Replacing Botball Kit Parts with 3D Prints

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***Abstract*—The authors emphasize the importance of material selection and evaluate their performance depending on various tasks. Either material type can have different impacts that are not limited to weight, but on robot design as well. Plastic parts are more lightweight, but need additional support and a more complex structure. While metal parts are simple and easy to use, they are limited by their weight, making them not adaptable, yet still the default and simple choice for less demanding environments. This paper provides an in-depth analysis to help teams select materials based on their specific needs.**

I. INTRODUCTION

In robotics, material selection—specifically regarding cost, stability, and weight—critically impacts a robot's performance and behavior. While various materials have been studied, limited research exists on the viability of replacing standard components with cheaper or lighter alternatives [2, 3].

This study evaluates the performance differences between 3D-printed plastic and metal components within the Botball Kit configuration. The focus is on durability, speed, and mechanical resistance, noting that metal provides structural rigidity and higher inertia, while 3D prints offer weight reduction at the cost of increased fragility.

Additionally, this paper examines how material changes necessitate adjustments in control logic. Failure to account for mass and friction differences can lead to mechanical failure or task inaccuracy, which is critical in a competitive environment. By testing tasks such as straight-line navigation and object manipulation, this research provides robotics teams with the data needed to make informed design decisions based on specific mission requirements.

II. TESTING CONDITIONS

The robot was constructed using metal components from the Botball Kit, which serve as the foundation for all test metrics. These parts include straps, channels, plates, and the chassis. First, we inspected the metal components. Then, to recreate the structural integrity of the metal while making it more lightweight, each one was replaced by a 3D-printed version using the default infill settings. This allows the parts to behave similarly and helps determine practical differences between each part and decide if changing the material is reasonable.

To assess long-term performance, each component was subjected to repeated loading cycles until failure. For each load test, mass was gradually increased until the part showed deformation or breakage. Failure thresholds were recorded for all 12 samples per component.

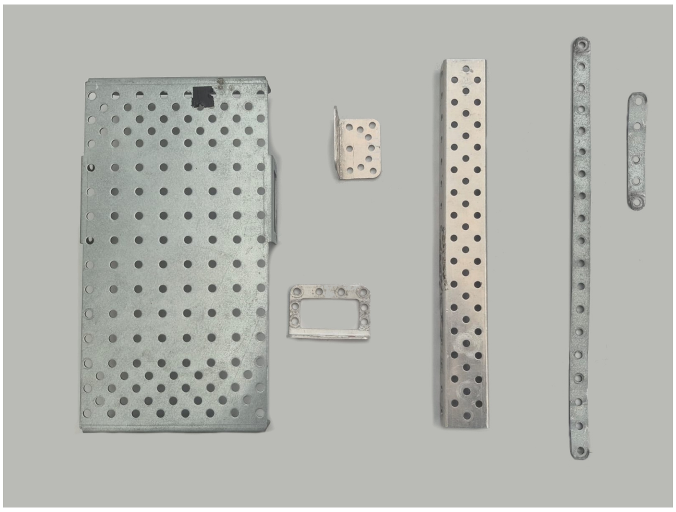

Fig. 1. Metal parts of the Botball Kit [7], including (from left to right) Chassis, Servo Brackets, Angle Brackets, Channels, Straps and Servo Horn. These represent the baseline components used for mechanical comparison.

The objective of the tests was to ensure that each replacement part could perform basic tasks. Three identical samples of each component were printed and tested to account for different print quality. Every part behaved the same, unless otherwise specified. If a component did not break during testing, the next step was to try to break it manually to verify whether it could be broken without using unrealistic weights. Any piece that is a replica of a larger piece will not undergo testing since longer parts tend to break more easily due to lever effects during bending or buckling. However, the required force depends on the geometry and loading conditions. In this configuration, the relationship follows a moment-based lever relationship, where the torque M is given by $M = F \cdot L$. Consequently, for a constant required torque, the force is inversely proportional to the lever arm length L.

III. PRINTING INFORMATION

The assessment of 3D-printed parts against their original metal counterparts covers quality, dimensional accuracy, and mechanical performance. All parts were manufactured using PLA filament on a standard fused filament fabrication (FFF) system. Dimensional accuracy of the printed parts was evaluated by comparing three measurements per part with the original metal templates. Deviations were typically within ±0.2 mm, which is within the expected tolerance for PLA FFF printers but insufficient for micro-precision parts such as servo horns.

To ensure maximum stability during the process, all parts were positioned with their largest surface facing the print bed. This meant that the walls were printed horizontally on top of the build plate. This orientation impacts the mechanical properties of FFF parts, as they are anisotropic [5]. In future work, it may be important to align layer lines with the expected stress vectors using different orientations. All test pieces were printed [6] under the following settings:

- Infill: 100
- Fill Pattern: Straight
- Support: None
- Printer: Bambu Lab A1 [1]
- Nozzle: 4 mm
- Other parameters: Default values from the Bambu Slicer software

TABLE I
3D-PRINTS OVERVIEW

Print	Time	Plastic (g)	Metal (g)	PLA (m)
Servo Bracket	21m 29s	5.51	10.00	1.73
Channel	55m 31s	23.41	39.00	7.37
Strap	24m 19s	8.69	33.00	2.74
Angle Bracket	17m 25s	3.36	11.00	1.06
Servo Horn	36m 29s	5.74	8.00	1.81
Chassis	2h 21m	69.57	383.00	21.91

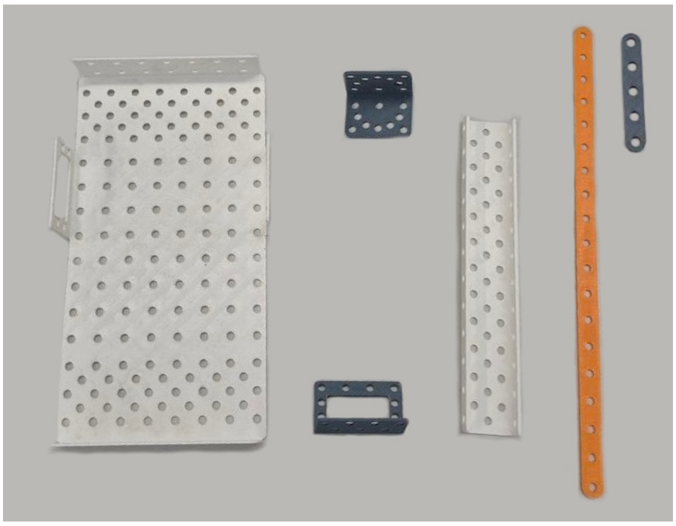

Fig. 2. 3D-printed replicas of Botball Kit components manufactured in PLA. (from Left to Right): Chassis, Servo Bracket, Angle Bracket, Channel, Strap, Servo Horn.

IV. TESTING

A. Servo Bracket

Although the printed servo bracket replicated the basic function of the metal one, its dimensions were poor. The inside was too small and required filing as part of the post-processing to allow the motor to fit. Although there was no fracture when tested, plastic deformation did occur when a mass of approximately 200 g ± 10 g was applied. Once deformed, it never returned to its original shape, indicating that the part had undergone permanent plastic deformation beyond the elastic recovery range of PLA. Even though design changes might solve fitting problems, real limits will always exist regarding load-bearing capability compared with strong metallic equivalents.

B. Angle Bracket

The printed angle bracket demonstrated effective functionality during the initial testing phase. However, upon the application of load, its performance was found to be suboptimal. The sample failed under a mass of approximately 100 g, with no occurrence of complete fracture. However, the extent of the damage was such that the component in question became unusable. In contrast to the servo bracket, this failure cannot be reasonably rectified. Increasing the thickness of the wall would result in the component deviating excessively from the original design, and it would not address the inherent weakness of PLA when subjected to concentrated loads. In this instance, PLA is not a suitable substitute for the original metal version.

C. Channel 1x12

The channel print behaved quite differently from the previous parts. The mechanical test revealed that the PLA structure could support 15 kg of mass without showing signs of failure. While this force exceeds the working forces expected in Botball, it proves that, for non-critical load paths, 3D-printed PLA parts can perform adequately for applications where high strength is not critical, despite their generally inferior mechanical properties compared to metal parts. [3].

D. Servo Horn

The printed servo horn broke. This failure was ductile, meaning the component experienced plastic deformation without fracturing brittlely. This was not due to a lack of strength, but rather because it was unable to recreate the fine geometric details available in the metal version. Servo horns require internal ridges to be picked up in the mounting holes, which interlock with the servo shaft in order to transfer torque. Without these ridges, the horn was unable to transfer rotational force. Therefore, despite the strength of the material, it failed. This highlights a key limitation of FFF printing: micro-precision features below 0.3 mm cannot be reliably manufactured, particularly the fine spline geometry required for servo interface engagement. Potential improvements include printing with resin (SLA) technology, using metal inserts or redesigning the horn to use clamping-based torque transmission instead of spline engagement.

E. Strap 1x19

The strap component performed exceptionally well in both directions, primarily because of its thin shape. Under tensile load, the strap stretched slightly before breaking at approximately 8 kg of applied mass. This is similar to what happened in earlier baseline tests with metal straps, though it is clear that the PLA version is not as durable. For light structural applications where only minimal loads are expected, the printed strap provides an acceptable substitute.

Summary and Comparison

Across all tested parts, results affirm that PLA printing is a viable alternative for specific configurations but not a universal substitute for metal. Robust components like the Channel 1x12 distribute stress effectively, sustaining loads up to 15 kg that exceed typical operational requirements. In contrast, the Strap 1x19 and Servo Bracket demonstrate lower thresholds, failing or permanently deforming under relatively light masses. Furthermore, the failure of the Servo Horn illustrates that FFF printing cannot replicate micro-precision splines under 0.3 mm required for torque transfer. For high-precision or high-load parts, especially where small engagement features are essential, metal remains indispensable.

V. STATISTICAL ANALYSIS OF FAILURE LOAD TESTS

Twelve loading tests were repeated for each of the three printed components, with multiple tests performed on the same sample (amount of tests, n = 12). Summary statistics for the failure loads are reported as mean ± standard deviation (SD). The X-Axis represents the test. The Y-Axis represents failure loads in grams. The failure load data for each component is illustrated in Figure 3, Figure 4, and Figure 5.

The strap demonstrated the highest overall strength (slightly above 8 kg of mass applied) and the lowest relative variability (CV = 0.53%), indicating very consistent behavior across all tests. The servo bracket and angle bracket failed at substantially lower forces, with the angle bracket also showing the highest relative variability (CV = 5.60%), suggesting greater sensitivity to minor geometric or printing deviations. Despite their lower strength values, the results for both the servo bracket and strap showed tight clustering, indicating good repeatability of the testing procedure.

Some components were deliberately not included in the statistical evaluation:

- Servo horn, as it could not be used or meaningfully tested in the present configuration.
- Channel, as the mass required to break it was too high; even at maximum test force, no fracture could be produced.
- Chassis, as no separate tests (other than the speed tests) were carried out for this.

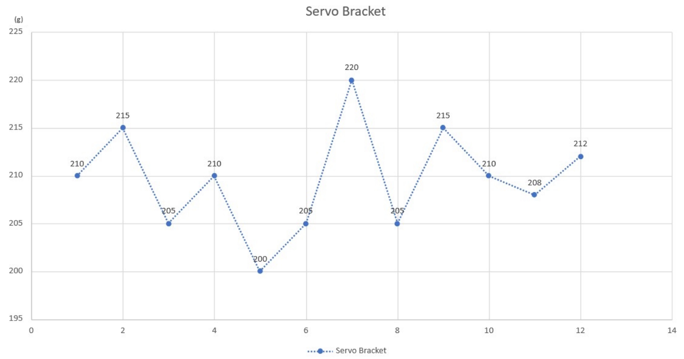

Fig. 3. Graphed Servo Bracket deformation

- Servo Bracket: mean = 209.58 g, SD = 5.48 g, median = 210 g, min = 2 g, max = 220 g, range = 20 g, CV = 2.62%.

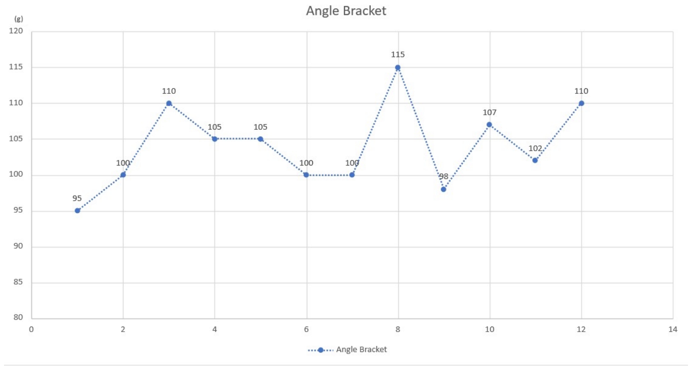

Fig. 4. Graphed Angle Bracket deformation

- Angle Bracket: mean = 103.92 g, SD = 5.82 g, median = 103.5 g, min = g, max = 115 g, range = 20 g, CV = 5.60%.

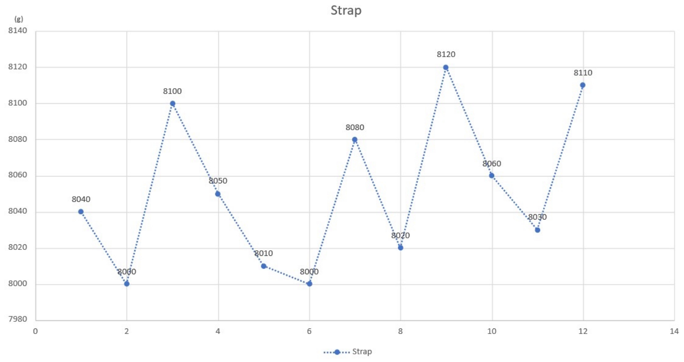

Fig. 5. Graphed Strap deformation

- Strap: mean = 8051.67 g, SD = 42.60 g, median = 8045 g, min = 8000 max = 8120 g, range = 120 g, CV = 0.53%.

VI. SPEED COMPARISON OF CHASSIS

Two different chassis types were used to test the speed of the robot: one metal and one 3D-printed plastic. Tests were run under two conditions: without a gripper and with a gripper attached. The results were normalized by noting the time it took the robot to travel one meter at its given speed. The time was measured via code, which stopped once the robot hit the back wall. A button was used to stop the timer.

There were no major deviations recorded for either chassis type when tested without a gripper over ten runs. The metal chassis averaged 6.342 seconds, while the plastic chassis averaged 6.298 seconds. In raw speed, the lighter plastic chassis offered a minor but measurable advantage. This difference translates into only about 0.04 seconds per meter and is negligible by whatever standards one applies, considering measurement tolerances as well as such outside influences as fluctuations in battery charges or surface friction.

Attaching the gripper arm completely altered the situation's dynamics. With the metal chassis and gripper arm attached, the robot's average speed was much slower at 0.7234 meters per second. This means that traveling with a gripper arm takes considerably more time than traveling without one. Adding a gripper arm to the front of the robot increased its weight, which diminished dynamic performance by reducing acceleration and, consequently, the attainable overall speed. Unfortunately, testing of this plastic chassis could not be conducted using the same gripper arm due to limitations in 3D printing and servo design. A servo horn was used to connect the arm with the chassis. The grooves in the metal servo horn match the holes in the servos, but there are no grooves in the 3D-printed plastic horn. This prevents the rotation of the servo and other parts of the gripper arm. These grooves are too small and precise for a 3D printer to produce.

These results show that, for now, the 3D-printed lightweight chassis performs equally well or slightly better; however, the metal chassis becomes significantly stronger with the addition of other components. This makes the metal structure a more reliable option for practical applications.

VII. SPECIAL CASE: ANGLE BRACKET

A structural evaluation of the 3D-printed angle bracket (Figure 6) revealed a maximum deflection of 3° ± 0.5° under load, especially at the servo-side connection when the gripper arm rises. At maximum extension, the bracket orientation deviates by 2° ± 0.5° from the local surface normal.

Although the bracket is functional for light-duty tasks, such as successfully manipulating Botguy, the observed flexibility indicates potential long-term risks of material fatigue and reduced precision under heavier loads. Increasing the bracket's thickness or adjusting the infill settings [8] could improve rigidity. However, these modifications would increase the bracket's weight and deviate from the original design intent of a lightweight frame.

The bending did not prevent the robot from performing the aforementioned simple manipulation tasks, which demonstrates that the part retains sufficient strength for low loads and moderate precision requirements. However, repeated bending may lead to material fatigue, and small angular deviations may reduce accuracy when heavier objects or stricter alignment is required.

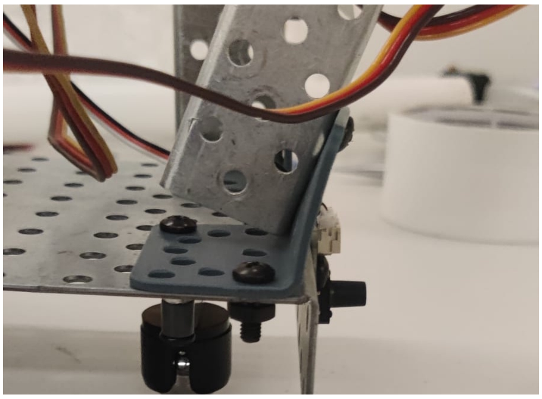

Fig. 6. Plastic Angle Bracket: Deflected Angle Bracket at Maximum Arm Extend

(± 0.5°)

In contrast, the metal angle bracket did not deform during operation, even at full extension of the gripper arm. This confirms that, while 3D-printed plastic is a viable, low-cost solution for prototyping and educational robotics, metal is better suited for real-world or competition environments, where durability and high precision are critical.

CONCLUSION

This study concludes that for general structural applications in educational robotics, replacing standard metal parts with 3D-printed PLA is generally not justifiable. While weight reduction was initially hypothesized as a significant advantage, the experimental results demonstrated that the benefits do not outweigh the risks associated with material reliability and precision.

For standard structural components like channels, plates, and brackets, the established metal parts proved superior. Although PLA components were able to sustain loads in non-critical geometries with large surface areas, the operational improvements, such as speed gains in the chassis traversal tests, were negligible within experimental tolerances. Conversely, the loss of reliability was significant. Metal parts offer inherent ductility and precision that PLA lacks, particularly in high-stress areas like servo horns and load-bearing joints, where the printed parts failed to maintain engagement or yielded under concentrated stress.

For components with highly localized geometrical features and precise geometrical shapes, PLA was found unsuitable for their fabrication. The servo horn test demonstrates this limitation. Even though bulk strength was acceptable, the printed part was rendered useless due to the printer's inability to reproduce fine details of ridges and engagements. In the same way, brackets that had to transfer concentrated loads suffered deformation at surprisingly low loads. Once the parts reached this yielding point, the inability to return to their original shape confirmed the low bend and torsion PLA strength at small scales and the inherent weakness of PLA material. The verdict is evident: for precision components with high-stress concentration, metal is irreplaceable.

The speed tests provided additional insights and details to the previous conclusions. Once a gripper was added, the advantage of the lighter chassis was overruled due to the dominant factors of mounting limitations and material incompatibility. Although a lighter PLA chassis is theoretically beneficial, the challenges of fitting servos, the durability of connecting parts, and the compatibility of standardized components diminish its usefulness in complex assemblies.

A vital conclusion from the research is the place of 3D printing technology not simply as a replacement but as a facilitator of customization. Teams are not restricted to duplicating metal components one-to-one; they can reinterpret components to take advantage of additive manufacturing's unique benefits. For instance, reinforcing ribs, optimized fill patterns, or hybrid assemblies could broaden the application scope for which PLA parts are dependable. This adaptability is a powerful argument for 3D printing technology in educational robotics [4] [2]. It is a tool for iterative prototyping with minimal expense, even if the final competition-ready model is mostly metal.

Therefore, the study suggests that 3D printing should not be viewed as a direct substitute for standard metal kits, especially because one can only print a maximum of six parts for Botball, but rather as a solution for specialized geometries. The true value of additive manufacturing in this context lies in creating components that do not exist in standard kits, such as customized grippers, complex sensor mounts, or specific adapter pieces. In these specific cases, the ability to customize geometry outweighs the material weaknesses of PLA.

Furthermore, the issue of stability could be addressed by incorporating a connecting truss into the Angle Bracket design. This can be explored in future studies, as this study only compared the current parts of Botball, not the improvements made to those parts.

Consequently, a practical design strategy prioritizes metal for the robot's core structure and drivetrain to ensure durability and precision, limiting 3D printing to specific, low-load functional attachments where customization is required.

Ultimately, the findings of this paper recommend a hybrid approach:

- Use 3D-printed PLA for large, non-critical structural components where weight reduction provides marginal benefits, but failure would not compromise the robot entirely.
- Retain metal parts for high-load, precision-dependent, or safety-critical components such as servo horns, angle brackets, and load-bearing joint
- Leverage 3D printing strategically for prototyping, rapid iteration, and creating novel geometries that cannot be achieved with standard kit parts.

Future research [9] should move beyond PLA and investigate engineering-grade thermoplastics such as PETG, Nylon, or Carbon Fiber reinforced filaments. These materials may offer the necessary toughness to bridge the gap between metal and plastic [10]. Additionally, future studies should implement automated, long-term fatigue testing to better understand how printed parts behave under the repetitive stress cycles typical of robotic competitions, an aspect that remains a critical variable for long-term reliability.

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