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Reviewed Paper

Route Your Ooze (RYO) Drive: A New Way to Route Flexible Filament in 3D Printing with Motion-Decoupled Rolling Joints

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Abstract

Flexible filaments such as Thermoplastic Polyurethane (TPU) are useful in a variety of 3D printing applications but are challenging to print due to their low stiffness and tendency to buckle, requiring constrained filament paths to ensure reliable feeding. To mitigate possible print defects, TPU filament is typically dried during printing using a filament dryer placed wherever necessary to accommodate the shortest and straightest possible filament path to the extruder. Traditional Bowden tubes, while simple and widely used, introduce high and nonlinear friction, particularly problematic when routing flexible materials over long distances or tight bends. This paper introduces the Route Your Ooze (RYO) drive, a modular, low-friction filament routing system adapted from rolling joint cable transmissions used in robotics. The RYO drive uses bearing-supported pulley joints to maintain constant filament path length and tension regardless of extruder position, offering a friction-insensitive alternative to Bowden tubes. The RYO drive exhibits significantly lower friction compared to Bowden tubes and is effectively length independent. The study also compared the RYO drive with Bowden tubes (specifically Prusa PTFE tubes and Capricorn PTFE tubes) on Original Prusa XL and found no improvements on material extrusion across its large print bed and no improvements on volumetric flow rate, likely due to the printer's already optimized path routing and customized hardware to print flexible materials. However, under tortuous filament pathway conditions — such as 2 meter paths with high total bend angles — PTFE tubes caused severe under-extrusion or print failure, while the RYO drive maintained consistent performance. These results validate the RYO drive's potential for flexible filament routing in constrained or custom configurations, where traditional Bowden setups fall short.

Introduction

3D printing has drastically expanded access to small-scale manufacturing, enabling individuals to readily design and produce components with a wide range of applications. One common form of 3D printing is fused filament fabrication (FFF), which utilizes polymeric filament feedstock that is melted and deposited over a substrate to build up components layer by layer. Several of the core advantages of FFF 3D printing are its small form factor, nearly unlimited design space, and wide range of compatible materials. The latter being particularly impactful for enabling difficult and niche applications where material properties such as mechanical strength, chemical and heat resistance, and compliance are critical design considerations. Most of these filaments are considered rigid along their length, meaning they resist axial stretching and compression, but they are still capable of bending to follow curved paths. However, low-stiffness or flexible materials such as thermoplastic polyurethane (TPU) are available and are highly valued for their ability to endure large deformations while remaining elastic. These materials account for nearly all of the design space for 3D printed large deformation and soft components such as variable stiffness foam[1], [2], wearables and medical devices[3], [4], compliant hinges, pneumatic actuators[5] and soft robotic components [2]. However, due to the inherent flexibility and compressibility of these materials, conventional FFF systems, which are commonly designed primarily for rigid materials, can struggle to achieve comparable reliability and geometric accuracy relative to rigid material printed components. This is largely due to two main forms of failure attributed to flexible 3D printing filaments: buckling within the extruder due to an unconstrained filament pathway, and loss of traction on the filament due to excessive resistance within the filament pathway. While buckling may be addressed by altering the internal extruder filament pathway, addressing resistance within the overall filament pathway requires a greater scope of modifications for the 3D printer system and therefore remains an ongoing challenge for the 3D printing community.

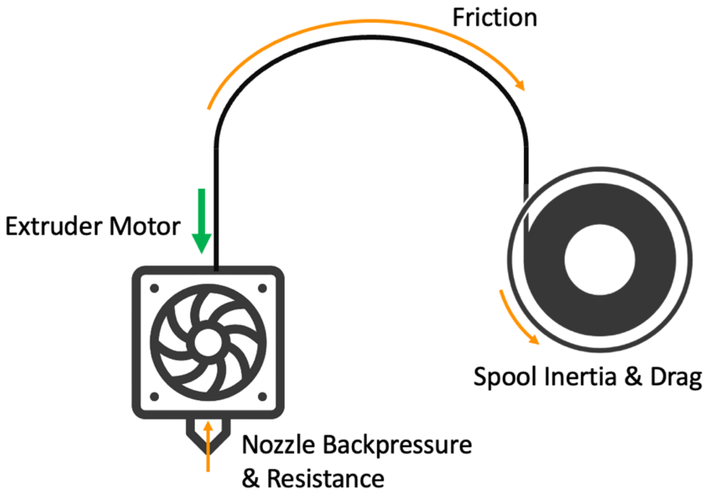


Figure 1: Typical filament path in a 3D printer. The extruder motor must overcome friction and resistance forces along the guide tube to ensure proper filament delivery and material extrusion.

Filament pathway optimization is further complicated by the common practice of actively drying hygroscopic filaments such as TPU during printing using external filament dehydrators. By default, many common FFF printers use open air filament paths routing filament from overhead spools down into the extruder thereby eliminating any potential sources of friction between the filament spool and extruder. However, most external dehydrators must use an alternate filament routing system to guide filament from the dehydrator to the printer. The most common routing method used to do so is PTFE tubes known as Bowden tubes. These flexible tubes introduce continuous curvatures into the filament, allowing the material to follow arbitrary paths to reach the extruder [6], [7]. This method is cost-effective, simple, and ensures consistent filament delivery regardless of the extruder's position during printing. It has long been a reliable solution, especially for common materials such as PLA, ABS, and PETG. However, when printing flexible materials like TPU, challenges arise due to the Bowden tube's high and nonlinear friction behavior, which can lead to inconsistent extrusion and print failures. Figure 1 illustrates the typical filament path in 3D printers that use a filament guide. As the extruder motor pulls filament from the spool and pushes it into the hot end, it must overcome various resistive forces to ensure successful material extrusion. Among these, friction within the filament pathway is particularly significant [6]. This paper investigates strategies and their effects to reduce friction to enable more reliable printing of flexible materials.

In this paper, the Route Your Ooze (RYO) drive with motion-decoupled rolling joints is introduced. The rolling joints are used as cable transmissions in robotic applications, such as [8], [9], where distal actuation is beneficial for reducing the mass of end-effectors and limb segments by relocating heavier components toward the base. Although various cable transmission methods exist — including Bowden cables and internally routed, bearing-supported cable systems[10] — the rolling joint has a distinct advantage: it mechanically decouples joint motion from cable motion. Specifically, rolling joints maintain constant cable length and tension within the joint regardless of joint angle, significantly improving transmission efficiency and system reliability compared to other types of cable transmissions. This fundamental benefit can be applied in 3D printing, where the filament can be treated analogously to a cable routed through a transmission system to reach the extruder.

Mechanical Design

To achieve a rolling joint, there are two primary methods: rolling contact using tendons or meshing gears. While rolling contact joints can be 3D printed, gear-based designs are much easier to fabricate. Each joint consists of the following components with an exploded view shown in Figure 2:

- 2x Main body
- 2x Pulley & Bearing
- 2x Shoulder screw
- 2x Bushing
- 2x Threaded Insert
- 1x Connecting link

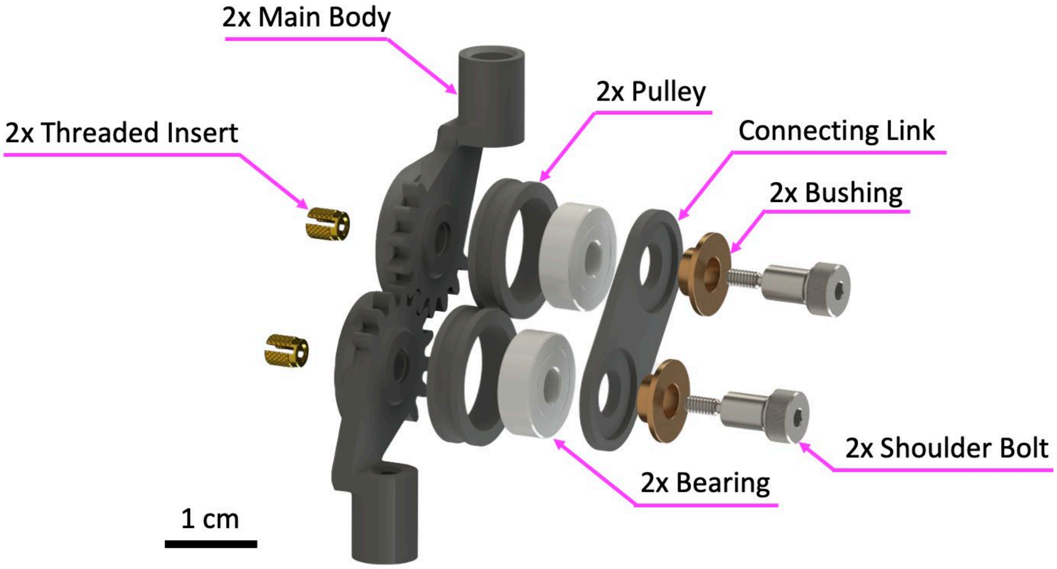


Figure 2: Exploded view of rolling joint. Main bodies, pulleys and connecting link are 3D printable. Simple and affordable hardware is used for assembly.

The main bodies have gear profiles and rigid contact surfaces, allowing the joints to roll against one another and maintain proper gear meshing. They also contain threaded inserts that secure the shoulder screws on which the bearings and bushings rotate. The pulleys are designed to accommodate filament up to 3 mm in diameter and have an outer diameter of 14 mm. These pulleys are press-fit with bearings. Although adhesive could be used, press-fitting is sufficient given the low load experienced by the filament while feeding. Lastly, the connecting link with bushings joins the two mating main bodies while preserving the correct spacing for gear engagement.

Rigid tubes are placed between each joint. While various materials can be used, it is best practice to choose those with low surface friction relative to the filament material. For this paper, carbon fiber tubes, Delrin, and nylon were tested and verified to be compatible with TPU filament. However, polycarbonate tubes exhibited excessive surface friction and were not suitable for this application. The tubes should be as stiff as possible to minimize bending, which can cause contact and rubbing with the filament, resulting in friction losses. In this paper, the experiments and analysis were done using the RYO drive with carbon fiber tubes, shown in Figure 3. Short segments of PTFE tubing were used to connect the RYO drive to existing Bowden tube hardware (such as at the extruder input and dryer output), also shown in Figure 3. Each rolling joint in the RYO drive provides three degrees of freedom (DOF): the rolling motion of the joint itself and axial twist at both interfaces between the joint and the connected rigid or PTFE tubes. These degrees of freedom are essential to ensure that the RYO drive can freely follow within the extruder workspace without introducing additional resistance or constraints.

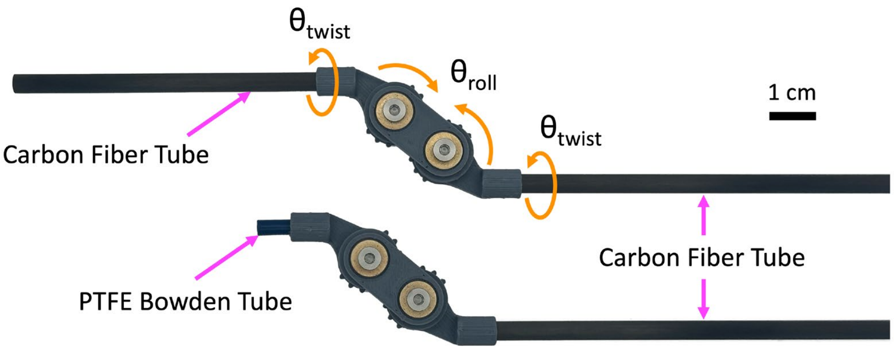


Figure 3: Assembled RYO drive. The joints are made to connect rigid links (such as Carbon fiber tubes shown here) or PTFE Bowden tubes to interface with existing tubing hardware. There are three possible degrees of freedom for each joint – rolling motion, and two axial twists between the rigid links or PTFE tubes and the joint itself.

The working principle of the rolling joint cable drive is thoroughly explained in [8]. It is important to note that the joint always maintains a certain amount of filament wrapped around the pulleys. In this paper, the term 'bend angle' of a rolling joint refers specifically to the angular difference between the incoming and outgoing links of an individual joint, rather than the total bend angle across all joints in the RYO drive.

The components used to construct the RYO drive were sourced from McMaster-Carr, with each joint costing approximately $20 USD. However, the cost can be significantly reduced through component optimization and by selecting more cost-effective suppliers.

Analysis

To analyze and compare the performance of the RYO drive with conventional flexible guide methods, the following experiment was conducted. A 100 g mass was attached to one end of a filament, and a motor pulled the filament from the opposite end. For baseline comparisons, segments of standard Prusa PTFE tubing and Capricorn PTFE tubing from Creality were tested, with each segment measuring either 200 mm or 350 mm. These tube segments were routed through varying bend angles ranging from 0° to 180°. At each bend angle, the force required to lift the 100 g mass was measured. The test setup is shown in Figure 4. The RYO joint was tested similarly, with pulling force measurements taken at joint angles ranging from 0° to 180°, defined by the angle difference between the two links. The filament used for testing was NinjaTek NinjaFlex TPU. Results are presented in Figure 5.

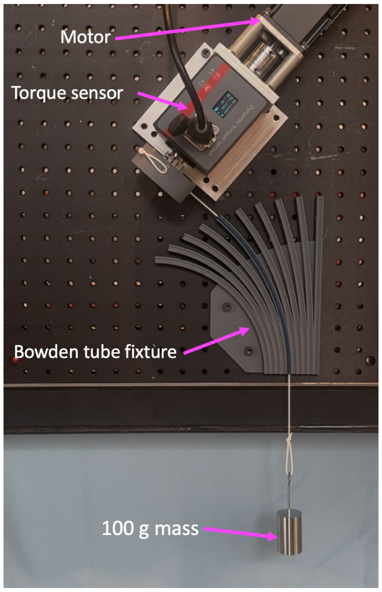


Figure 4: Test setup for measuring pull force on a 100 g mass. A motor connected to a torque sensor was used to pull NinjaTek NinjaFlex TPU filament with a 100 g mass attached. A fixture was used to bend the PTFE Bowden tubes to precise angles, enabling accurate measurement of pulling force under different routing configurations.

The results indicate that greater force is required to lift the 100 g mass as the bend angle and length of the Bowden tubes increase. This observation aligns with expectations, as friction in Bowden tubes typically increases exponentially with bend angle, following the capstan equation [11]. Detailed modeling of friction and energy loss in Bowden tubes, however, is beyond this paper's scope due to inherent complexity and the combined effects of frictional losses, filament deformation, elongation, and actual weight lifting during measurement.

Although Bowden tubes designed specifically for reduced friction along their length, such as Capricorn PTFE tubes, significantly reduce friction along the filament path, they cannot eliminate exponential friction growth at increased bend angles or tube lengths. Furthermore, during printing, changes in the extruder's position continuously alter the total bend angle and radius, causing nonlinear frictional behaviors. Consequently, extruders must overcome the fluctuating frictional forces to ensure consistent and accurate material extrusion, and a failure to do so results in poor print quality or failed prints.

In contrast, the RYO drive consistently maintained the same force to lift the 100 g mass regardless of joint angle. This characteristic is highly beneficial for 3D printing as it eliminates nonlinear force fluctuations experienced by the extruder. Stable filament tension prevents undesirable filament movements, such as slackening or unintended retraction, ensuring reliable extrusion under dynamic movements throughout the printing process and thus improving print geometric accuracy, surface finish, and success rates. Additionally, the RYO drive is length-independent: because links between each joint do not contribute additional friction, filament routes can be lengthened without increasing friction, unlike Bowden tubes.

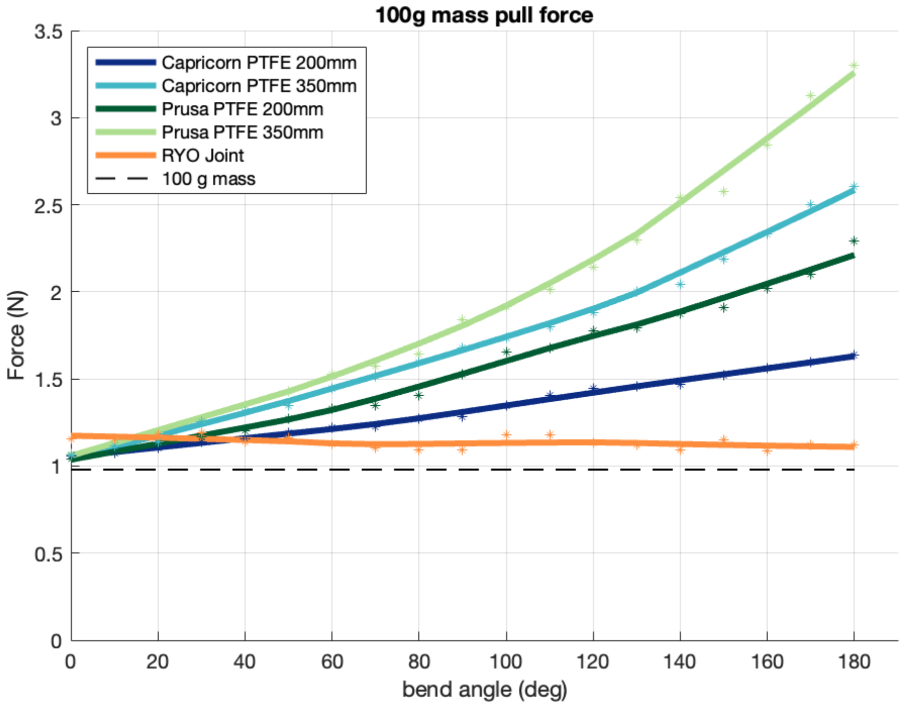


Figure 5: Force required to pull a 100 g mass under various conditions. Bowden tubes exhibit exponentially increasing friction with bend angle, while the RYO joint maintains minimal and consistent friction across all joint angles. The length of Bowden tubes also contributed to the change in friction.

To further characterize the RYO drive, a second experiment was conducted to evaluate joint efficiency. Using the same experimental setup as before with a 100 g mass, each joint was locked at 90 degrees for consistency. The number of joints was progressively increased, and the force required to lift the 100 g mass was measured. Three filaments of increasing durometer — NinjaTek Chinchilla 75A, NinjaTek NinjaFlex 85A, and NinjaTek Cheetah 95A — were tested to examine joint performance across varying material properties, particularly the material stiffness. The results are shown in Figure 6.

The results show a linear relationship between the number of joints and the force required to lift a 100 g mass for all three materials. Notably, the RYO drive performs better with more flexible materials (75A) than with stiffer materials (95A), which differs from the behavior of Bowden tubes. Printing flexible materials with Bowden tubes is challenging due to high friction, which can cause the filament to stretch significantly under the extruder's increased force applied to overcome friction, leading to thinning of the filament or jamming. In contrast, stiffer materials such as PLA do not pose the same issue, as they do not noticeably stretch under small loads.

In the case of the RYO drive, the filament is routed through a series of pulleys, causing it to undergo repeated bending and unbending as it passes through each joint. Flexible materials perform better in the RYO drive because their lower stiffness allows them to navigate these directional changes with less resistance compared to stiffer materials. As shown in Figure 6, the 95A filament required nearly four times the force of the 85A filament and almost ten times that of the 75A filament. However, the pulley diameter can be adjusted to provide a larger bend radius for stiffer materials to go through to accommodate stiffer materials.

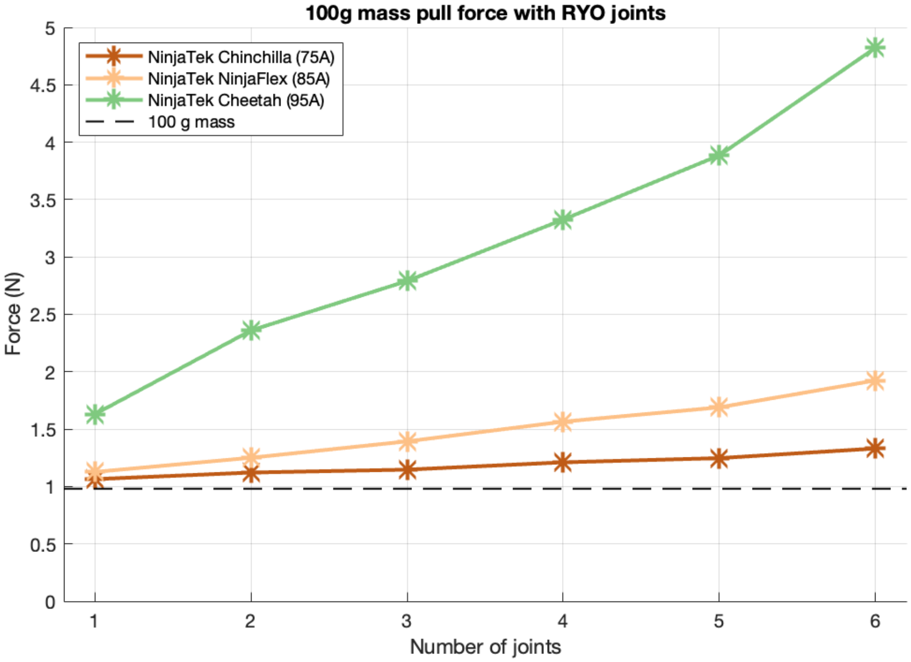


Figure 6: Force required to pull a 100 g mass using the RYO drive with an increasing number of joints and three different filament materials. The force increases linearly with the number of joints, with the slope varying by material stiffness. Softer materials exhibit lower resistance, while stiffer materials result in higher pulling force.

Drive Implementation

To investigate the high and nonlinear friction behavior of Bowden tubes and their potential impact on print quality, an Original Prusa XL printer was used to maximize variations in Bowden tube curvature. In order to isolate path resistance as the primary form of failure within the system, the default internal extruder filament pathway was modified to constrain lateral motion, thus mitigating buckling. [12] The printer system was tested using three filament routing configurations:

- The RYO drive from a filament dryer placed next to the printer (shown in Figure 7)
- The default pathway with the side-mounted filament sensor bypassed
- A Capricorn PTFE tube from a filament dryer placed next to the printer, roughly 1 meter in length

First, 100 mm of NinjaTek NinjaFlex TPU filament was extruded at each point of a 7-by-7 evenly spaced grid on the print bed and the mass of material deposited at each location was measured. As the extruder moves across the bed, the curvature of the filament pathway changes dynamically, potentially altering friction and affecting extrusion. Consistent material deposition across the print bed is particularly critical for achieving reliable and high-quality prints.

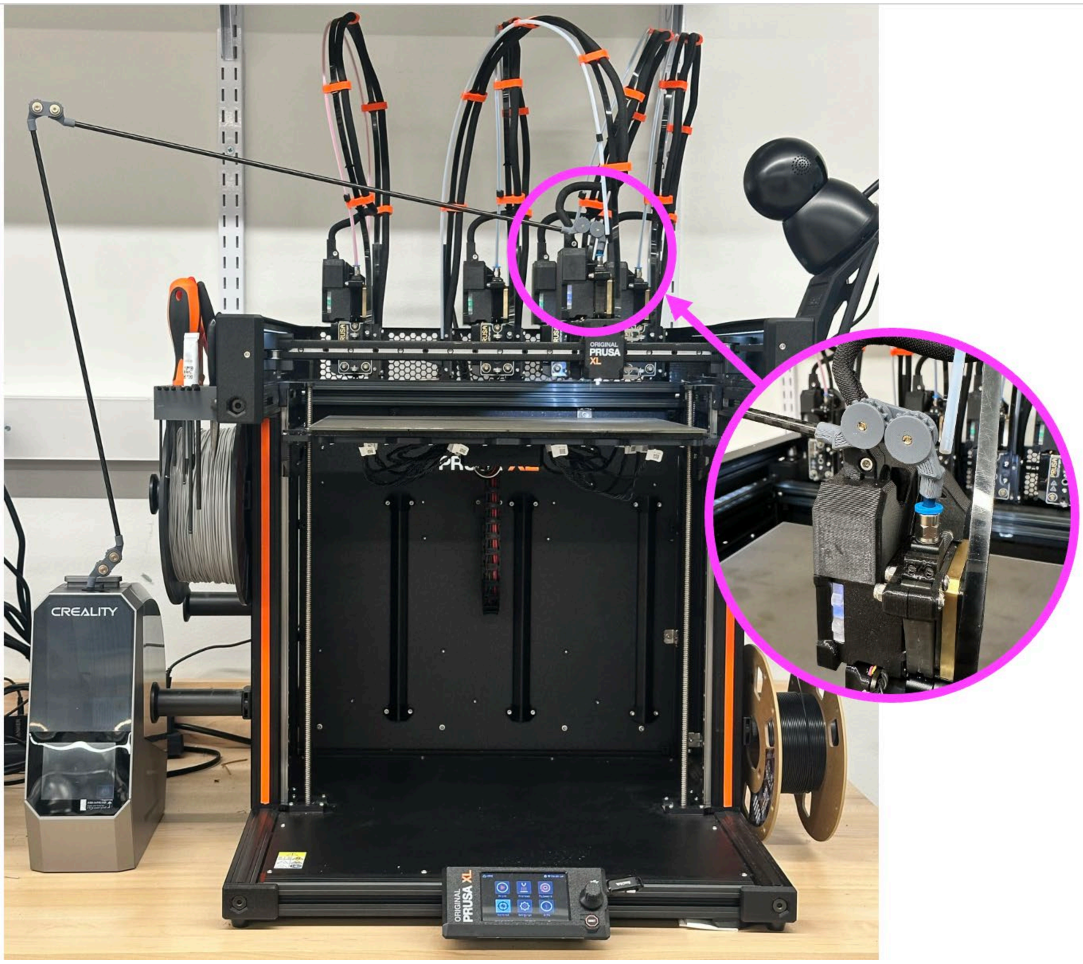
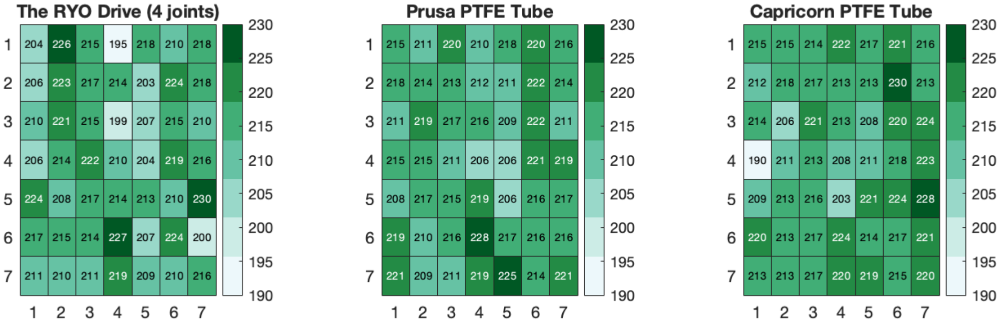


Figure 7: Original Prusa XL with the RYO drive and anti-buckling modification in the extruder implemented. A filament dryer holding a NinjaTek NinjaFlex TPU spool was placed adjacent to the printer, and the filament was routed to extruder #2 using the RYO drive.



The RYO Drive (4 joints)

	1	2	3	4	5	6	7
1	204	226	215	195	218	210	218
2	206	223	217	214	203	224	218
3	210	221	215	199	207	215	210
4	206	214	222	210	204	219	216
5	224	208	217	214	213	210	230
6	217	215	214	227	207	224	200
7	211	210	211	219	209	210	216

Prusa PTFE Tube

	1	2	3	4	5	6	7
1	215	211	220	210	218	220	216
2	218	214	213	212	211	222	214
3	211	219	217	216	209	222	211
4	215	215	211	206	206	221	219
5	208	217	215	219	206	216	217
6	219	210	216	228	217	216	216
7	221	209	211	219	225	214	221

Capricorn PTFE Tube

	1	2	3	4	5	6	7
1	215	215	214	222	217	221	216
2	212	218	217	213	213	230	213
3	214	206	221	213	208	220	224
4	190	211	213	208	211	218	223
5	209	213	216	203	221	224	228
6	220	213	217	224	214	217	221
7	213	213	217	220	219	215	220

Figure 8: Heatmap of material deposition across the print bed, measured in milligrams (mg). Using a Prusa XL printer, 100 mm of filament was extruded at each point on a 7-by-7 evenly spaced grid to assess consistency across the bed. The bottom row corresponds to the front of the printer. The heatmap shows no statistically significant patterns of under-extrusion across all three cases.

Despite the RYO drive's benefit of low and consistent friction, the results in Figure 8 did not align with expectations and showed no clear relationship between extruder position and the mass of extruded material. Across all configurations, the deposited material ranged from 190 mg to 230 mg. Specifically:

- The RYO Drive: average 213.6 mg, standard deviation 7.5 mg

- Default Side Input: average 215.3 mg, standard deviation 4.9 mg
- Capricorn Tube: average 215.8 mg, standard deviation 6.6 mg

No consistent trends were linked to filament routing or spool orientation. This outcome suggests that while friction variations due to Bowden tube curvature likely exist, they were not large enough in this setup to significantly affect extrusion or cause under-extrusion due to stretching and thinning.

Furthermore, reduced friction in the filament pathway is expected to improve extruder performance and allow for higher volumetric flow rates before encountering failures such as jamming or filament thinning caused by excessive force. To evaluate this, the same printer and filament path configurations were used to print a series of 10 mm × 10 mm × 10 mm cubes with 100% infill and no vertical or horizontal shells. Printing speed was incrementally increased, starting from the default maximum PrusaSlicer setting for 'NinjaTek NinjaFlex TPU,' with a 10% increase at each step up to 300%. By measuring the mass of each cube, the degree of under-extrusion was measured as print speed increased.

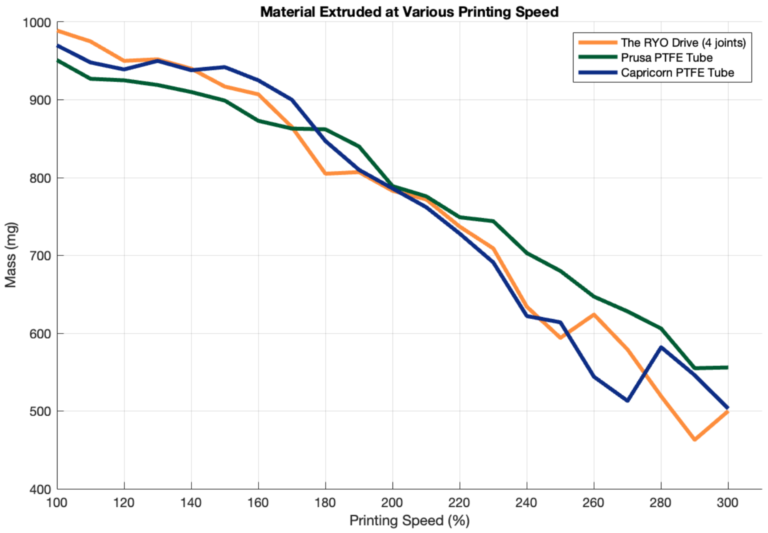


Figure 9: NinjaTek NinjaFlex TPU extruded mass at various printing speeds, starting from the default setting found on PrusaSlicer. The printing speed was increased incrementally by 10% until 300% printing speed was achieved. The plot shows no difference in mass between the different filament routing systems.

Despite the significantly reduced friction provided by the RYO drive, the results shown in Figure 9 indicate no measurable improvement in the volumetric flow rate of TPU filament due to friction reduction in the filament pathway. The default Prusa filament feed path was able to perform just as well as the RYO drive configuration with much lower friction along the filament pathway. Across both experiments conducted on the Original Prusa XL, the data suggest that filament routing in this printer does not introduce enough Bowden tube friction to cause material thinning or under-extrusion. However, in other printers — particularly enclosed systems with sharper filament turns due to space constraints, or less capable extruder systems — increased routing friction may still contribute to print quality issues.

To simulate and evaluate the effectiveness of the RYO drive in challenging filament routing scenarios, such as long paths or extreme bend angles, an Original Prusa Mk4 printer was used with an artificially created filament path approximately 2 meters in length, double in length from the previous Original Prusa XL setup. Using the RYO drive, the test began with three joints totaling 1.8 meters, and joints were incrementally added until the total path reached 2 meters with six joints. For comparison, Capricorn PTFE tubes were used to represent the best-case scenario for conventional routing. The test started with a 180° bend and progressively added loops, increasing the total bend by 360° each step. For each configuration, 1 meter of filament was extruded and weighed to quantify material output. Extruding 1 meter of material ensures that the filament is actively feeding through the system and not simply stretching within the path. Due to the high friction associated with long and sharply bent PTFE tubes, print failures were expected under these conditions.

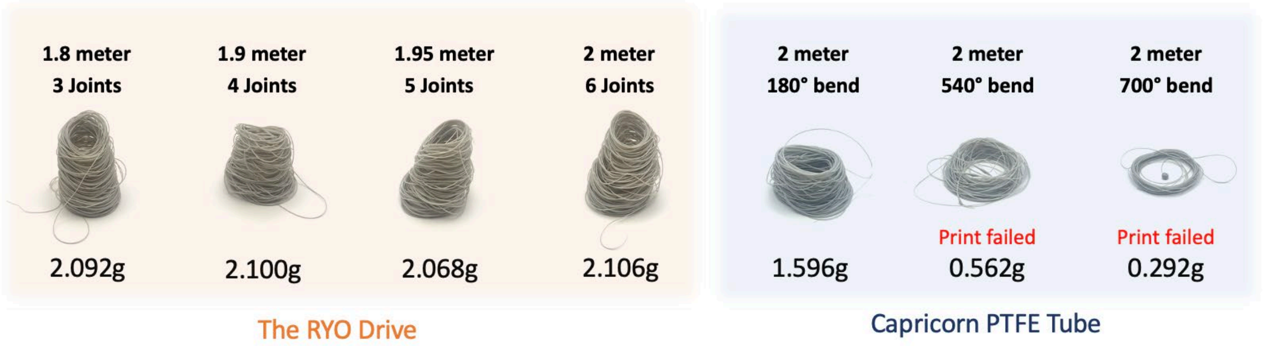


Figure 10: 1 meter of TPU extruded under each test condition. (Left) With the RYO drive, configurations ranging from three to six joints (up to 2 meters total length) consistently produced approximately 2 g of extruded material, showing no significant loss. (Right) Using a 2-meter-long Capricorn PTFE tube with increasing bend angles. At 180°, approximately 25% under-extrusion was observed relative to RYO results, though the print was completed. Beyond this, added loops introduced excessive friction, leading to filament stretching and feed failure.

Extrusion results are shown in Figure 10. The RYO drive, performed consistently even with an extremely long filament pathway. Across all tested configurations, from three to six joints and up to 2 meters in total length, the mass of extruded material remained around 2 g, demonstrating consistent performance regardless of path complexity. Each joint can redirect the filament up to 180°, allowing for a total routing angle of up to 1080° with six joints. In contrast, the Capricorn PTFE tubes experienced significantly higher friction at this length. As a result, the extruder motor was unable to reliably overcome the resistance and feed filament properly. Approximately 25% under-extrusion was observed at 180° of bending relative to the results observed on RYO samples, and complete print failure occurred at higher bend angles, with only 0.5 g and 0.3 g of material extruded at 540° and 700° bend angles, respectively. These results highlight and confirm the key advantages of the RYO drive: its path-length independence and exceptionally low friction, both enabled by a bearing-supported filament routing system.

Conclusion & Discussion

In this paper, the Route Your Ooze (RYO) drive was introduced. The rolling joint cable transmission concept used in robotic applications was adapted to maintain constant filament length and tension regardless of extruder position. These joints use bearing-supported pulleys, meaning the filament is bearing supported end-to-end, eliminating friction sources such as rubbing, and the capstan effect found in conventional Bowden tubes.

Analysis showed that the RYO drive exhibits significantly lower friction compared to standard PTFE tubes used for filament routing. Unlike Bowden tubes, which tend to perform better with stiffer materials, the RYO drive performed better with softer and more flexible filaments. This could enable successful printing of materials that are typically problematic due to issues like filament thinning from high routing friction. Moreover, friction in the RYO drive scales with the number of joints rather than total bend angle (path complexity), allowing flexible filaments to be routed over longer distances or more complex paths with minimal resistance.

However, in practical testing on the Original Prusa XL, results showed that, with anti-jamming modifications, all tested configurations, including the factory PTFE routing, 1 meter of Capricorn PTFE tubes, and the RYO drive, extruded material consistently across the full print bed. The experiments confirmed that under-extrusion can occur at high speeds, but filament routing method did not influence this outcome. These findings suggest that modern printers designed with flexible filament compatibility in mind may not benefit substantially from specialized routing systems like the RYO drive under typical filament routing conditions.

That said, the RYO drive still holds potential in other scenarios. It can be integrated with PTFE segments to eliminate sharp turns or prevent kinking in more constrained or customized setups. This added flexibility in routing could allow filament spools to be placed farther from the extruder without introducing significant friction. While this study tested up to a 2 meters filament path with six joints, longer and more complex pathways are certainly feasible.

This capability can open the door to centralized filament storage and routing in large-scale print farms, in contrast to current decentralized setups that require each printer to be equipped with its own dehydrator if environmental control is desired. By enabling long-distance, low-friction filament delivery, the RYO drive could simplify material management, reduce equipment redundancy, and improve consistency across multiple machines. Moreover, longer reliable filament routing could also support larger printer workspaces, expanding the printable volume for flexible materials.

Future work include long-term durability testing of the joints under repeated use, as well as the design of a filament-loading mechanism that can automatically guide flexible filaments through the RYO drive's multi-joint structure. Additionally, exploration of cheaper and more compact modular designs and integration with existing printer architectures could facilitate broader adoption in both hobbyist and industrial use.

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