MAE 263F Project Proposal: Simulation of tendon-driven meta-material

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***Abstract*— Bipedal locomotion offers significant advantages in human-centric environments, but traditional rigid robots face challenges with impact absorption and stability. Soft robotics presents a promising alternative, yet the development of agile, soft bipedal robots remains limited. This work focuses on a novel soft humanoid platform constructed from 3D-printed Thermoplastic Polyurethane (TPU) meta-materials, which allows for variable stiffness and is actuated via tendons. This design provides inherent impact absorption, low cost, and high accessibility. A critical prerequisite for developing dynamic control for this platform is a fast and physically-accurate simulation. Simulating such a material is non-trivial, as its variable stiffness renders common explicit integration methods unstable, while other fast methods like Position-Based Dynamics (PBD) lack physical accuracy, leading to large sim-to-real gaps and explict Euler struggles on large stiffness system. We propose the development of a simulation platform based on implicit integration, which is unconditionally stable for high-stiffness systems. Our approach will first establish a baseline using a standard Implicit Euler solver and then explore Projective Dynamics (PD) implemented on CUDA to achieve real-time performance. The primary contributions will be a stable simulation platform for this tendon-driven meta-material and a validated model mapping tendon inputs to the material's bending angles, paving the way for future reinforcement learning and control strategies.**

I. INTRODUCTION

Legged locomotion has always been prevalent in robotics, inspired by the nature of most of the land animals. It advantages in obstacle avoiding, unstructured terrain adapting yet achieving agile and fast mobility. Among legged locomotion strategies, biped locomotion, mimicing human's walking gaits, is distinctly advances in its adaptability to human-centric environments and is potentially able to have a lower energy consumption compared to multi-legged locomotion due to less actuation effectors[1]. Biped robot is a well-studied area since the first creation of the humanoid robot, the P series by Honda[2]. Research on biped dynamic locomotion has been mainly focused on rigid mechanisms[3] and achieved great success in dynamic locomotion. For instance, Atlas, the hydraulic driven humanoid robot developed by Boston dynamics[4], is able to walk in challenging environments, jump, and maintain balance when performing pick and place tasks for human body sized or heavy objects. RoMeLa developed a biped robot named ARTEMIS recently. Taking advantage of the proprioceptive actuators for torque-force control, ARTEMIS is capable of agile locomotion[5]. Multiple humanoid robots platform with rigid bodies for research purposes have been proposed[6], [7], [8].

Dynamic locomotion for rigid robots has been challenging. Traditional servo motors for biped robot with a high gear ratio has less capability to properly handle contact impact. To address this issue, apart from hydraulics on Atlas and proprioceptive actuators on Cheetah or ARTEMIS, series elastic actuators (SEAs) might be promising[9], but there is still disadvantage on low control bandwidth. As opposed to rigid robots, soft robots advantages in absorbing impact benefiting from its low stiffness and compliant capability to deform continuously. And it can be potentially safe from falling down or even dropping from high, which is a eager need for biped robot due to it's difficulty on balancing and more frequently to fall compared to multi-legged robots. Unfortunately, although soft robotics is a well-studied area, and many multi-legged soft robot has been developed[10], limited research has been conducted on soft agile biped robots. In [11], the authors proposed a soft octopus like biped soft robot, but it only works in underwater environment and slow in locomotion. Soft humanoid robot is proposed in [12], but it only works in simulation and failed in real hardware due to huge sim-to-real gap.

A soft humanoid robot platform whose limb and outer body are all soft can take advantage of it's capability of absorb impact, it is safe from falling down or dropping from a high place which benefits for the unstable nature of biped robots. With design of stiffness distribution and driving with tendons by motors, the limb may have multiple degree of freedom and achieve agile motions and fast locomotion. Using TPU as the material and 3D-printing as the fabrication method, the robot would have great accessibility with a low cost. Simulation of the soft joint is essential for control or using Reinforcement Learning(RL) for the robot locomotion. In this project, we propose a simulation platform for the tendon-driven 3D printed meta-material.

II. RELATED WORKS

A. *Freeform Fabrication of Soft Robots*

Fabrication of soft robots has been time consuming. Taking advantage of the capability of rapid prototyping and freeform fabrication, additive manufacturing techniques can make robot parts rapidly in complex shapes with limited human effort. Many 3D-printing soft robots has been proposed[13], [14], [15]. However, most of them are using uncommon materials and can not take advantage of great accessibility of 3D-printing. Among those, Boxi et. al used Thermoplastic polyurethanes (TPU) as the material of their soft robot[16]. They demonstrated that with different infill density and flow rate, the printed part can achieve varying meta-material stiffness as shown in Figure 1. In this work, the authors just use a certain infill density and flow rate for their quadruped robot limbs. However, this material has great potential if applying varies stiffness on the robot, the robot limb may have multiple degree of freedoms, and also can be the one of the most accessible soft robot platform as TPU is a widely used material in fused deposition modeling (FDM).

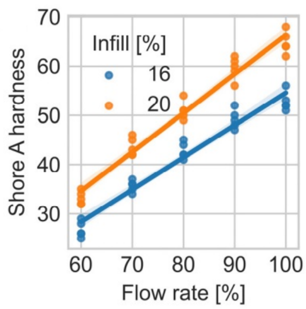

Fig. 1: Shore hardness vs. flow rate and infill density of TPU with gyroid infill pattern

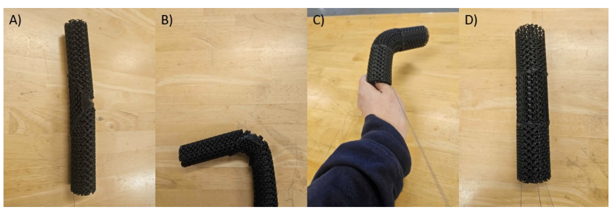

Fig. 2: A) test print part with one tendon. B) test print part with tendon pulled. C) test print part with one of the tendons pulled. D) test print part with three tendons.

B. *Simulation methods of soft body*

The simulation of soft bodies involves a fundamental trade-off between computational speed and numerical stability, particularly when dealing with high-stiffness materials. Explicit integration schemes, such as the Explicit Euler method, are computationally efficient and highly parallelizable, as demonstrated by the Titan library [17], which utilizes NVIDIA CUDA for large-scale robotics simulation. However, explicit methods are only conditionally stable and fail when high stiffness (large k) or necessitating very small time steps to ensure stability. Conversely, implicit integration methods, like the standard Implicit Euler, are unconditionally stable and can handle high stiffness, but traditionally require solving a large, non-linear system of equations at each step, which is often too slow for real-time applications. To achieve real-time interactivity, Position-Based Dynamics (PBD) [18] was introduced, offering exceptional speed and robustness by omitting the force/velocity layer and directly solving positional constraints. PBD's critical drawback, however, is that its material stiffness is not a physical parameter but an unphysical artifact of the solver's iteration count, leading to "mushy" and uncontrollable behavior. This was directly addressed by eXtended Position-Based Dynamics (XPBD) [19], which modifies the PBD algorithm to correctly decouple stiffness from the iteration count, allowing for physically-based compliant constraints. Bridging the gap between implicit methods and PBD, Projective Dynamics (PD) [20] formulates the simulation as an implicit Euler integration step that is solved using a fast, alternating local/global optimization. This allows PD to be robust, efficient, and accurate, achieving real-time performance even for complex models by pre-factoring the most expensive computational step.

III. Proposed approach and anticipated contributions

Our proposed simulation strategy addresses the limitations of existing methods for this specific application. While our preliminary investigations using explicit Euler with a spring-mass discretization achieved parallel computation in CUDA (reaching a dt of $10^{-5}s$), this method proved unstable for the high-stiffness components of the meta-material, failing to capture its true mechanical properties. Furthermore, methods like PBD are unsuitable due to their non-physical handling of material stiffness, which would likely introduce a significant sim-to-real gap. We, therefore, propose an approach centered on implicit integration, which is unconditionally stable for high-stiffness systems. We will begin by implementing a standard Implicit Euler solver with a Newton-Raphson method to establish a baseline. Subsequently, to achieve real-time performance suitable for high-frequency control or reinforcement learning applications, we will explore the implementation of Projective Dynamics (PD) on CUDA. The anticipated contributions of this work are twofold: 1) A stable and physically-accurate simulation platform for tendon-driven, 3D-printed TPU meta-materials. 2) A validated model that provides a precise mapping from tendon actuation (length) to the resulting kinematic output (bending angle) of the soft structure.

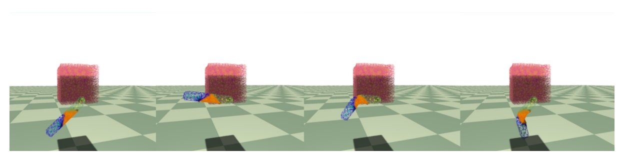

Fig. 3: Simulation of the tendon-driven meta-material with explicit Euler.

References

[1] C. L. Vaughan, "Theories of bipedal walking: an odyssey," *Journal of biomechanics*, vol. 36, no. 4, pp. 513–523, 2003.

[2] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura, "The intelligent asimo: System overview and integration," in *IEEE/RSJ international conference on intelligent robots and systems*, vol. 3. IEEE, 2002, pp. 2478–2483.

[3] Y. Tong, H. Liu, and Z. Zhang, "Advancements in humanoid robots: A comprehensive review and future prospects," *IEEE/CAA Journal of Automatica Sinica*, vol. 11, no. 2, pp. 301–328, 2024.

[4] E. Guizzo, "By leaps and bounds: An exclusive look at how boston dynamics is redefining robot agility," *IEEE Spectrum*, vol. 56, no. 12, pp. 34–39, 2019.

[5] M. ElDiwiny, "An interview with dennis hong," *Robotics Reports*, vol. 1, no. 1, pp. 89–97, 2023.

[6] G. Ficht and S. Behnke, "Bipedal humanoid hardware design: A technology review," *Current Robotics Reports*, vol. 2, pp. 201–210, 2021.

[7] I. Ha, Y. Tamura, H. Asama, J. Han, and D. W. Hong, "Development of open humanoid platform darwin-op," in *SICE annual conference 2011*. IEEE, 2011, pp. 2178–2181.

[8] Y. Liu, J. Shen, J. Zhang, X. Zhang, T. Zhu, and D. Hong, "Design and control of a miniature bipedal robot with proprioceptive actuation for dynamic behaviors," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 8547–8553.

[9] M. Hutter, C. Gehring, D. Jud, A. Lauber, C. D. Bellicoso, V. Tsounis, J. Hwangbo, K. Bodie, P. Fankhauser, M. Bloesch *et al.*, "Anymal-a highly mobile and dynamic quadrupedal robot," in *2016 IEEE/RSJ international conference on intelligent robots and systems (IROS)*. IEEE, 2016, pp. 38–44.

[10] Z. Yu, A. Duan, Z. Zhu, and W. Zhang, "Biomimetic soft-legged robotic locomotion, interactions and transitions in terrestrial, aquatic and multiple environments," *Sustainable Materials and Technologies*, p. e00930, 2024.

[11] Q. Wu, Y. Wu, X. Yang, B. Zhang, J. Wang, S. A. Chepinskiy, and A. A. Zhilenkov, "Bipedal walking of underwater soft robot based on data-driven model inspired by octopus," *Frontiers in Robotics and AI*, vol. 9, p. 815435, 2022.

[12] B. Xia, *Soft actuator and agile soft robot*. Columbia University, 2022.

[13] R. MacCurdy, R. Katzschmann, Y. Kim, and D. Rus, "Printable hydraulics: A method for fabricating robots by 3d co-printing solids and liquids," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2016, pp. 3878–3885.

[14] J. D. Carrico, K. J. Kim, and K. K. Leang, "3d-printed ionic polymer-metal composite soft crawling robot," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2017, pp. 4313–4320.

[15] M. H. D. Ansari, V. Iacovacci, S. Pane, M. Ourak, G. Borghesan, I. Tamadon, E. Vander Poorten, and A. Menciassi, "3d printing of small-scale soft robots with programmable magnetization," *Advanced Functional Materials*, vol. 33, no. 15, p. 2211918, 2023.

[16] B. Xia, J. Fu, H. Zhu, Z. Song, Y. Jiang, and H. Lipson, "A legged soft robot platform for dynamic locomotion," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2021, pp. 11 812–11 819.

[17] J. Austin, R. Corrales-Fatou, S. Wyetzner, and H. Lipson, "Titan: A parallel asynchronous library for multi-agent and soft-body robotics using nvidia cuda," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2020, pp. 7754–7760.

[18] M. Müller, B. Heidelberger, M. Hennix, and J. Ratcliff, "Position based dynamics," *Journal of Visual Communication and Image Representation*, vol. 18, no. 2, pp. 109–118, 2007.

[19] M. Macklin, M. Müller, and N. Chentanez, "Xpbd: position-based simulation of compliant constrained dynamics," in *Proceedings of the 9th International Conference on Motion in Games*, 2016, pp. 49–54.

[20] S. Bouaziz, S. Martin, T. Liu, L. Kavan, and M. Pauly, "Projective dynamics: Fusing constraint projections for fast simulation," in *Seminal Graphics Papers: Pushing the Boundaries, Volume 2*, 2023, pp. 787–797.