

## Using Solid Freeform Fabrication to develop a low-cost Robotics experiment platform to complement classroom learning and exploring topics in STEM Education.

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### Abstract

Educational and competitive robotics provide avenue for hands on experimentation and hence effective tools for STEM education. Cost of physical components continues to be a limiting factor. Within the Educational Robotics, the kits (LEGO, VEX, REV, etc.) are beyond the reach of most of the communities across the world. “Robotics for All” is an initiative to enable a versatile cost-effective platform to provide a minimum set of parts that students can integrate with general purpose as well as custom controller/microcomputers (Arduino, Raspberry-Pi, BBC microbit) to perform range of experiments. Various sensors and camera modules can be easily integrated to further learning and experimentation. It will be possible to perform experiments in Robot Navigation, Process planning, object manipulation, industrial architectures, Machine Learning etc. Solid Freeform Fabrication was used to enable manufacturing, verification and improve the design of piece parts with emphasis on low cost without compromise on learning opportunities.

### Introduction

Quantifiable experimental outcomes and evidence-based approach to learning are important to understand STEM subjects. Relatively complex ideas within physics, geometry when coupled with verifiable cause and effect experimental verifications enhance the learning for students. Educational and competitive robotics provide many avenues to experiment with complex ideas, logical thinking, and programming. By virtue of reconfigurability and multifunctionality a robot can be used for solving variety of tasks, navigate, and traverse different terrains as well as use sensors for environment perception and work in autonomous fashion. Additionally, the education robots also offer a range of scenario to explore ideas in advanced topics such as programming, Machine Learning and AI [1] Possibilities and context for experiment therefore are many. To list a few [2,3,4] (Figure 1):

1. Correlation between the motor rotation, mobile robot wheel diameter, and total distance covered, provide in-depth insight into many principles of geometry.
2. A kinematic chain, simple machines, and torque to force relationship when lifting objects with the robot arm help understands the principles of dynamics.
3. Robot navigation, movement between points, finding the shortest path between two points, and manipulating robot wheels for straight motion, turn, and error correction.
4. Understanding the principle of center of gravity when the robot climbs on an incline and decline.
5. Acceleration, deceleration, velocity, and displacement relationships to ensure robot travels between two points accurately and in minimal time.

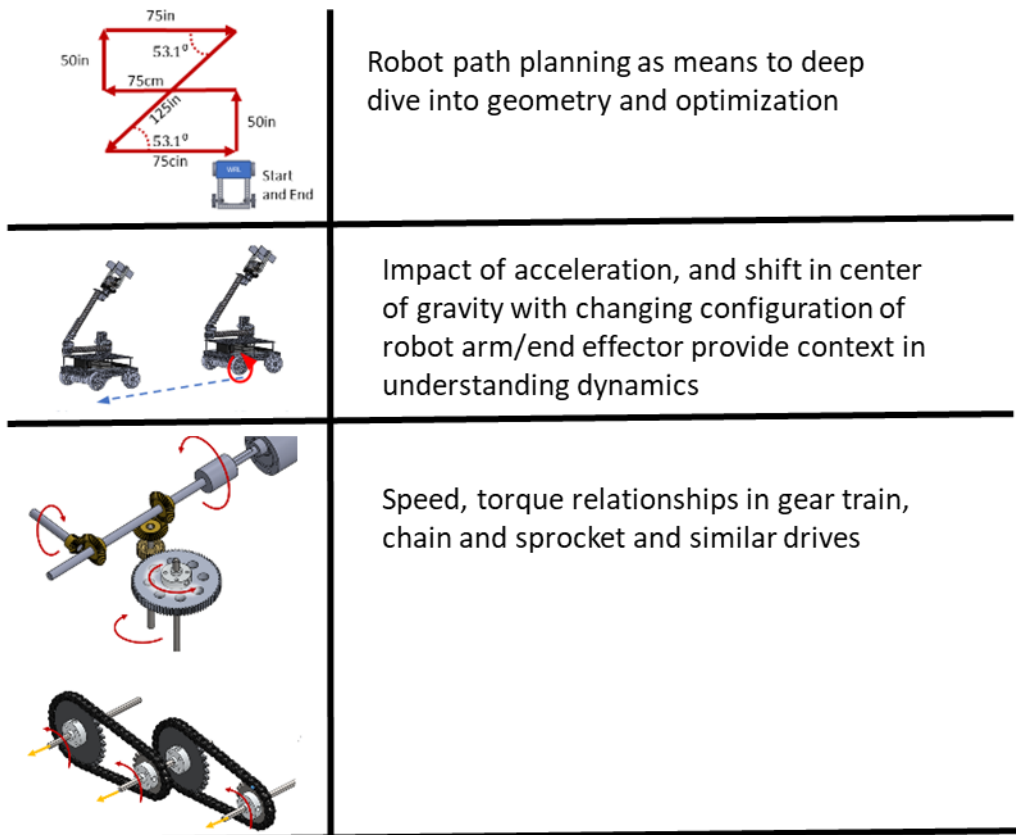


Figure 1 : Educational Robots as means to experiment and dive deep into principles of Math and Physics

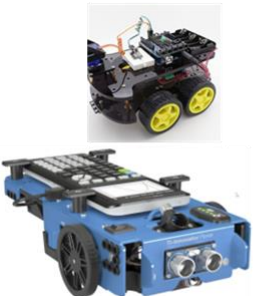
In their research, Ardito et al. and Sana et al. [5,6] demonstrate effective use of robots to teach complex ideas in geometry such as ratios, estimation, and geometry but also finding real life relevance to classroom learning. In their article, Amico, Guastell, and Chella [7] suggest that when using robots for learning, students exhibit better understanding of concepts and higher participation in various topics in physics. Consequently, many educators, parents, and self-motivated individuals learn and participate in learning using robots [5–7]. With the potential to offer many learning-by-doing opportunities, classroom robotics has found wide-range acceptance. In a survey of 147 recently published studies [8], it was found that there are a variety of ways in which students can benefit from robotics program, including (1) understanding of abstract concepts, (2) a platform for feedback-oriented learning, (3) establishing collaboration with peers, and (4) opportunities to explore and find deeper insight into real world problem.

Classroom/Educational Robotics uses multiple reconfigurable pieces including structural elements, motion manipulation elements such as gear, chain drives etc., electrical drives such as motors, sensors and perception modules, and a programmable controller. Different elements are typically available as kits and are used by many learners and DIY enthusiasts.

Under *Robotics for Everyone* initiative [9], a comprehensive low-cost general educational Robotics platform was developed. Solid Freeform Fabrication was used to, design, test and iteratively improve multiple pieces for educational Robot. Based on the learnings from parts, a comprehensive minimum part-type item list was prepared. The paper also describes how the cost-effective part set can be used for experiments that will enable a comprehensive curriculum for the educational robotics and introduces a cheap but comprehensive kit that can be used to perform the experiments. Paper concludes with a future work and suggests a mechanism for learners across various communities to access the resources.

## Description/Survey of the kits available

Recent advancement in technology and significant interest from DIY community has been instrumental in development of many low-cost programmable boards, sensors, computational resources as well as motors and drives. Many open-source control and computation platforms such as Arduino, Raspberry-pi, and Beagle board are very popular in the DIY community and provide significant potential to learn and experiment. Additionally, there is an ecosystem of a range of very cost-effective control, sensing communication, and display modules that is usable with the open-source platforms. The cost effectiveness of such kits has become the de-facto choice for many disadvantaged schools and communities who wish to engage in STEM activities. Despite many possibilities, the kits are not as comprehensive and easy to work with. Many other kits that are based on open-source platforms are adequate only to build a fixed architecture and single mobile robot. The robots are not designed to expand. Hence opportunities for experimentation are limited.

	Lego Spike prime and expansion set Price \$515.00. Reconfigurable
	Vex IQ, Price \$449. Reconfigurable
	Other fixed architecture systems such as Arduino based, TI-Rover, price Range \$125-\$300 have fixed architecture mobile Robot only platform. Not Reconfigurable

*Figure 2 : Configurability and Cost comparison of popular educational Robotics kits*

Many other proprietary kits are extremely expensive and cost prohibitive to most of the communities and educational institutes across the world. Figure 2 shows a comparison of various control and drive kits available in the market. One of the most fundamental issues with each of the kits is interchangeability. Each kit is compatible with items manufactured and sold by specific supplier. Once initiated with a manufacturer kit, a learner is limited by design to a supplier. To offset and overcome the price issues, many a students work as teams sharing single kit between as many as 10 students. This severely limits each participant to perform many experiments.

In order to assess the access to robotics kit, we used the competitive Robotics participation across FIRST, VEX and BEST Competitions. In a general survey across the world, it is found that most of the leading number of teams participating in educational and competitive Robotics are from financially advanced countries such as United States, Canada, Western European countries, Australia, Israel, China [10,11] etc. In fact, the number of teams participating from united states are almost 10 times more than the next country. Ability to purchase the kits becomes a limiting factor. Within United states, the representation from financially disadvantaged and rural communities is significantly low.

In order to offset the pricing many teams are very large. Primary reason for larger teams is financial. Many times, a team of up to 10 students share a common Robot kit. In a survey of 24 teams that have participated at least two seasons of different competitive leagues within North Texas and Western Washington students found that larger teams limit the opportunity for experimentation and learning. Many teams choose to define the roles such as designer, coder, program manager etc. that skews the learning opportunities. Many educators and

coaches feel that it is too early for the students to decide where their interest truly lies. They should be given ample opportunity to explore every aspect of educational Robotics. In fact, the close compatibility between design and programming puts unwanted hurdles when students work in a team by task distribution based on specialization.

Another key observation is that if a kit once purchased by a learner be used over multiple years will distribute the cost investment over multiple years. This will also motivate educators to invest in a platform with higher reusability. Within different competitive leagues, the challenges offers are mostly limited to material handling and maneuvering [12]. While the scale and payload requirements increase from elementary to middle and high-school leagues, the complexity of the challenges and hence the learning opportunities don't improve significantly. In fact, the junior leagues such as First Lego League (FLL) have challenge in autonomous mode whereas advanced challenges such as FTC, VEX have only 30 second of autonomous mode and rest of the challenge is remote control. As a learning opportunity, only payload increases, and the mode of item delivery is same through the challenge. As a reference FLL Cargo Connect, 2021-2022 season, the missions included avoiding an obstacle to simulate accident avoidance, delivering large objects and cargo containers to specified locations within Robot work space. Similarly, in the Superpowered season for 2022-23, the robot could be launched from the two positions and the mission for included moving energy units tokens across the robot work area and dropping them precisely in specific locations. Additional missions required pulling and/or pushing certain LEGO components of the mission to score points. Solving each of these missions require precision in navigation of the robot and skills in mechanical movement of various attachments that are built and attached to the robot. With about 15 missions to solve each season in an autonomous mode, the robot must be built and programmed for consistency and reliability. Small variations in physical performance of the robot can accumulate over a period of time and must be accounted for via feedback to prevent penalties. Teams also incorporate strategies to attempt, multiple missions in single robot run and motorized or non-motorized end effectors to perform multiple tasks.

Senior leagues such as FIRST Tech Challenge (FTC) and have larger workspace. The game is 2 minutes 30 seconds with only the first 30 seconds being autonomous. The robot for rest of the game can be operated manually through a controller. As a reference the 2021-22 season was called Freight Frenzy with two containers containing balls and cubes of different weights that can be moved to various places on the field to earn points. FTC challenges allow use of wide variety of tools, materials, and components to build the robot making it harder to design and build the robot. Availability of resources and expertise in utilizing these resources can make a big difference in how the team performs at an event. The robot is programmed in Java but the only 30 seconds of the game being autonomous, the coding can be simpler than FLL. Use of color, touch, gyro and cameras are allowed but often their extent of use is limited. The variety of problems to solve in FTC could be smaller than in FLL as there are fewer missions but the scale of components used is larger.

VEX Robotics is another robotics program like FIRST that offers elementary through university students various leagues based on ages and skill level. The 2021-22 season is called Tipping Point with teams scoring points by moving rings, moving mobile goals to alliance zones and elevating on platforms.

For the middle and high school leagues, the complexity of the challenge can be enhanced by retaining the autonomy of the robot to enable learning and exploring wide variety of sensors and other environment perception modules.

### **Minimum viable curriculum and a recommended path of progression**

A general path to learning with educational robotics is to first experiment with physical system then identify a context for adding complexity, autonomy and need for programmability. This offers a natural path to establishing context for logical thinking and programming. Popular educational robotics curriculum starts with programming, which to some extent leaves students confused and struggling to connect classroom learning to experiments. With the commercial learning platforms, it is the platform that come to define experiments and

learning that can be performed. For example, each manufacturer provides their own curriculum and learning that is strongly associated with the capabilities of structural as well as programmable platform manufactured and sold by them [13,14]. The courses continued to be skewed to limitations of manufactured kits, hence limiting many opportunities to learn and experiment. There is no universal accepted path to advancement or a universally accepted curriculum. STEM and Robotics academy, borrowing from many years of training and teaching as well as in reference to studies and initiatives has been following path of learning and progression as defined in Figure 3. While there has been an emphasis on technological aspects, the learning and progression continues to establish strong context with classroom learning as described in the Figure 3.

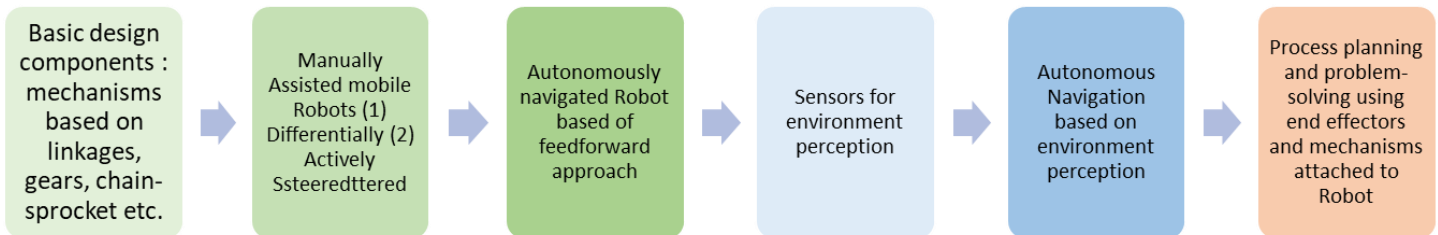


Figure 3: Path to learning and experimentation

Minimum set of experiments that the kit should be able to help perform include:

1. Build various mechanisms including- Kinematic chains, Gears, Chain and Sprocket etc.
2. Mobile robot with differential navigation
3. Mobile robot with active steering
4. Mobile robot with environment perception using sensors such as US, line following, color and region perception.
5. Passive end effectors: pusher and retriever
6. Motorized articulated arm
7. Motorized end effector with motorized end effector
8. Omnidirectional navigation architecture: mecanum drive
9. Omnidirectional navigation architecture: kiwi drive
10. Navigation architecture for complex 3D terrain
11. Platform for Machine Learning (ML) and vision experiments
12. Platform for inertial and GPS guided navigation

### **Low Cost solution with Robotics for Everyone initiative [9]**

Under Robotics for everyone initiative we have designed a comprehensive cost-effective kit that will be accessible to most of the learner community across the world. Following tenets were followed when developing the kit:

1. Kit should allow performing wide range of experiments.
2. Cost of the kit should not exceed 100USD.
3. Kit should be reconfigurability with a BOM of parts with minimal part variation.
4. Parts should be Interchangeable and compatible with most of the Open-Source controllers and modules.
5. Brackets should be manufactured from flat stock material. Where required use flat patterns to simulate 3D features.

### **Development of Economical Robotic kit using SFF**

Platforms such as Lego and VEX have patterned holes (Figure 4). All the structural members, connectors, functional components such as motors, drives and sensors can be connected along the defined pitch. Additionally, the directionality of connecting the parts is limited. To add the parts in direction other than that of the base member, additional adapters and members are required.

To overcome the limitations of various robotics kits, our Robotics for everyone kit structural members are fabricated using 10mmX10mm T-slot aluminum framing elements. These rails have continuous T-slots for attaching different types of fasteners. Rail profiles with slots on all sides offer the most design flexibility. Contrary to many other structural elements where assembly requires features such as holes drilled for assembly a T-nut or bolt can be slide inside the framing to provide an assembly feature. While other structural elements can be assembled along fixed position (Figure 4) and are limited to the hole pitch; T-slot structures can be assembled to almost any increment.

Using different types of brackets lightweight extrusions can be easily customized for a variety of structural as well as functional purposes. SFF was used extensively to design and test variety of attachments for first pass concept. Figure 6 describes a variety of designs that can be 3D printed to assemble the structural elements. The models are available on Robotics for All [9] website to download and 3D print. In addition to the structural

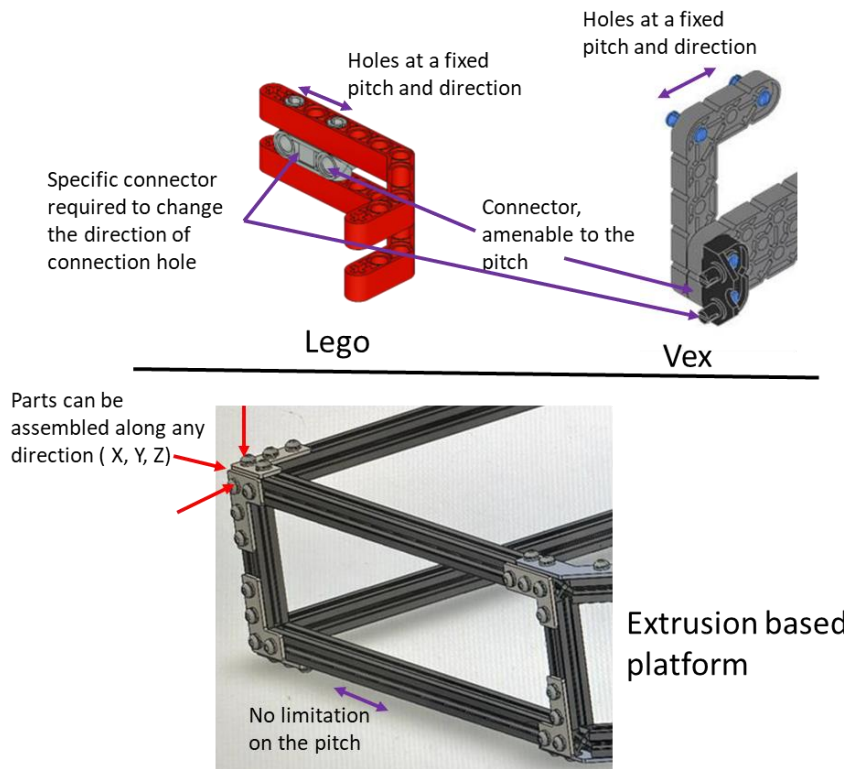


Figure 4 : Assembly and configurability comparison of different platforms

assembly elements, the brackets for mounting functional elements such as motor and sensors were designed and are available to download. Figure 8 describes various 3D parts that were manufactured using the 3D printing. The printing was performed using the Ender 3 Pro. with PLA+ filament. To keep the pricing of the parts low, each bracket and mount design was simplified to flat pattern piece parts and sub-assemblies made from flat patterns. The flat patterns would enable manufacturing parts from cheap stock material such as FR4, plexiglass etc. Cheap manufacturing cost as well as common flat stock material enable a very cheap alternative with price of each bracket ranging between 5cents to 12cents for a production volume of 1000 parts each.

Other brackets such as motor mounts, end effectors, angular attachments etc. have 3D features defined by function or to enable load driven mounting features. The design for those brackets is done and tested with inbuilt 3D features; however, as a second phase of the project the parts were simplified to be assembled using flat stock material. Motivated by 2-1/2 axis based approach for manufacturing, many brackets are modified to be built by uniform thickness 2D structures. The parts can be manufactured using simple flat pattern.

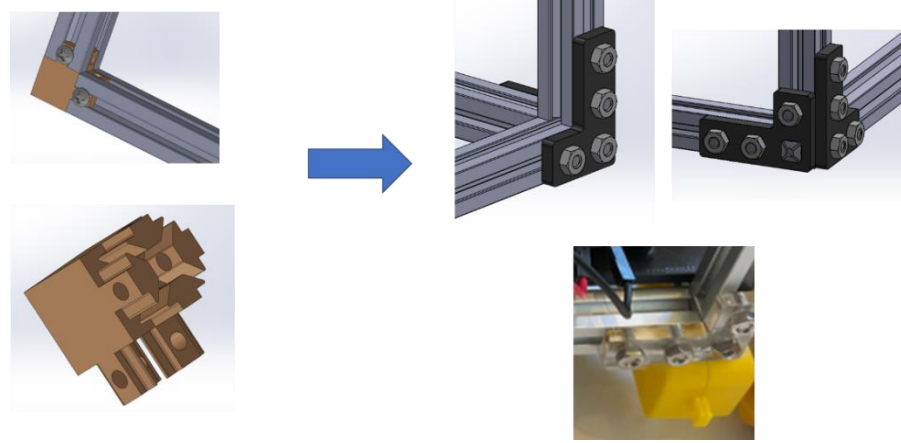


Figure 5 : A sample example of replacing complex bracket with 3D features by a uniform thickness part built from flat stock

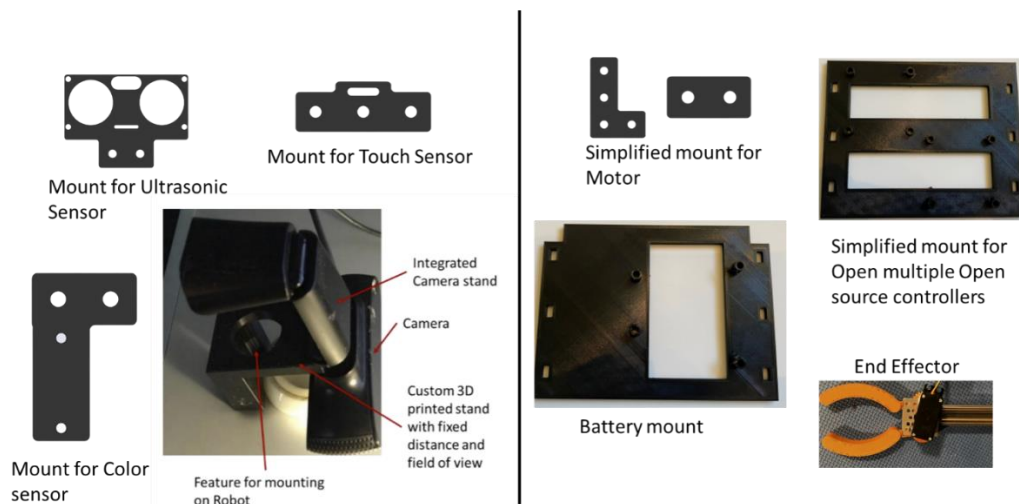


Figure 6 : Different parts that were manufactured using 3D printing for testing

Figure 7 and Figure 8 show example of two brackets that require 3D features; however, are modified to be built using flat stock material. Many structural elements within the robot are assembled at angles other than 90degree. A typical kit has specific bracket that enable assembly along popular angles including 45 degree, 135degree, 60 degrees. The kit may have a fixed number of those angular bracket. Quite often participants may not have enough angular brackets to meet their design requirement. Figure 7 describes a bracket used for assembling two extrusions along different angles. As shown in the figure, the bracket has multiple holes that can be aligned and then bolted to enable angles at increments. To compensate the spacing requirement, the original design has 3D features. The part is then redesigned to be manufactured using flat stock.

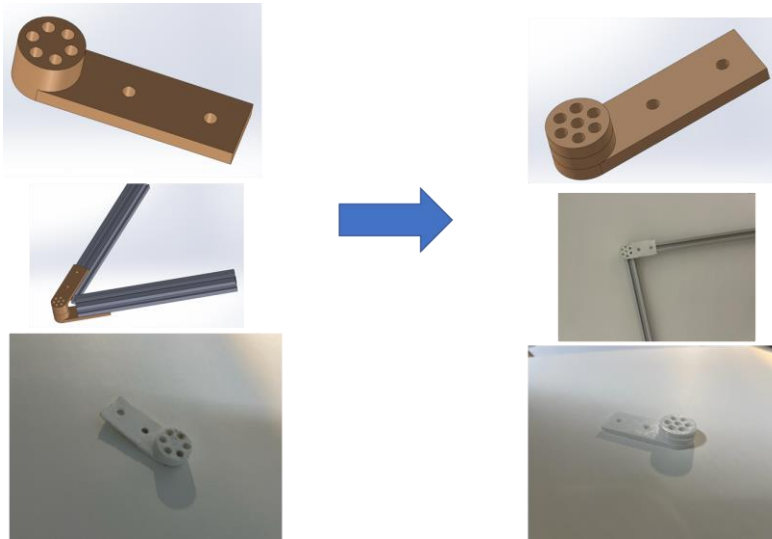


Figure 7: Reconfigurable bracket to assemble extrusions at multiple angles

Similarly, Figure 8 describes a part with 3D features to enable optimal encapsulation of the motor. Part is simplified to manufacture using flat stock material.

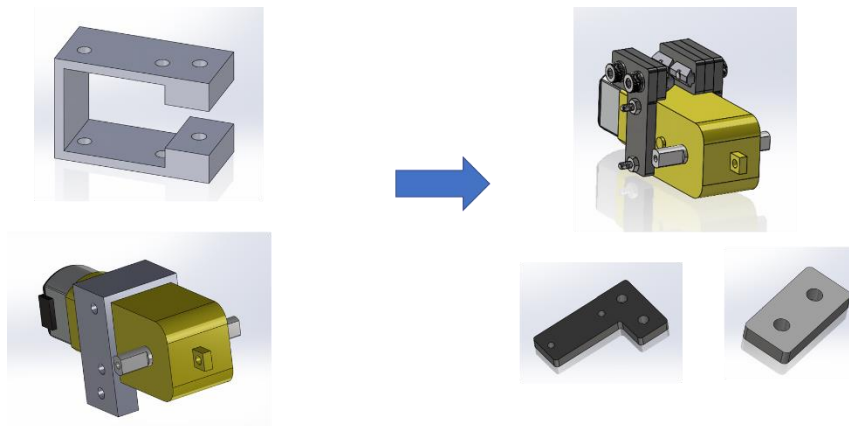


Figure 8 : Motor mounting bracket with 3D features, simplified to manufacture using flat material stock

### Kit details minimum BOM and price estimates

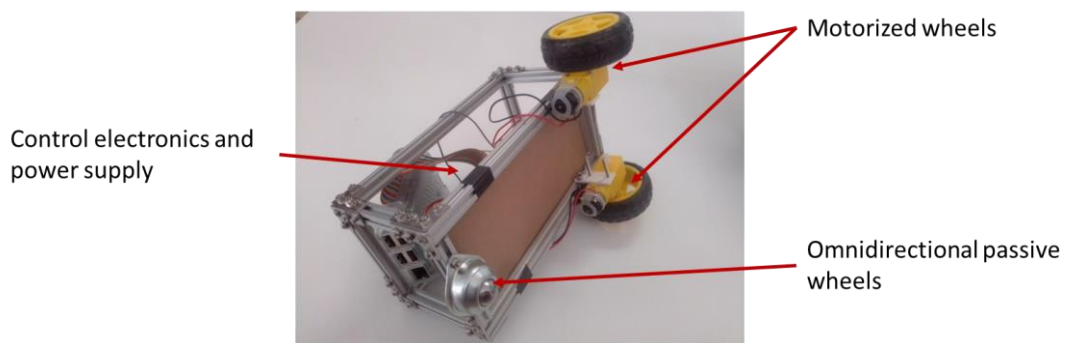


Figure 9 : Differentially driven mobile Robot

**Differentially driven mobile Robot:** This is the most widely used architecture. The architecture allows navigation by powering two individually motorized wheels and a minimum third point of support using a omnidirectional caster wheels. This type of robot will be limited to mostly 2D smooth terrains. However, many end effectors such as one shown in Figure 10, can be attached to the Robot for completing different tasks.

Additionally, various sensors and camera can be attached for robot environment perception and exploring advanced ideas such as Machine learning.

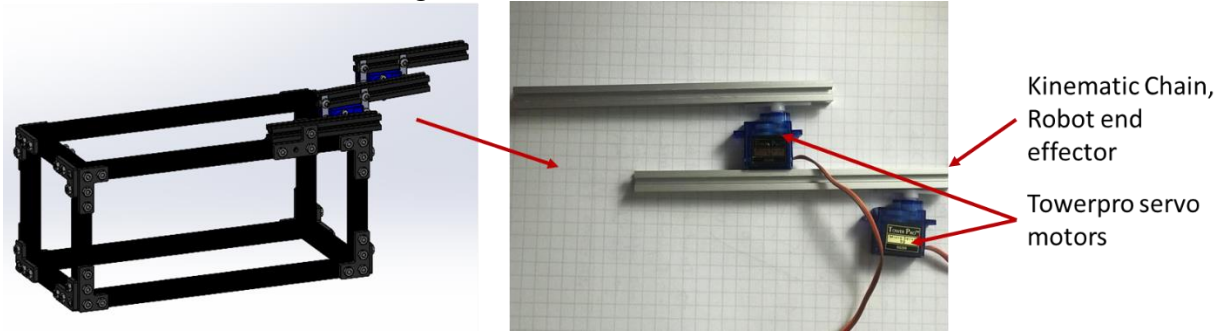


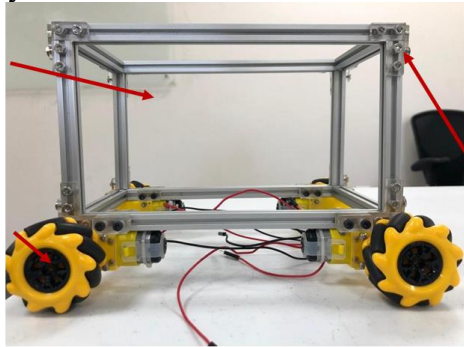
Figure 10 : End effector connected to Robot platform

Figure 10 describes two link arm that can be attached to the Robot and actuated using hobby grade servo motors.

**Omnidirectional mobile Robot:** Mecanum drives have recently become very popular in competitive as well as education Robotics. Inherent to the Omnidirectional mobile robot is, traversal along any direction by synchronized adjustment of the speed of wheels. The basic mobile robot can be modified by replacing casters and regular wheels by a set of mecanum wheels.

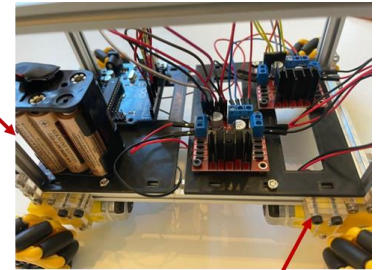
General Purpose – Reconfigurable frame

Other Omni directional drives such as mecanum and kiwi drives



Ability to install different open-source controllers, drivers, power supplies

Flat stock material brackets used for assembly



Modified brackets to mount motorized wheels

Figure 11 : Omniwheel mobile platform

As built price of the Robot is approximately \$97.5 usd (based on the latest price for custom and commercial off the shelf part). The basic Robot kit allows all the experiments listed in Section above. The kit also allows assembly of popular Open-source controllers: Arduino Uno, Arduino Mega, Raspberry Pi, Beagleboard and BBC micro. Specialized motor controllers, H-Bridges, general purpose breadboard and 9VBattery holders can be installed.

Should a user wish to enhance the capability of a commercial platform a sample of parts can be 3D printed to adapt the platforms.

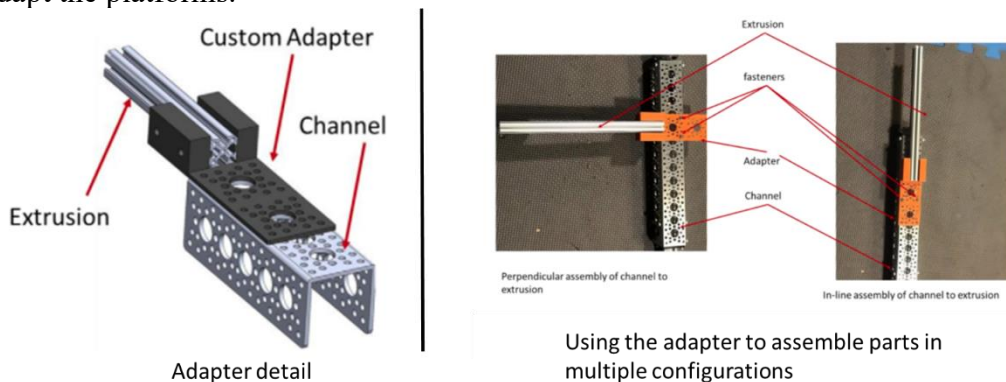


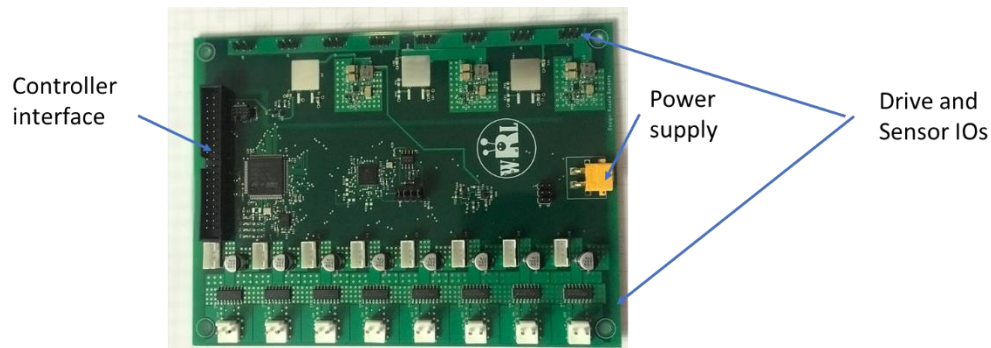
Figure 12: A 3D printed adapter to enable expansion of commercial kit using extrusion based platform

Figure 12 shows an adapter that is 3D printed to assemble parts from channel and extrusion system into a common assembly. The part is manufactured by Fused Deposition Modeling (FDM), using Orange Acrylic Styrene Acrylonitrile (ASA) printed with T40 tip.

### Conclusion/Summary/ Future work

In this paper we described how 3D printing was used to design and test different components to enable a low-cost educational robotic platform. The research described is limited to structural components and limited number of functional components. In future the same approach will be used to design functional components such as gears drives, linkage elements, and other complex end effectors.

Under Robotics for everyone initiative a general-purpose control board (Figure 13) is prototyped and tested. The control board allows integration of multipled DC motors, Servo motors and power management. Currently



*Figure 13: A general purpose control board to integrate motors, sensors and power management*

as manufactured price of the board is \$35, with further optimization and increased scale of manufacturing the price of the board will be further reduced. A common board will reduce the complexity of electrical assembly, reduce the number of parts and overall reduce the price of Robotic platform.

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