may design the adapting bracket per need. The adapter, as described is 3D printed to assemble parts from popular channel-based system in two different configurations. The part is manufactured by Fused Filament Fabrication, using Orange Acrylic Styrene Acrylonitrile (ASA) printed with T40 tip.

Field Elements for Robot environment.

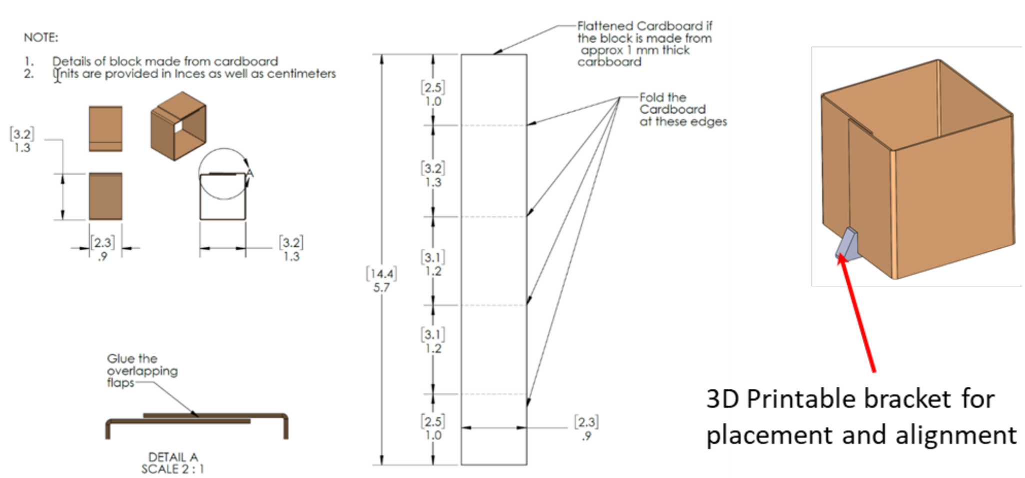
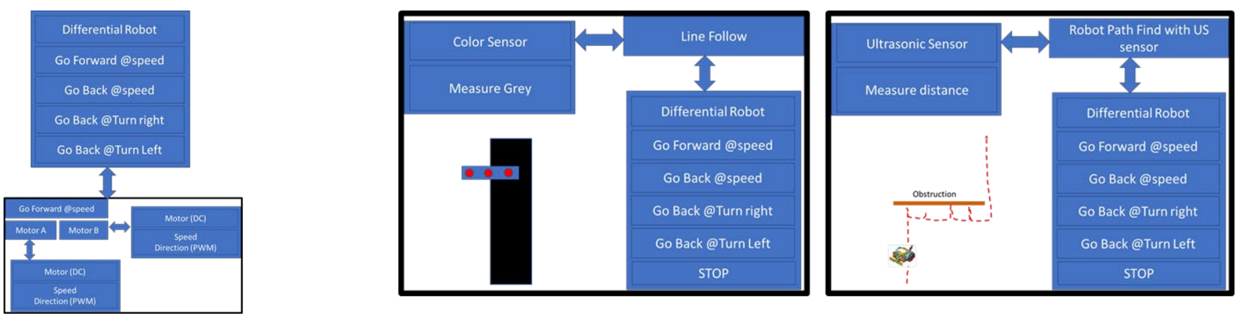


Figure 12 : Sample field elements built using cardboard and tape -1. (The plat pattern is provided)

Robotic experiments require interaction of the robot with different types of environments for navigation and process planning. The robot may be programmed to move from one point to another and solve different tasks in feedforward mode or interact with the environment using sensors to take decisions. The robot environment elements may be simple obstacles or complex three-dimensional elements. Alternatively, the robot elements may be systems that can be actuated by engaging with the Robot. To keep the cost for building field elements low, we are providing schematics and details so that easily available material such as tape, paper, wire and carboard can be used to build field elements. As described in Figure 12, CAD tools provide utilities to create flat-pattern to build the parts out of cardboard. However, accuracy of the shape as well as accurate placement of field elements is required. 3D printed parts can be used for accurate placement and assembly. Additionally, as described in Figure 12, 3D printed parts can be combined with cardboard based part to build and place field elements accurately.

Models and coding library

A survey encompassing 147 recently published studies, [20] suggests that programming the robot provides additional benefits including (1) enhancing their understanding of abstract concepts, (2) providing a feedback-oriented learning platform, (3) fostering collaboration with peers, and (4) offering opportunities for exploring and gaining deeper insights into real-world problems. To allow ease of entry, many basic programs are made available by Robotics 4 Everyone as a library. The coding library as provided is created in C++ for Arduino platform. The details of programming libraries and functions are beyond the scope of this paper. However, we would like to introduce the basic coding model of how it is made available to the learners to integrate and experiment.



Motor Control and navigation using the motor control function

Using navigation library and color sensor library for line following

Using navigation library and ultrasonic sensor library for obstacle avoidance

Figure 13 : Pictorial representation of the Coding libraries and hierarchy

As described in Figure 13, basic DC motor control is using Pulse Width Modulation (PWM) and is made available as basic function. The Robot navigation library is implemented as a combination of motor controls including the speed and direction. The sensing functions can be combined with navigation functions for higher level robot autonomy. This approach allows learner to dive deep and explore the programmability of the robot. Pseudocode described in Appendix provides the details of navigation implementation. The modules may be combined with input from sensor and potentially vision-based machine learning to control a Robot.

Conclusion and future work

This paper outlines the utilization of 3D printing to manufacture brackets and elements that can be coupled with cost effective extrusion and tubular elements to assemble different types of robotic platforms. Additionally, 3D printing can be used to manufacture field elements for Robot environment.

The models are provided online for the learner community to download and use to build cost effective robots. Design of parts is done for reusability of parts. The designed elements are used for structural, functional and accurate mounting of sensors. Additionally, source files are provided for users to modify when need basis.

As a pilot program, 5 sets of kits were made available to two middle schools in one of the financial back ward regions of North Eastern India. Each school was provided with (1) Arduino based kit along (2) extrusions set and (3) a 3D printer each. Across 3 months of learning and experimentation many students were able to implement differential robots along with passive as well as active end effectors. The pilot concluded with a competitive event were teams in group of 2-3 student each implemented pick-up and place challenges. The educators suggested that the cost effectiveness was helpful in their ability to offer the program to multiple students. The comparative price of off-the-shelf robot kits such as Lego spike prime, VEX were not affordable. Authors believe that free availability of resources and models will enable additional communities to benefit from this initiative.

Ability to build and test various functional units such as different types of gears and kinematic-linkage was limited. The functional elements such as gears when produced with hobby grade 3D printers lack tolerance and do not function smoothly. We intend to improve the design to overcome performance impact due to staircase effect.

Appendix: Pseudocode for Navigation

```
# Function to move the robot forward
def move_forward(speed):
    # Set the left wheel to move forward at the specified speed
    set_left_wheel_speed(speed)

    # Set the right wheel to move forward at the specified speed
    set_right_wheel_speed(speed)

# Function to move the robot backward
def move_backward(speed):
    # Set the left wheel to move backward at the specified speed
    set_left_wheel_speed(-speed)

    # Set the right wheel to move backward at the specified speed
    set_right_wheel_speed(-speed)

# Function to turn the robot left
def turn_left(speed):
    # Set the left wheel to move backward at the specified speed
    set_left_wheel_speed(-speed)

    # Set the right wheel to move forward at the specified speed
    set_right_wheel_speed(speed)
```

```python
# Function to turn the robot right
def turn_right(speed):
    # Set the left wheel to move forward at the specified speed
    set_left_wheel_speed(speed)

    # Set the right wheel to move backward at the specified speed
    set_right_wheel_speed(-speed)

# Function to stop the robot
def stop():
    # Set both the left and right wheels to stop
    set_left_wheel_speed(0)
    set_right_wheel_speed(0)
```

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