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Reviewed Paper

Impact of Solid Freeform Fabrication in enabling design and prototyping capabilities for Competitive Robotics such as World Robotics League, FTC, FRC, WRO etc.

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Abstract:

Competitive Robotics such as World Robotics League (WRL), World Robotics Olympiad (WRO), BEST, FIRST programs such as FTC and FRC, etc. have recently evolved as an avenue for learning, innovation and providing real life perspective to classroom learning. Given the short duration for Robot Development and diverse range of challenges, innovation, and product development has to happen at fast pace. Typical challenges include stow, configure, launch, traverse 3D environment, sorting, assembly etc. Many challenges include underwater and aerial spaces. Participants typically use reconfigurable "Robotics Kits". However, "Robotics Kits" are limited in many ways and do not go beyond mobile platform and simple mechanisms. Many participants are turning to quicker alternatives such as Solid Freeform Fabrication. This paper provides a current state of the Competitive Robotics, the existing solutions, and examples of how Solid Freeform Fabrication is accelerating innovation in competitive robotics.

1. Introduction

Ability to correlate the classroom learning with real life system, verification and qualification of ideas via experimentation is cornerstone of learning and excelling in Science and Math. For many learners as well as educators, reconfigurable equipment such as hobby and learning grade Robots have become a natural medium to learn and experiment. Robots are a special category of machines distinguished by an architecture that allows- multifunctionality, reconfigurability, and re-programmability [1]. The design, building, and operating the robots therefore requires a varied range of skills. Various aspects of robotics therefore become instrument for experiments in logical thinking, programming, and principles of math and physics. To list a few examples:

1. Robot navigation and impact of acceleration, deceleration, velocity, and displacement relationships for accurate and time effective motion of robot between two points in a 2D or 3D environment.
2. Correlation between wheelbase, the motor rotation, mobile robot wheel diameter, and total distance covered, steering about the obstacles.
3. Levers, gears, kinematic chain, simple machines, and torque to force relationship when lifting objects with the robot arm.
4. Load distribution and the principle of center of gravity when the robot climbs on an incline and decline.

In their research, Ardito et al. and Sana et al. [2,3] 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 [4] 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 participate in various robotics competitive leagues [5,6,7, 8].

The application of the robots subdivide them into mobile and non-mobile robots [9,10]. The kinematic control of the robot further classifies it as autonomous or a teleoperated system. However, within competitive robotics most of the challenges are based on mobile robots. At the start of the game, the robot is placed in what is referred to as robot base. During the game, the robot travels to different part of the robot field and completes a variety of tasks. The tasks may include pushing, pulling, moving objects, actuating mechanisms, etc. The robot game is usually time bound. The scores assigned are based on total tasks performed within specified challenge duration. In case any exceptions are made, a penalty is assigned. The penalty may negatively impact the total score. In many other competitions, such as robosoccer, sumo-robots, or one-robot events, multiple robots compete as opponents and the scores are determined not only by the robot's direct accomplishment but also by inhibiting the opponent. Many competitions require autonomous mode, others require teleoperated mode and some have both the rounds. World Robotics League follows a progressive approach, and the challenges are based on specific skills.

This paper is an outcome of efforts from our Robotics team – ROBOMakers, from North Texas. The team has participated in various competitions since last 4 years and has been recognized for technical excellence. While preparing, the team experimented with many kits, designed and manufactured many parts using the various additive and subtractive freeform fabrication processes. In this paper the team is going to provide a survey of different competitions, kits and their limitations as they are available. The team will provide various case studies as they pertain to limitations with the equipment and usage of Solid freeform fabrication for functional and structural design improvements, adjustment of form factors, load optimizations increasing reliability and customizations for end effectors for the task.

2. A brief survey of various competitions

In this section we are describing popular robotics leagues. Competitive Robotics leagues offer challenges in land, underwater and Aerial Robots. This paper describes application of SFF technology particularly in context of on-land, wheeled robots. Most of the competitions are either completely or in part restrictive about the manufacturers and kits to be used. The format of competition can range from just one set of challenges to structured and systematic progression. Table below summarizes a brief overview of various leagues.

Table 1 : Brief description of popular competitive robotics leagues

Competition	Manufacture Specific Kit	Structured Learning	Short description	Reference
World Robot Olympiad	Lego with other limited custom parts	No	Competitions are in four different categories: Regular, Open, Football, and ARC.	[11]
BEST Robotics	VEX kit and Other specified materials	Limited	Specific kit comprising of wood, PVC, DC motors, VEX Hub, wires, motor drivers, and other parts is provided annually.	[16]
World Robotics League	No restrictions	Yes	Challenges are offered through the year with emphasis on each participant learning and quantifying progress in structured manner leading to participating in larger team and complex challenge settings.	[15]
FIRST Lego League	Only Lego	No	Robotics is just one part of league competitions. It involve designing and programming using only LEGO Mindstorms, NXT, and SPIKE Prime robots to complete tasks based on the year's theme.	[12]
FIRST Tech Challenge and FIRST Robotics Challenge	REV, Modern, Servocity, Gobilda and some custom parts	No	Robotics is just one part of league competitions. It involve designing and programming using only league prescribed items to complete tasks based on the year's theme.	[13,14]
Robocup, Junior	No	Limited	The robots compete in one of three main leagues: Soccer, Rescue, or Dance varying in complexity from line-following on a flat surface to negotiating paths through obstacles on uneven terrain.	[17]
Robo One	No	No	Based on bipedal humanoid robots. The competition includes an autonomous stage, followed by one-on-one matches.	[19]
VEX Robotics Competition	Only VEX	No	A challenge is announced annually and the participants design, build, program, and drive in part autonomous and part teleoperated mode.	[18]
National Underwater Robotics	No	No	Requires creation of remotely operated underwater vehicle tethered to the surface and manually controlled through underwater camera telemetry. A multitude of end-effectors are used to complete several different tasks	[20]

3.0 Architecture of a Competitive Robot

A typical competitive robot has three main parts:

1. The vehicle

2. The End effector
3. The Controller and power supply

The vehicle, as name implies, is a mobile platform that takes the robot from one point to another. Additionally, for the objects to be moved and manipulated, end effectors are attached to the robot. As described in Figure 1, the end effectors can be grippers, collection tray or launcher. The end effector itself may be connected to an arm. While the vehicle itself may be capable of manipulating the end effector to the desired location and orientation, arm connected to the end effector provides additional articulation.

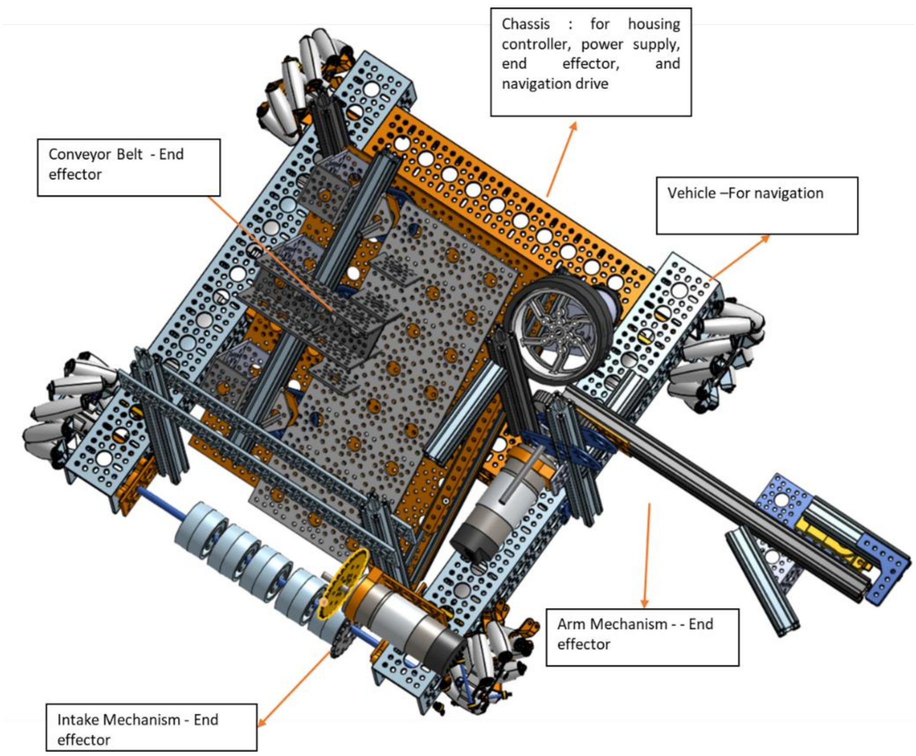


Figure 1 : Architecture of Competition Robot

The wheels as well as the arm and manipulator are connected to DC or Servo motors. Certain competitions require the robots to complete the tasks in autonomous manner [12,15], whereas in other competitions[11,13-20] the robot may be teleoperated, or have two-part events teleoperated, as well as autonomous. A robot controlled in teleoperated mode communicates with remote via WiFi, Bluetooth or similar wireless electronic communication. Motors are powered by an onboard battery and are connected to the controls and communication module. Robots functioning in autonomous mode use multiple sensors such as touch, ultrasonic or vision modules connected to them. Based on the inputs from the sensor, a program in the onboard computer maps the environment and navigates the robot to accomplish the missions.

Figure 2, Figure 3 and Figure 4 describe a representative set of challenges offered by different leagues recently. World Robotics League describes a challenge in 3D space. The robot needs to travel from left to right. As the robot travels, it starts on a platform then in the middle section, it travels on two beams then lands on the platform on the other side.

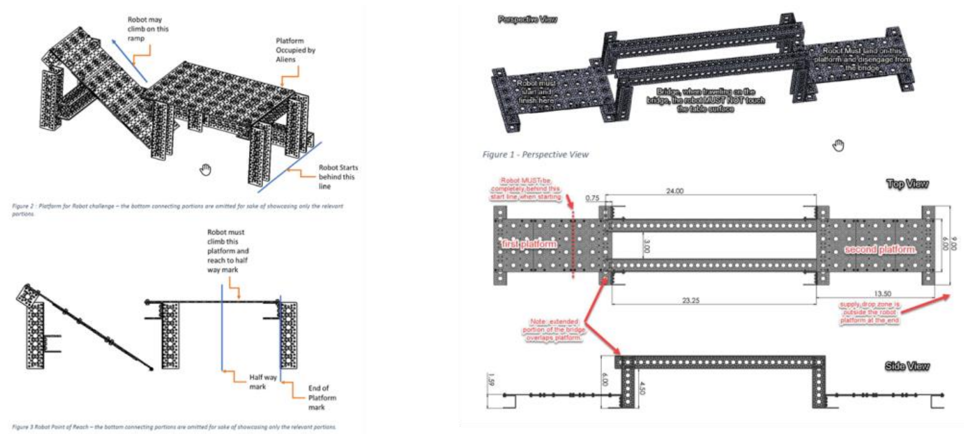


Figure 2 : World Robotics League, Challenge 2 and Challenge 3 of Season 2018[15]

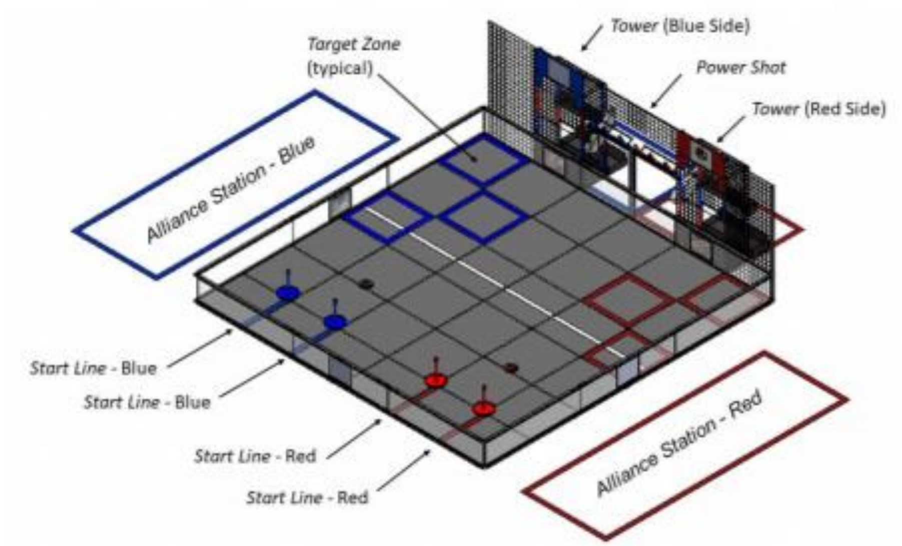


Figure 3 : FTC, Challenge Ultimate goal, year 2020-2021[21]

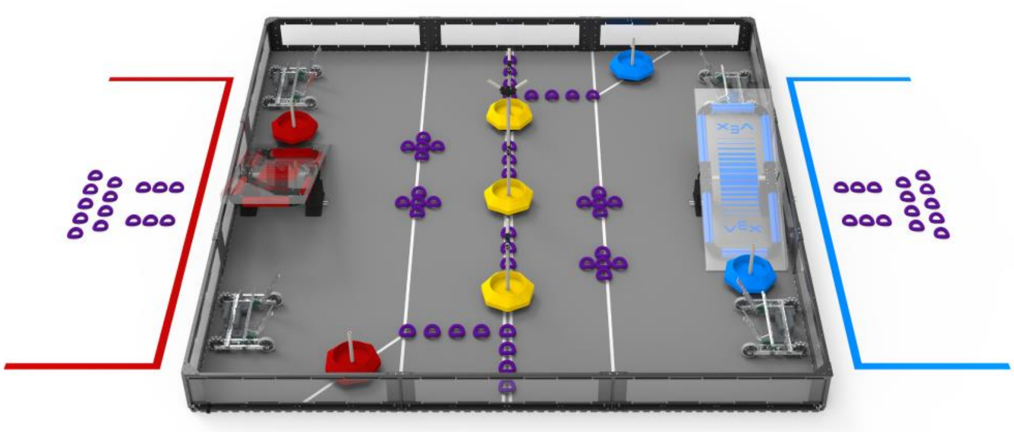


Figure 4 : Vex Challenge Tipping point, year 2021-2022[22]

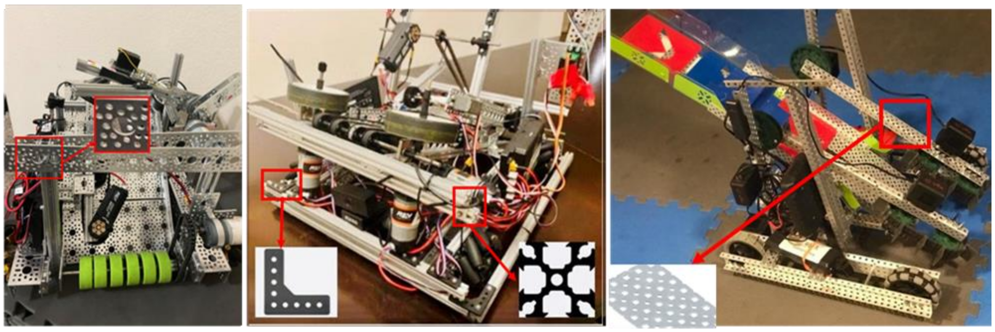
For the FTC challenge, during the Autonomous period, robot needs to deliver Wobble Goals to the randomized Target Zone and then Launch Rings. During the teleoperated mode robot needs to collect and Launch Rings. In the VEX challenge Robot needs to scoring rings, move mobile goals to alliance zones, and elevate on Platforms. It is apparent from the modes of challenges that the missions require quick testing and verification of many different ideas by the teams.

4. Description of the kits

The configurability of the robot kits is required to be able to build and test various mechanisms and subsystems within robot. Popular manufacturers for the kits include Lego[23], goBILDA[24], ServoCity[25], Tetrix[26], REV[27], AndyMark[28], and VEX[29]. The kits include various functional and structural arts including DC motors, servo motors, wheels, metal channels, extrusions, screws, nuts, gears, chains, sprockets, conveyor belt, brackets, connectors, and more.

As described in Figure 5 the reconfigurable robot building kits fall into two primary categories, channels with patterned holes, and extrusions. The channels with patterned holes have a set of holes that are arranged in a sequential array. The channels can be attached to each other along the patterned holes. The patterned hole also allows assembly of the channels along different angle. The angle between the channels is limited to the pitch of the holes. The functional components such as gears, sprockets, and pulleys are connected to shafts via blocks or bearings at the patterned holes. Different elements of the channel-based robots are restricted to linear and the circular pitches of the channel holes.

The channel-based kits have a pattern of holes to assemble the structural as well as functional parts. A specific pattern is available to assemble the channels in line or at an angle. Additionally, the adapters for motors, shafts, etc. are designed to adapt to the hole patterns in the channels. The hole design in channels vary based on the manufacturer. The same applies to extrusions. In addition to the structural elements, the hardware between the kits may be incompatible. The DC motors are the strongest motors provided and are usually paired with wheels and/or the mechanisms of the robot. Hex and Servo motors are typically used for mechanisms and are used for driving gears, chain, sprocket, and a conveyor. The total motors and drives may not be adequate to build a robot, teams usually end up buying additional parts.



Channels with Round hole pattern based robot, Team ROBO*Makers*, Allen TX

Extrusion based robot, Team RoboPlayers, Irving TX

Channels with square hole pattern based robot, Team V*Extraordinaries*, Seattle, WA

Figure 5 : Sample of robots built using extrusions and different channels

Extrusion-based kits are similar to most of the industrial extrusion systems with brackets and angles to connect the parts and blocks for mounting motors, shafts and gears and pulleys. Assemblies and subassemblies that are based on extrusion are governed by the size and pitch of the extrusion. Similar to the channel-based subassemblies, the extrusion-based assemblies are restricted by the pitch of the extrusion system.

The interchangeability of different kits is extremely limited. What further limits this ability is the shaft geometry of motors and other rotational components. A team may primarily design and manufacture the robot based on one kit, however, due to the inherent form factor advantage, may want to use the items from a different kit. The team may design and manufacture an adapter that allows use of components from two different kits. Similarly, gears and other such similar elements are available in the matching pattern of the channel or extrusion system. While the robot chassis and arm may be easily built with the extrusion or channel-based elements, end effectors need to be optimized based on the task. The channel and extrusion-based systems become extremely restrictive.

In following sections, we will describe different scenarios where 3D printing is used for optimizing and improving overall performance of a competition robot.

5. Design and optimization Examples using the 3D printing

5.1 Adapters for different Robotic kits

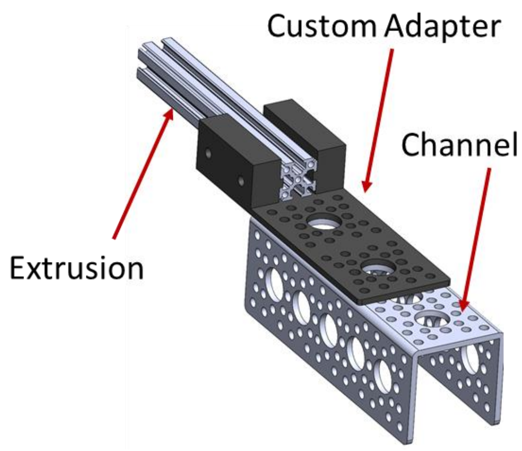


Figure 6 : Custom adapter designed to assemble extrusion and channel based structural elements

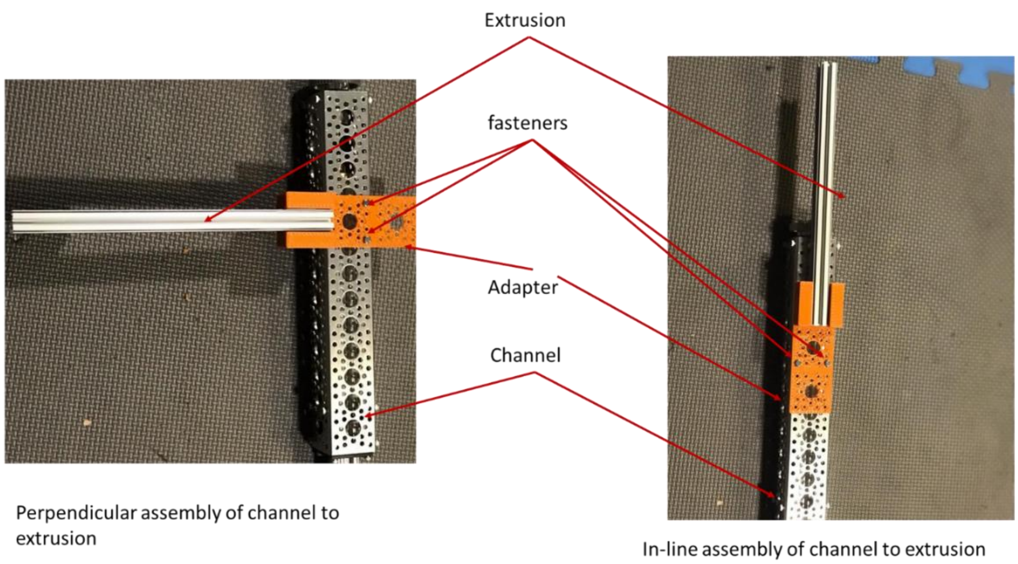


Figure 7 : Attaching 3D printed adapter along in line and perpendicular configuration

As described in one of the earlier sections, the ability to interchange parts from different kits is extremely limited. A team may design and manufacture the robot based on one kit but build other subsystems such as drives from another system either due to the form factor advantage or the availability. Figure 6 and Figure 7 show a set of parts that are designed and 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. Total time required to manufacture the part is 20 minutes.

5.2 Optimization of Gripper End effector

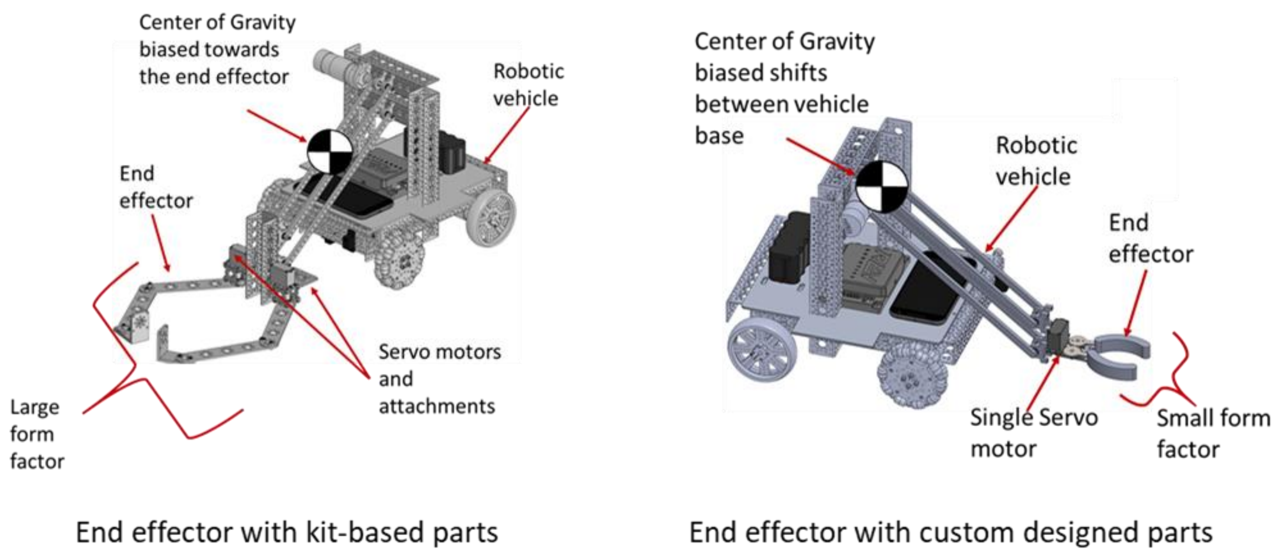


Figure 8 : Impact on the Robot due to kit provided vs custom designed and 3D printed parts to build end effectors

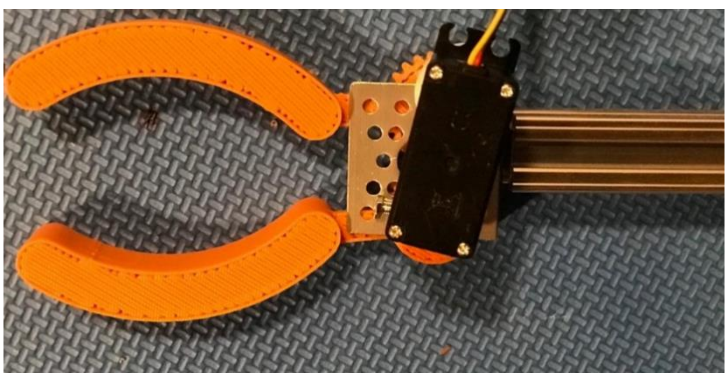


Figure 9 : End effector built using 3D printed parts

Figure 8 describes a robot with a gripper end effector. The end effector of the robot is built to pick up objects approximately 2inches in diameter. The robot is built using the items provided in the channel-based kit. The system has two griping fingers each actuated by a servo motor. The end effector is mounted on a parallel bar-based arm. When built with the kit provided elements, the size of the end effector becomes extremely large. Usually such an end effector is optimized by using two spur gears driven by a single motor. The engagement of the gear teeth not only allows transfer of torque to both the gears, but also synchronized motion of the two fingers. The gear assembly each requires multiple bearings and mounting blocks, shaft and the gear itself. With the maximum robot weight limitation of 45lbs, the overall weight of the gripper itself is approximately 3.5lbs. Additionally, when the robot arm extends, the center of gravity of the robot shifts beyond the wheelbase, making the robot unstable. The challenge item to be lifted with the help of the gripper is round. The contacting surface it planar and doesn’t comply with the object to be lifted, thus reducing the reliability of the mission.

As shown in Figure 9 an alternate gripper is manufactured using 3D printing. The total number of parts is significantly reduced. The gripper is driven using a single motor. The gripper is designed to comply with the shape of the object, hence increasing the total contact. The gripper weight is significantly lesser (.37lb). The part is manufactured by FDM, using Orange (ASA) printed with T40 tip. Total time required to manufacture the two parts is 37 minutes.

5.3 Cable organization, Shock and vibration reduction using custom suspension for controller

a. Empty space under the ramp

b. Hub and battery on the side of the robot

Figure 10 : First pass installation of controls and power module.

In one of the challenges robot mechanism needs to launch objects. Clear obstruction free surface is needed for smooth launching of objects. As shown in Figure 10. that leaves only sides of the Robot available to install Controls and battery. The hubs installed on the side of the robot are very bulky and take up a lot of space. Additionally, they make the load distribution asymmetric. Mounting the hub under the ramp using screws would restrict the rings from going up smoothly. There is empty space available below the ramp where the battery and controls can be easily accommodated. The problem with this arrangement is: (1) inaccessibility and (2) unreliable wire connection. A custom cartridge-like housing is designed for a better organization of wires and reduce overall tension on the wires.

The control system and the electronics is extremely susceptible to mechanical shocks. The robot turns quickly, travels an uneven terrains, and bumps into objects for a better alignment. The vibration isolation of the control system, receiver and the power supply are required. The kit as such does not provide any fasteners, similar damping or isolating mechanisms

3D printed housing is described in Figure 11, instead of on the side, the hubs and battery could go under the ramp with 3D printed part. Pockets are designed for the hub and battery. Features for assembling and guiding the wires are added. Silicone based shock absorbers and features to tie the wire for stress release are added to the fixture. Platform with the integrated mechanism isolates the mechanical shocks. The part is manufactured by FDM, using Orange (ASA) printed with T40 tip. Total time required to manufacture the part is 41 minutes.

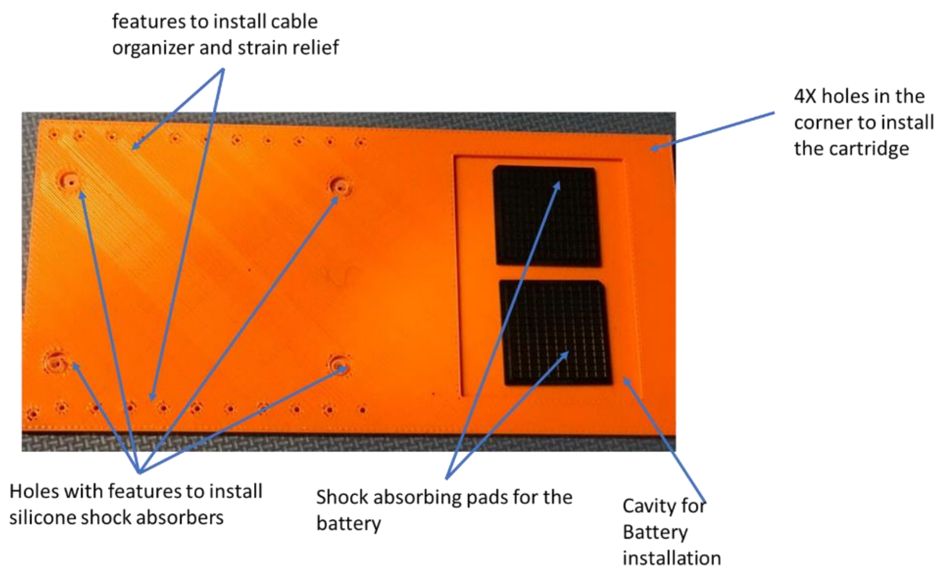


Figure 11 : Custom designed and 3D printed cartridge base for Robot control and power module

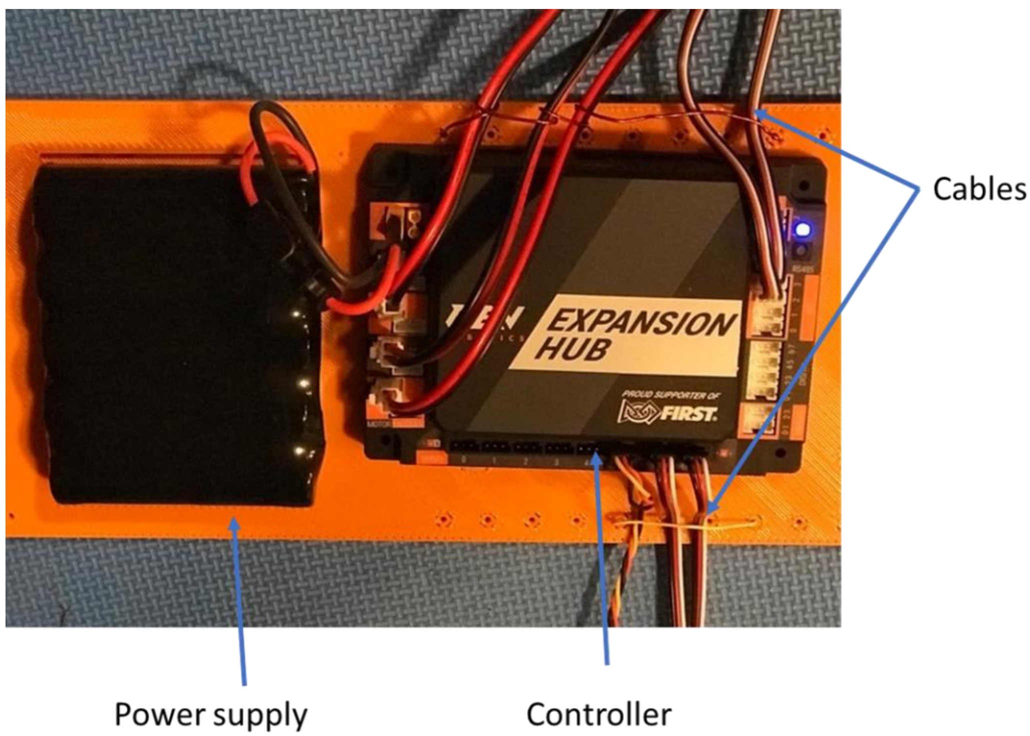


Figure 12 : Hub and power supply installed on the custom base

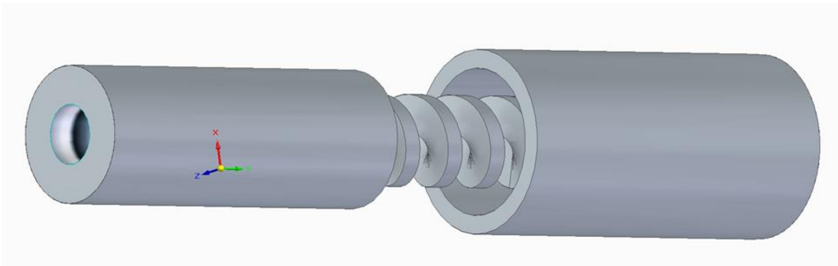


Figure 13 : Suspension housed in a telescopic arrangement

In another experiment to improve the ride quality, team built custom Linear Suspension system. As described in Figure 13, the suspension system contains two cylinders that enclose a spring. Both cylindrical enclosures have threaded holes to attach screws to mount to robot. However, a basic kinematic analysis suggests that, the suspension system should have additional degree of freedom to move. The thickness of the spring is increased, and the telescopic enclosure is removed.

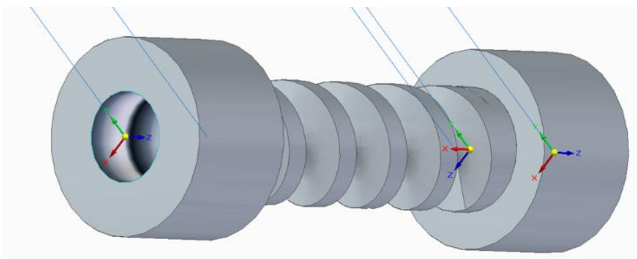


Figure 14: Modified suspension system with additional degrees of freedom.

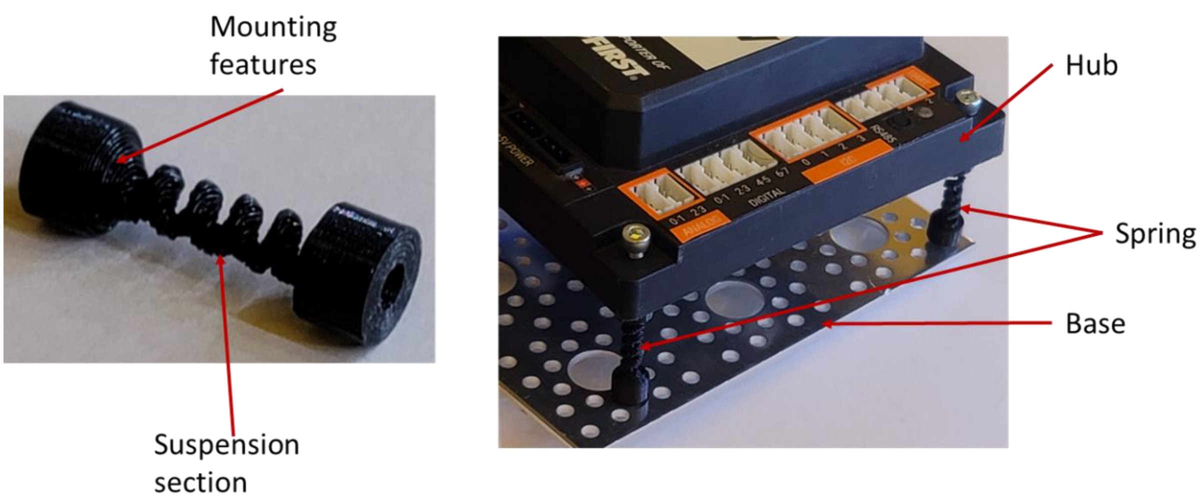


Figure 15: Hub installed via modified suspension

Figure 14 describes the modified suspension system. As shown in Figure 15, the part is manufactured on an Ender 3 Pro using Pla+ material. The total weight of the mechanism is 1 gram. With the telescopic system removed and the thickness of the spring adjusted to match the acting load, the hub ride quality is improved. However, the large mechanical shocks make the part susceptible to stresses. The final solution as described in Figure 11 and Figure 12 uses the 3D printed base and an off the shelf silicone suspension.

5.4 Camera

Figure 16 : The first pass mount for the camera and the camera.

The camera is used in the autonomous mode of the robot to analyze the field using machine learning principles. The field of view and distance are critical for proper detection of the features. The camera mount that comes with the kit is about 4 inches in height. Required height should not exceed 2 inches. As shown in Figure 16, in the first revision, the mount for the camera is built using components from the channel system. The limitations of the mounting hole positions still prevent the camera height to exceed 2 inches. The parts from channel system take up a lot of space.

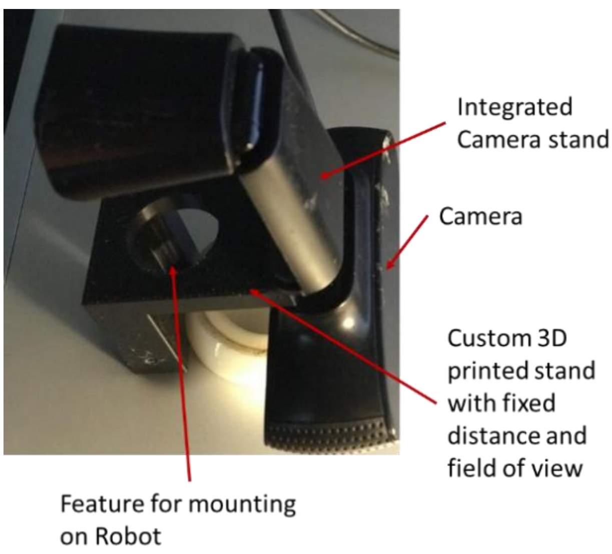


Figure 17 : 3D printed custom camera mount

A custom mount as shown in Figure 17 is designed and 3D printed for the camera. The 3D printed part is designed precisely to the alignment and with the mounting. This allows better space utilization along with repeatable and accurate camera performance. The part is manufactured by FDM using Nylon 6. Total time required to manufacture the part is 32minutes.

5.5 Custom Gears

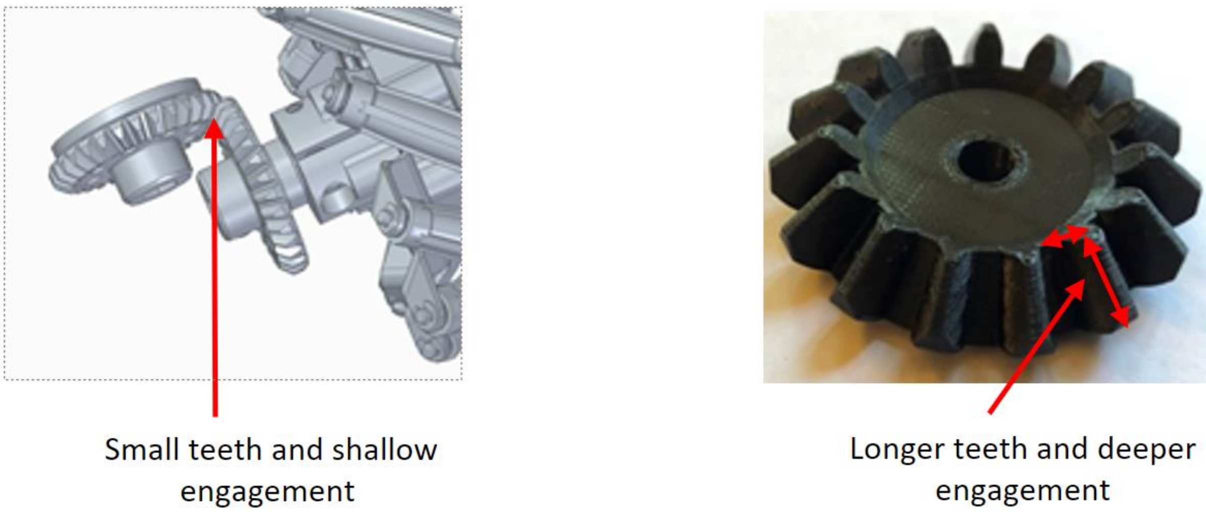


Figure 19: 3D printed custom bevel gear

Bevel gears are used for changing the direction of motion and usually arranged in an open configuration (Figure 19). It was quickly realized in our applications that the gears that came with the base kit had small teeth and had limited engagement. This led to frequent slipping between the gears. As shown in figure 19, a bevel gear was designed and then manufactured using an Ender 3 Pro. It was created with PLA+ filament and weighs 4 grams. The 3D printed gear had deeper and wider teeth which reduced the instances of gear slip.

5.6 Other opportunities to use 3D printed parts

The ideas discussed in this section were considered during various competitive seasons but not implemented, since other alternative solutions were find. However, they are discussed here due to relevance.

5.6.1 Solenoid and kinematic chains

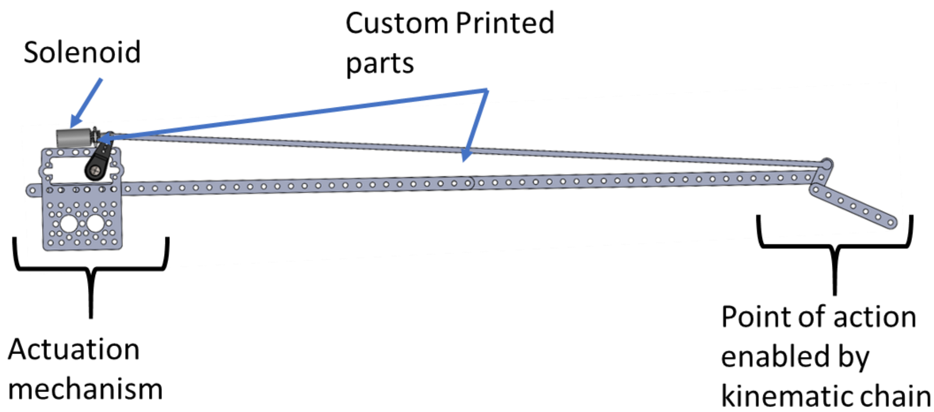


Figure 18 : A custom solenoid activated kinematic chain

With the motor being the primary drive where motion emanates, rack and pinion and kinematic chain mechanisms are used for the conversion of the rotary motion to linear motion. Actuators such as linear solenoids can be used. Pneumatic systems can be used alternatively; however, many leagues do not allow using pneumatic systems. Custom 3D parts can be designed, and 3D printed to build various kinematic chains. Figure 18 describes a kinematic chain actuated by asolenoid. The solenoid is placed remotely from point of actuation. The point of action stroke is amplified using kinematic chain. To keep the weight low and to maintain the accuracy of the link length, the two links are custom designed and can be fabricated using 3D printing.

5.6.2 Custom Pulley for Launching mechanism

The launching mechanism launches a set of disks by spinning two flexible disks in CW and CCW directions respectively. The launch accuracy is dependent upon the speed and the torque of the motor. Space and torque requirements restrict the mechanism to be based on two motors and the speed is synchronized using controllers. Unfortunately, most of the motors used are hobby grade gearmotors and with limited speed monitoring using the feedback. The placement of the two motors close to the launch point also makes the mechanism heavy. The weight from the motors can be shifted away from the launch point a timing belt and pulley arrangement. The kit provided pulleys are large and limit the extent of the engagement from the compression wheels. Using 3D printing, a smaller custom pulley can be printed. A mechanism based on gears and pulleys is made to synchronize the two spinners, not only reducing the total part count, but also increasing the accuracy of the system

6. Conclusion/Summary

Competitive robotics offers many learning opportunities and various mechanisms can be built and tested using Robotics kits provided by various manufacturers. Limitations of such kits can be overcome in cost effective manner by custom design and 3D printing various parts. This paper demonstrates the same with different examples. The team, in near future will make catalog of parts available to other learners, and participants to use and invite other participants to contribute to the catalog.

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