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The Design of a New 3D Print-in-place Soft Four-Legged Robots with Artificial Intelligence

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ABSTRACT

Soft and flexible robots are designed to change their flexibility over a wide range to perform tasks adequately in real-world applications. Current soft robots require cast moulding, high assembly effort and large actuators. Soft origami structures exhibit high levels of compliance. In this paper, we designed a new 3D print-in-place soft four-legged robot (3DSOLR). Our soft legged robot is an endurance application adapted from the soft origami zigzag gripper. This novel and innovative design are inspired by the rigid joint Theo Jansen legged robot with highly adaptive 3D print-in-place soft origami legs capable of fluid motion and even surviving drop tests. The robot mechanism consists of four soft origami flexible legs driven by two DC motors. The 3DSOLR is lightweight and semi-autonomous using two Hall effect sensors and a wireless Bluetooth module. Being 3D print-in-place using Thermoplastic polyurethane also increases its durability while having flexibility, simplicity and safety. The robot also has a gripper inspired by the mandible of male European stag beetle (Lucanus cervus). These features make this robot suitable to be used in social robotics and rescue robotics applications. The transmitter program is implemented in Bluetooth serial communication using MIT App Inventor 2 smartphone apps and a microcontroller Arduino ATMEL is used as the main controller and code in Arduino IDE. It has artificial intelligence (AI) capability with ESP32 CAM onboard which has an object classification accuracy of 95.5% using custom Edge Impulse neural network MobileNetV1 96 x 96. This AI capability enhanced the robot's capability in object classification for grasping.

Keywords: Four-legged robot; 3D Print-in-place; Flexible actuation; Theo Jansen

INTRODUCTION

Legged robotics has become one of the fastest expanding fields of scientific research due to increasing demand for its application in logistics and unstructured terrains (Ruan et al. 2020). The legged robots have high adaptability and manoeuvrability in extreme environments as compared to the traditional wheeled and tracked robots which have good stability and fast-moving speed (Liu et al. 2007). They could transverse soft and uneven terrain, and easily coped with obstacles or cracks found in the environment. They also have better energy efficiency, better stability, and a smaller impact on the ground (Hirose et al.1991). Legged robots have widespread applications especially in performing high-risk tasks (Chen et al. 2021; Biswal et al. 2021). Among the multiple types of legged robots, the quadruped robot is the most widely used. A quadruped robot system imitates the movement, skills or skeletal structure of four-legged animals in nature (Seok et al. 2015). Quadruped robots have better stability and higher payload relative to biped robots. They require fewer motors and simpler control systems as compared to hexapod and eight-legged robots (Vinayak 2006). Due to its many advantages, quadruped robots have become a popular subject in the field of robotics research (Cao et al. 2015). Rygg (1983) manufactured the quadruped mechanical horse using the principle of a closed-chain linkage mechanism to produce high step frequency walking. A lizard quadruped robot with a quadruped linkage mechanism can run on water with high step frequency resistance (Park et al. 2010). Other examples of four-legged robots with greater locomotion capabilities include HyQ (Semini et al. 2011) and its successor HyQ2Max (Semini et al. 2017), MIT's Cheetah (Seok et al. 2015) and Cheetah II (Park et al.2017), ETH's StarlETH (Hutter et al. 2012) and ANYmal (Hutter et al. 2017), Boston Dynamics' Spot and SpotMini robot, a direct successor to Big Dog (Raibert et al. 2008). However, the control and leg coordination of these larger robots are complicated and the systems require a high computational speed. The motors and power storage system required for these systems are also costly. Yan et al (2022) built a quadruped robot with a pure mechanism, multi-connecting rod and single motor design which allows simple control, a reliable motion system and a linear walking gait.

Technological advancements and innovations have attributed to the development of soft robotics that has provided options and solutions to address the limitations of conventional rigid systems. Soft robots are made of soft polymers, fluids, gels, and other easily deformable materials which render them soft and compliant natures. These characteristics allow the robots to have safe and biomechanically compatible interactions with humans (Majidi, 2013). The soft robots are able to adjust and conform to the environment, handle delicate and irregular shaped objects without damaging them, and operate in unpredictable and unconventional environments with high flexibility. They can be made using the cast moulding technique. They may be actuated using fluid-driven muscle or a pneumatic pump. However, using only soft material as a robotic structure is a challenge due to its compliant nature and unconventional geometry as compared to conventional robotics. The ancient Japanese Art of Origami allows various shapes and forms to be built just by following a fixed structure of foldable geometry making it a very viable application in soft robotics. Robots that can carry heavy loads require high stiffness and rigidity whereas low stiffness allows safe and compliable movement that is safe for humans. Origami structures have coexisting properties of rigidity and flexibility which may fulfil the unmet needs of rigid robotics in situations involving crowded, unknown environments, unspecific tasks or close interaction with humans (Schenk and S. D. Guest, 2011; Rus and Tolley, 2018). They are lightweight, flat and with a large number of degree-of-freedom. They display motions via structural reconfiguration (Bowen et al. 2013). The making of paper-based origami robots involves cutting and folding multiple sheets of paper using specific methods for different origami designs.

With technological advancement, additive manufacturing or 3D printing could bring digital flexibility and efficiency to manufacturing operations. Its technologies have the capability to realize objects that include various types of joints and moving parts. The print-in-place and the multi-material deposition capabilities have been used to produce a stable junction between rigid (Poly-Lactic Acid, PLA) and flexible (Thermoplastic polyurethane, TPU) materials in order to manufacture elastic hinges without any assembly operation (Rosa et al. 2017).

The goal of this project is to develop a 3D print-in-place soft origami four-legged robot that is low cost, easy to assemble, safe for human interaction and able to emulate the walking gait of a rigid joint legged robot. The soft legged robot was designed based on Theo Jansen's leg design. It has novel 3D print-in-place multiple linkage gait legs using TPU with origami flexure joints formed by thinner layers of material that allow hinge movements. The legs have no rigid linkage and joints leading to low assembly and build time.

METHODOLOGY

The 4-legged robot design is based on Theo Jansen's rigid multiple linkage gait legs. All Theo Jansen's legged robots are built from rigid linkage with multiple joints that require meticulous fabrication, joints, and tedious assembly. We built using soft Thermoplastic polyurethane (TPU) material to create the Theo Jansen multiple linkage gait legs (as shown in Figure 1) but minus the rigid linkage and heavy assembly and build time. All our Soft Origami Legged Robot Theo Jansen's legs are made with 10 origami flexure joints.

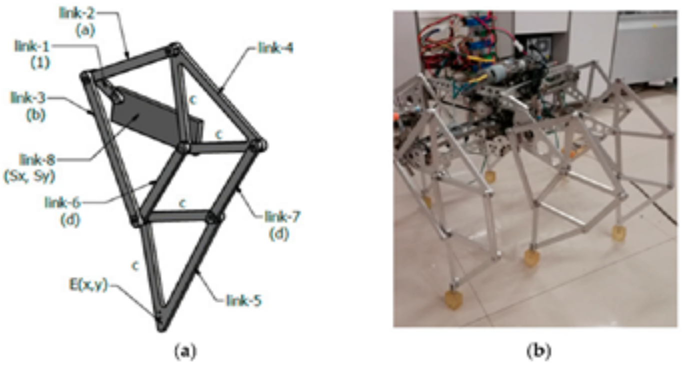


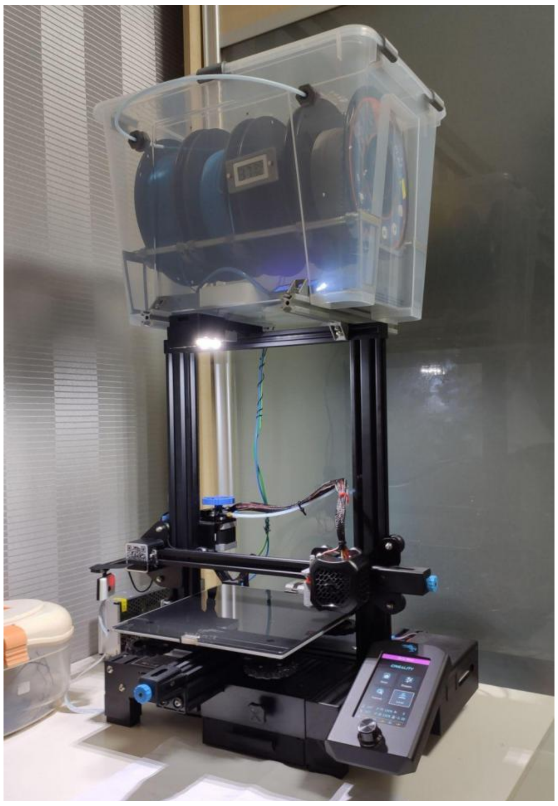
FIGURE 1. Theo Jansen's rigid multiple linkage gait legs

We print-in-place using 3D Printed soft TPU material (as shown in Figure 2). The characteristics of 3D print-in-place Soft Origami Legged Robot (3DSOLR) is listed in Table 1. By depositing thicker material that becomes rigid and while thinner material shape at the joint location allows flex joints capability just like a paper origami. All these were printed in one piece to reduce assembly time.

TABLE 1. The characteristics of 3D Print-in-place Soft Origami Legged Robot (3DSOLR)

Origami Soft Compliance Design Shape	Material thickness (mm)	Shape of linkage/Joint	Linkage
Linkage	3mm	Long parallel linkage	Rigid
Joint	0.4mm~0.5mm	Circular 4mm diameter	Flex

We designed our 3DSOLR soft origami legs that are inspired by a soft origami zigzag gripper using Autodesk Fusion 360 software. Additional thin links were printed in the centre to provide additional support to the legs during locomotion while still maintaining its compliance properties. A single soft origami leg consists of 17 printed flexible hinges, 10 printed rigid links and zigzag origami ribs.



Specifications of TPU	
Print temperature	210-235 °C
Baseplate temperature	50–75 °C
Heat deflection temperature	85–110 °C
Melt flow index	14–28 g/10 min
Tensile yield strength	21–36 MPa
Elongation at break	26–60%
Flexural strength	60–97 MPa
Flexural modulus	1.8–3.0 G/Pa
Impact strength	120 kJ/m^2
Filament diameter	1.75 mm (±0.05 mm)

FIGURE 2. 3D Printer Ender3V2 Pro with Dry Box for Filament printing.

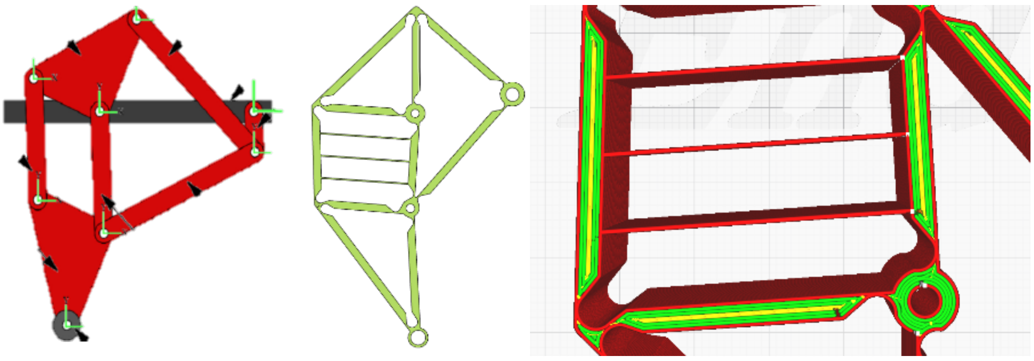


FIGURE 3. 3DSOLR soft origami leg design

After designing the soft origami legs (as shown in Figure 3), we analyzed them with Finite Element Analysis (FEA) using ANSYS software (Siew et al. 2017). By inputting the parameters required, we could visualize our design from directional deformation to equivalent stress, as shown in Figure 4. Thus, we could make adjustments based on the analysis of the design before printing. The isometric view of the 3D print-in-place soft legged robot is presented in Figure 5. Figure 6 showed the final design of the 3D print-in-place soft legged robot (3DSOLR).

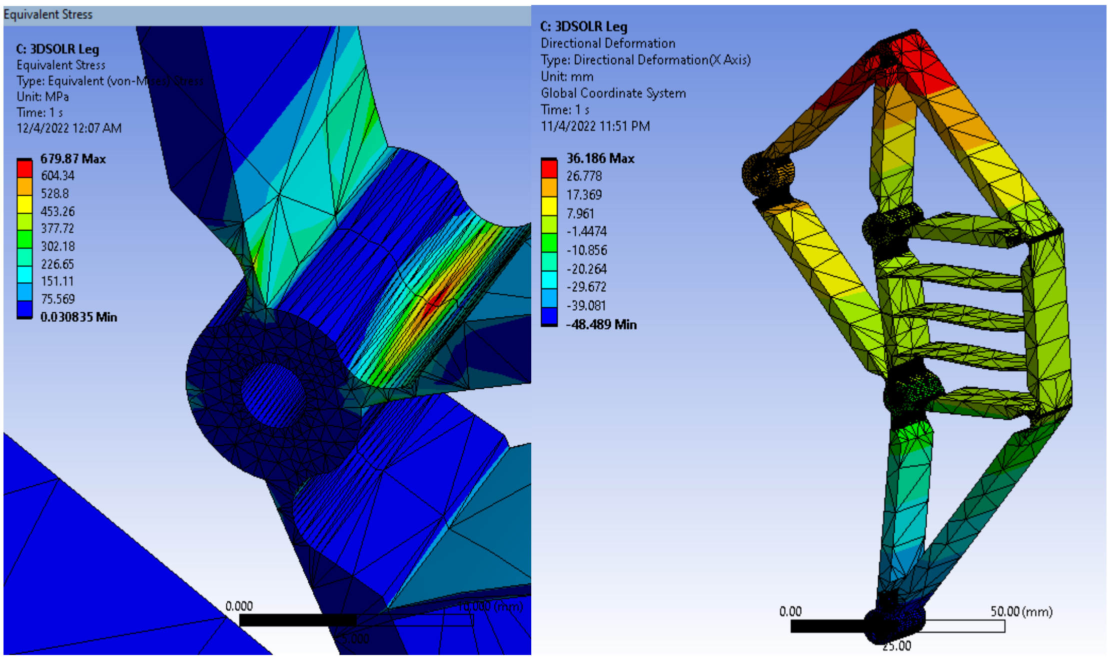


FIGURE 4. Finite Element Analysis (FEA) showing the thin area of 0.4mm having deflection strain feature

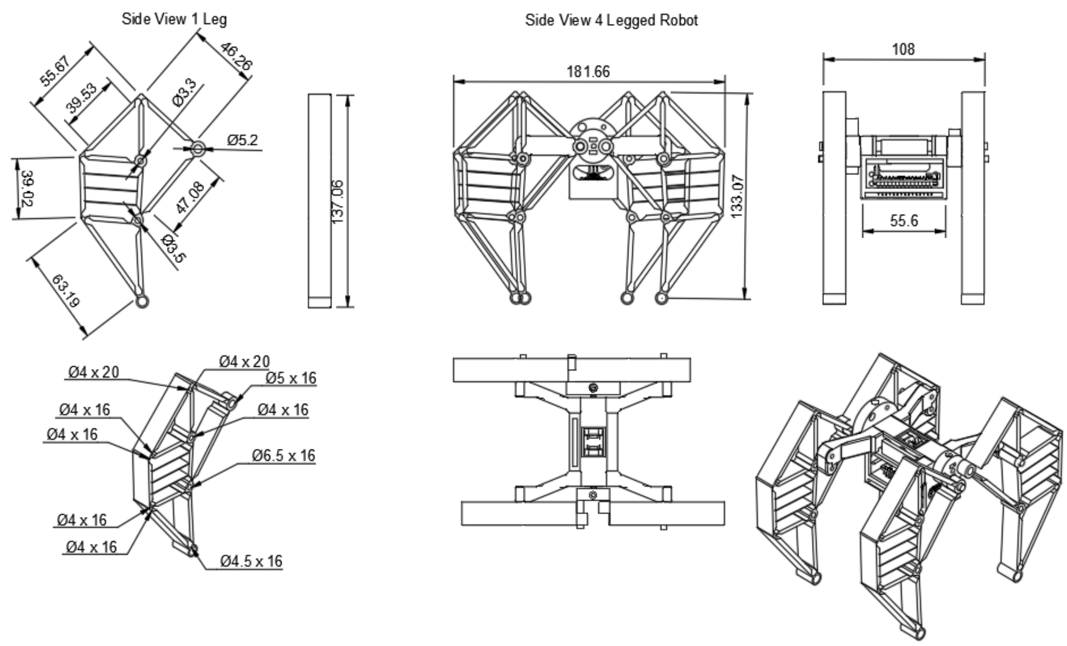


FIGURE 5. Isometric View of 3DSOLR

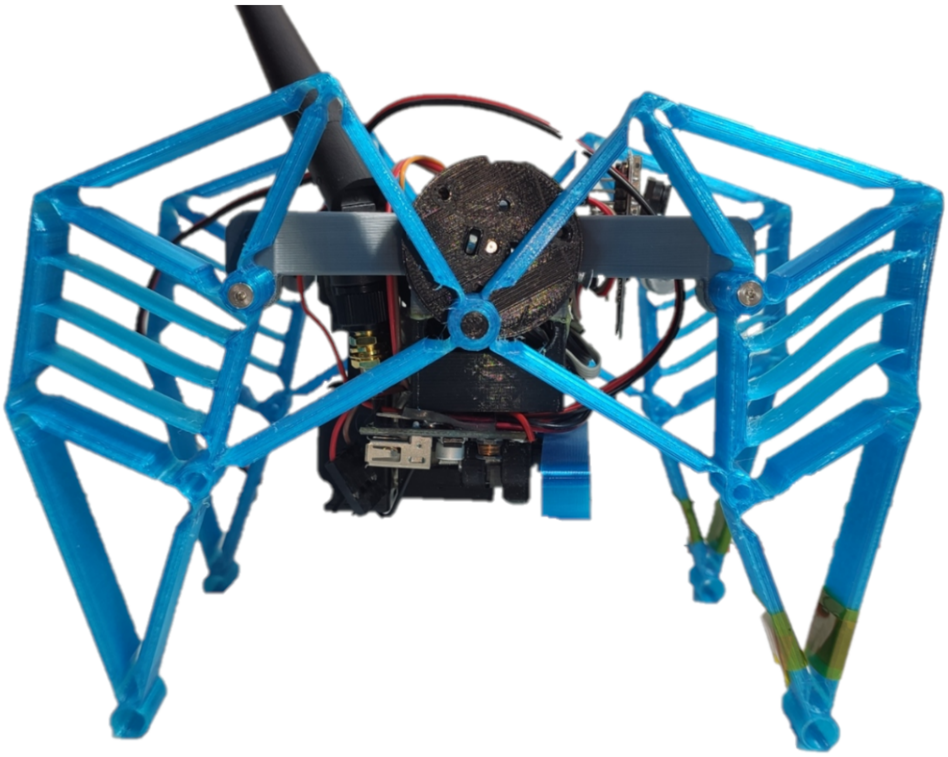


FIGURE 6. Final design for 3DSOLR

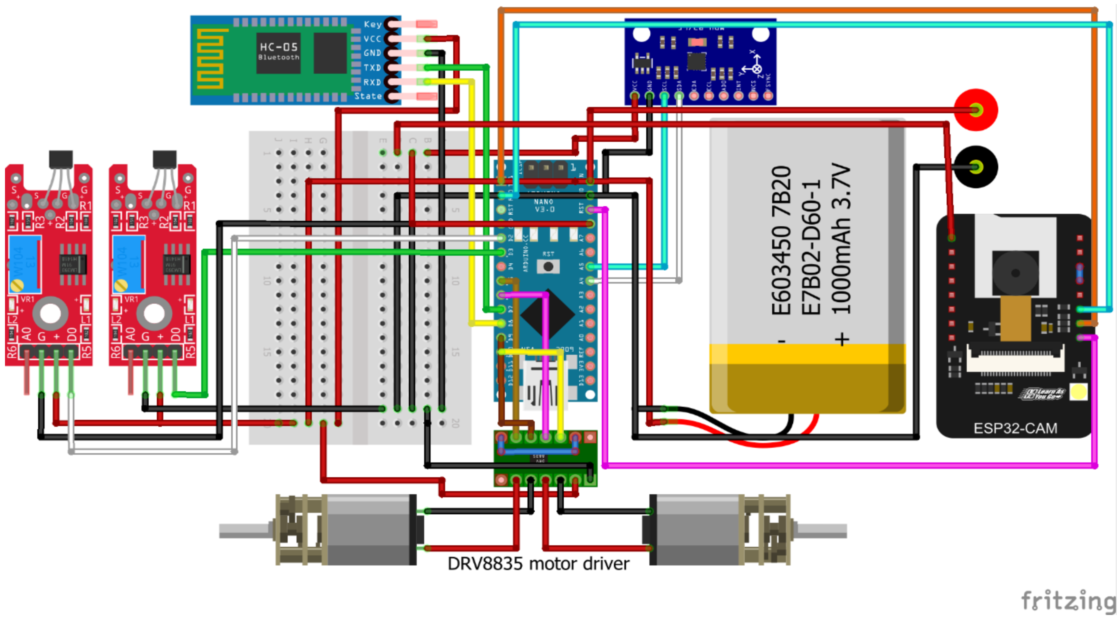


FIGURE 7. 3DSOLR's base electronics wiring

For the electronics of 3DSOLR, it is primarily made up of synchronous walking gait, Hall effect sensors, MEMs sensor, Bluetooth module, motor driver, 2 DC motors, an Arduino Nano and ESP32 CAM (as shown in Figure 7). The presence of Hall effect sensors was to ensure that all four legs are moving in a coordinated manner. A Bluetooth module was added for app control purposes. The 3DSOLR software flow chart is given in Figure 8. Figure 9 showed the smartphone apps Bluetooth control of 3DSOLR.

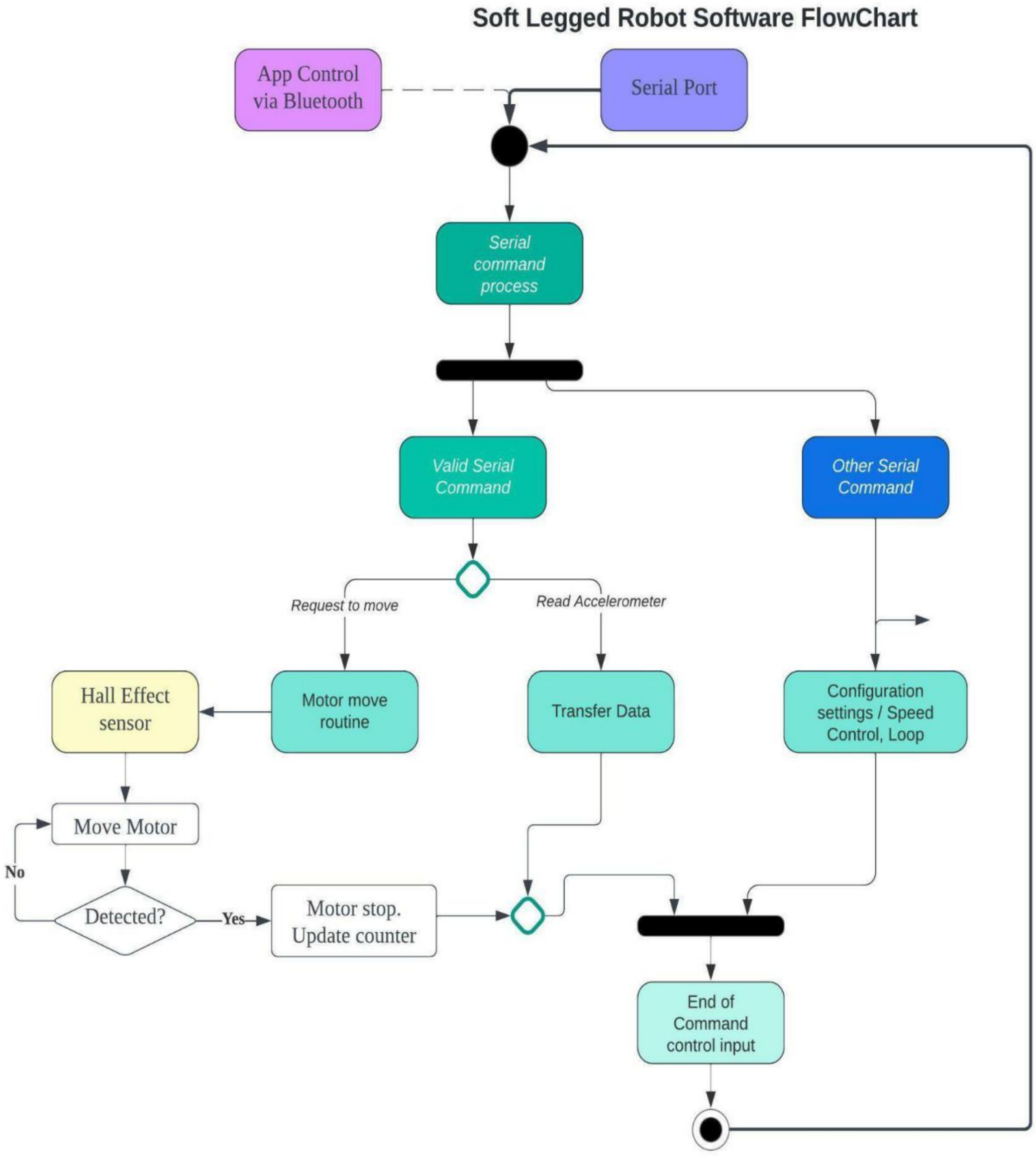


FIGURE 8. 3DSOLR Software Flow Chart

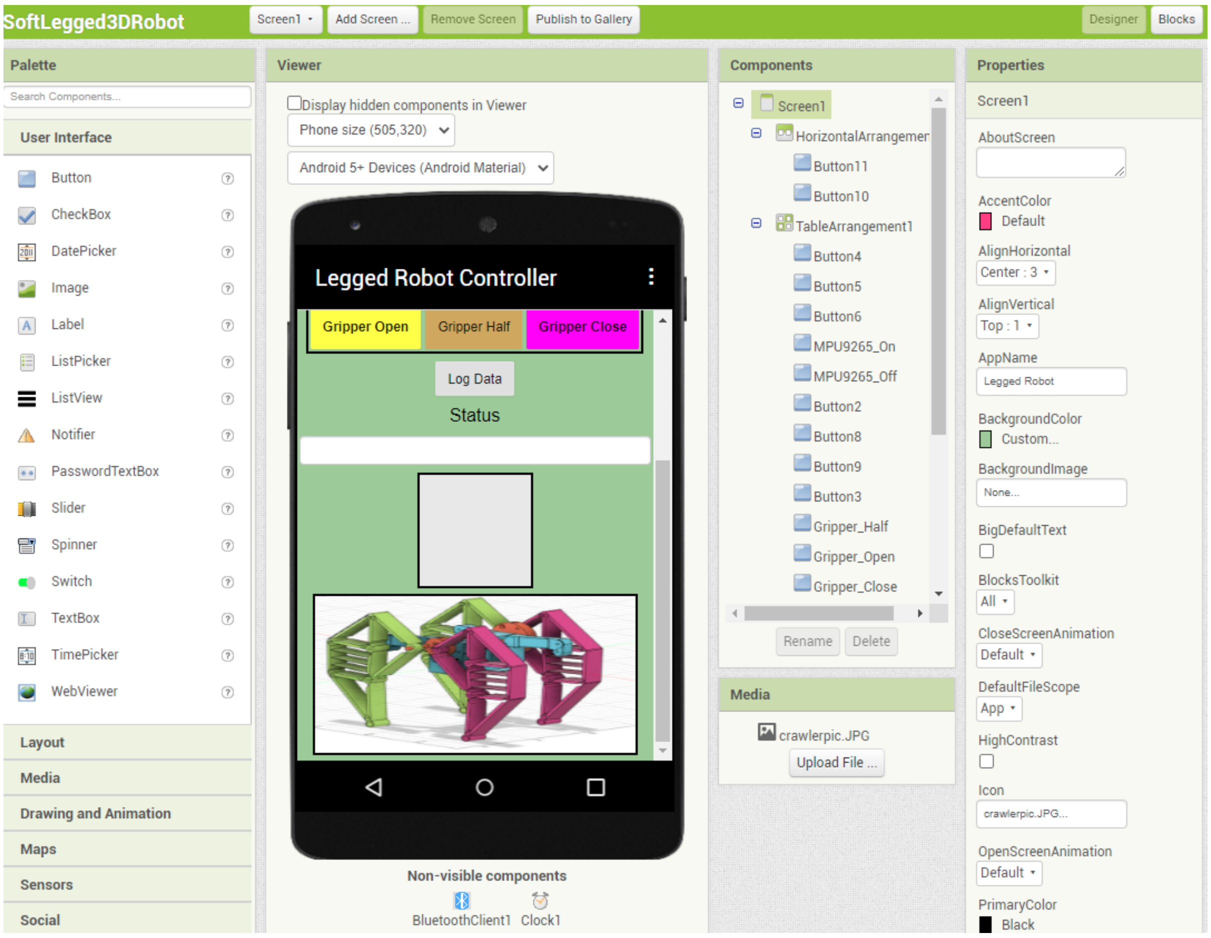


FIGURE 9. Smartphone Apps Bluetooth Control

After 3D print-in-place the soft origami legs and assembling all the components, we added a soft gripper built using TPU material to grasp different kinds of objects during mobility. The soft gripper, which is inspired by the mandible of the male European stag beetle, has a semi zigzag origami design that uses its 60-degree slant ribs to grip small objects, as shown in Figure 10. 3DSOLR has artificial intelligence (AI) capability with ESP32 CAM onboard which has object classification using custom Edge Impulse neural network MobileNetV1 96 x 96. This will further enhance the robot's capability in object classification for grasping.

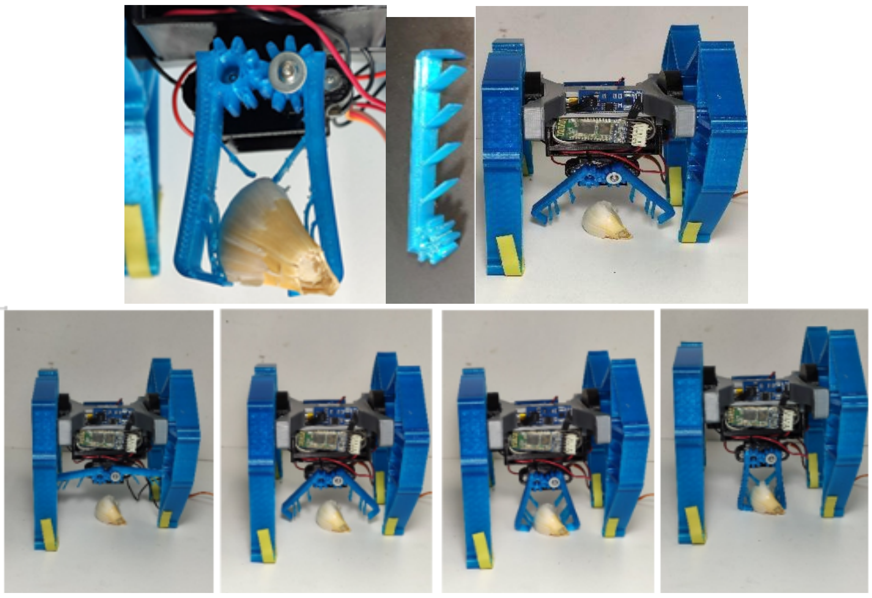
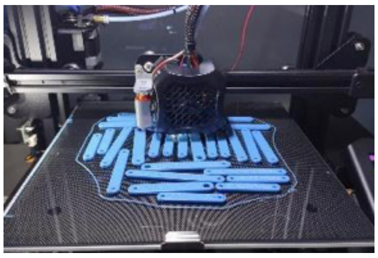
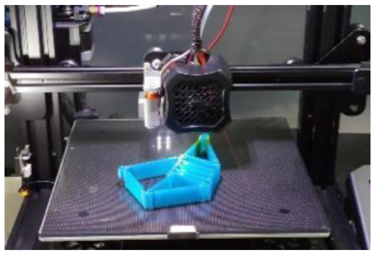


FIGURE 10. 3DSOLR with soft origami gripper performing grasping tasks

RESULTS AND DISCUSSION

To perceive the differences between 3DSOLR and Rigid Legged Robot, different types of tests and comparison has been conducted, as shown in Table 2. Since 3DSOLR and Rigid Legged Robot use the same legged robot base, electronics, and leg dimensions, we were able to compare the soft origami design and TPU material versus the standard design and PLA filament. The first comparison is on fabrication and assembly efforts. By 3D print-in-place the soft origami legs, we can incorporate the hinges and joints without the need for additional components to assemble them together.

TABLE 2. 3DSOLR required significantly less assembly effort, leg parts and installation time compared to Rigid Legged Robot

	Rigid Legged Robot	**3DSOLR**
		
Printing times	10 min x 40 (PLA)	4hr x 4 (TPU)
Leg parts	10 links x 28 bolts	4 legs x 2 bolts
Assembly effort	10x28 = 280 points	4x10 = 40 points
Installation time	2.5 hours	10 minutes

We also compared the compression and deformation of the respective legged robots, as shown in Figure 11 below.

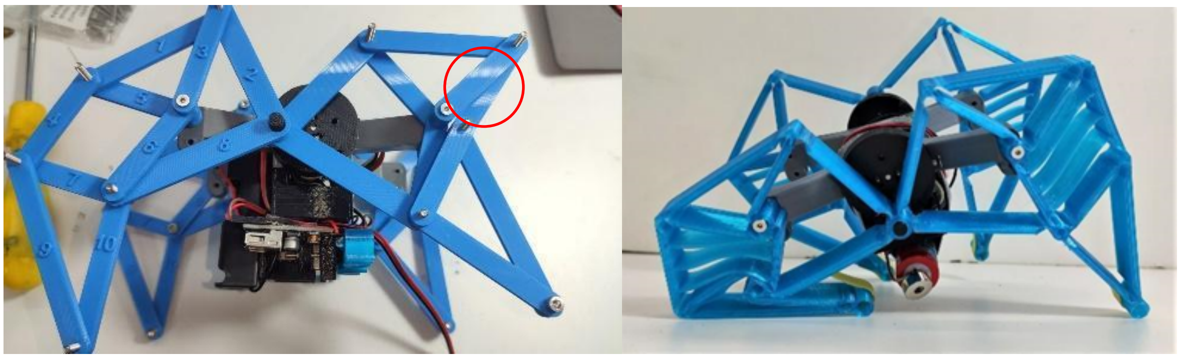


FIGURE 11. Rigid Legged Robot with stuck joint and 3DSOLR when subject to compression and deformation.

Rigid Legged Robot when subjected to high locomotion intensity has link joints "4-7-9" stuck due to microwear on the joint resulting in heavy backlash. The frequency of a jammed link joint event increases as the bolts and nuts start to loosen over time. Eventually, link joint "4" needs to be reprinted with a longer length to reduce this effect. In contrast, due to its unique high foldable origami shape with compressible legs, 3DSOLR regains its original legged shape despite subjecting the same test with no backlash or weakening on the flexure hinge whatsoever.

Next, mobility tests were being conducted on both legged robots with a MEMs sensor that records 3 axis acceleration. By travelling a distance of one meter, 3DSOLR has a maximum speed of 6.734 cms^{-1} whereas Rigid Legged Robot has a maximum speed of 9.675 cms^{-1}. During the mobility tests, the 3 axis acceleration data were recorded and analyzed.

FIGURE 12. Axis acceleration data for 3DSOLR and Rigid Legged Robot

To get a more comprehensive understanding of the differences in acceleration data, we used Fast Fourier Transform (FFT) to analyze the same acceleration data, as shown in Figure 12. A fast Fourier transform (FFT) is an algorithm that computes the discrete Fourier transform (DFT) of a sequence. In Figure 13, 3DSOLR FFT revealed multiple peaks of X and Y-axis acceleration from the soft legged compliance joints and movement.

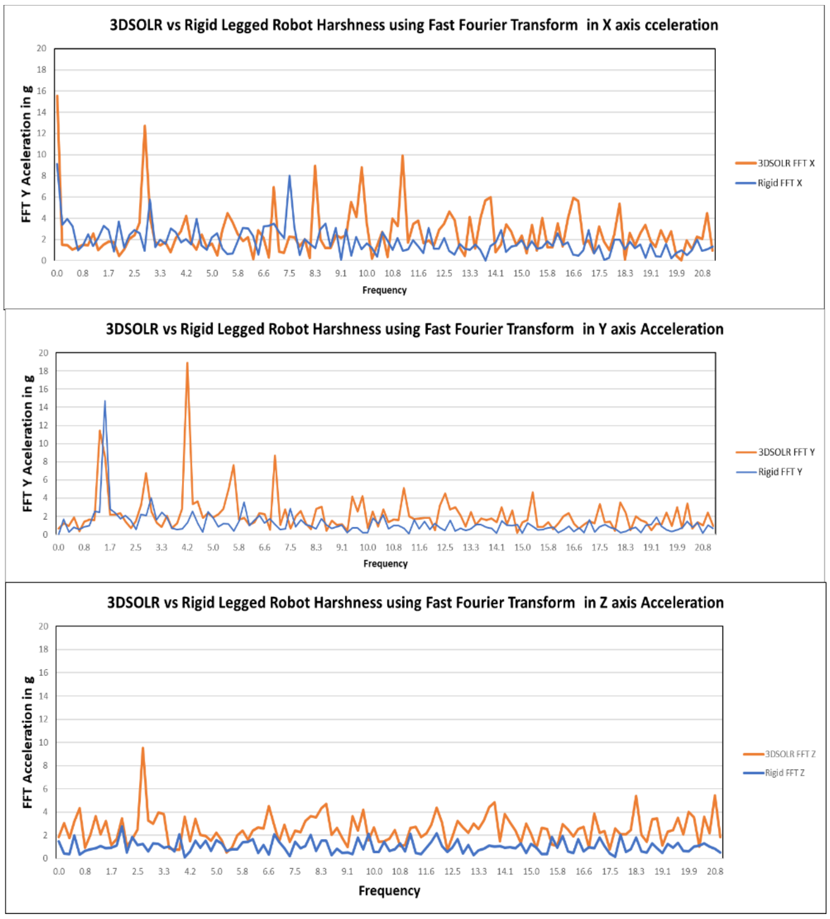


FIGURE 13. 3DSOLR FFT revealed multiple peaks of X and Y-axis acceleration from the soft legged compliance joints and movement.

During the mobility test, it is observed that 3DSOLR has a unique characteristic that is capable of "walking" in an inverted manner too, as shown in Figure 14.

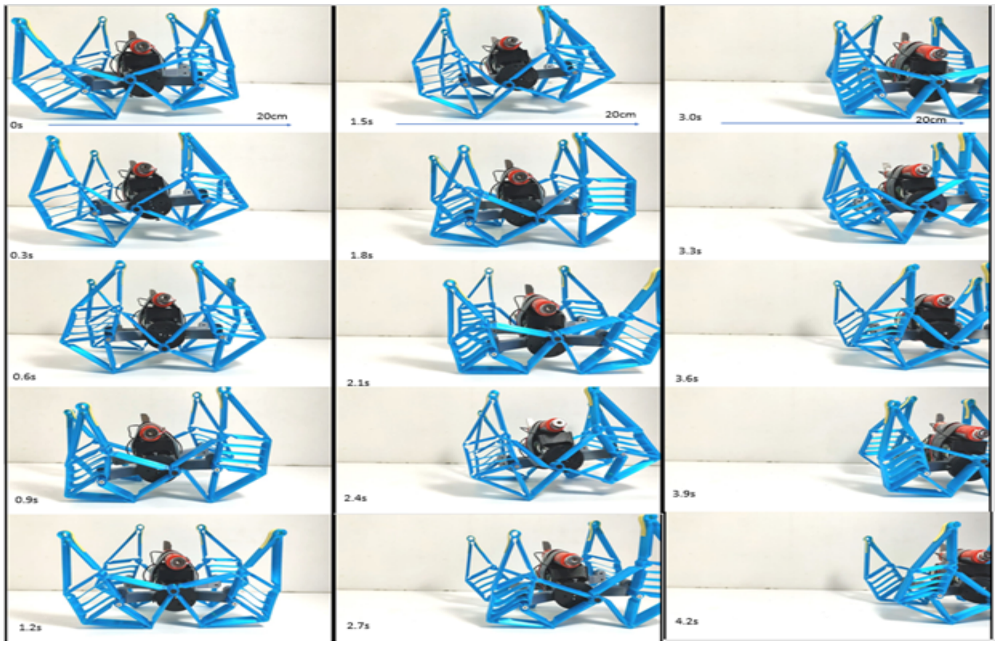


FIGURE 14. 3DSOLR walking invertedly

To test the shock-absorbing capabilities of 3DSOLR and Rigid Legged Robot, we conducted a 50cm free-fall drop test for both legged robots for comparison. By capturing the dropping sequence in slow motion of 940fps, 3DSOLR performed successful landings without damaging the legs and was still able to be at an upright position, as shown in Figure 15. This is tested by checking the origami legs and mobility test. The soft compliance origami zigzag shape acts as an impact absorber and distorts and softens the landing.

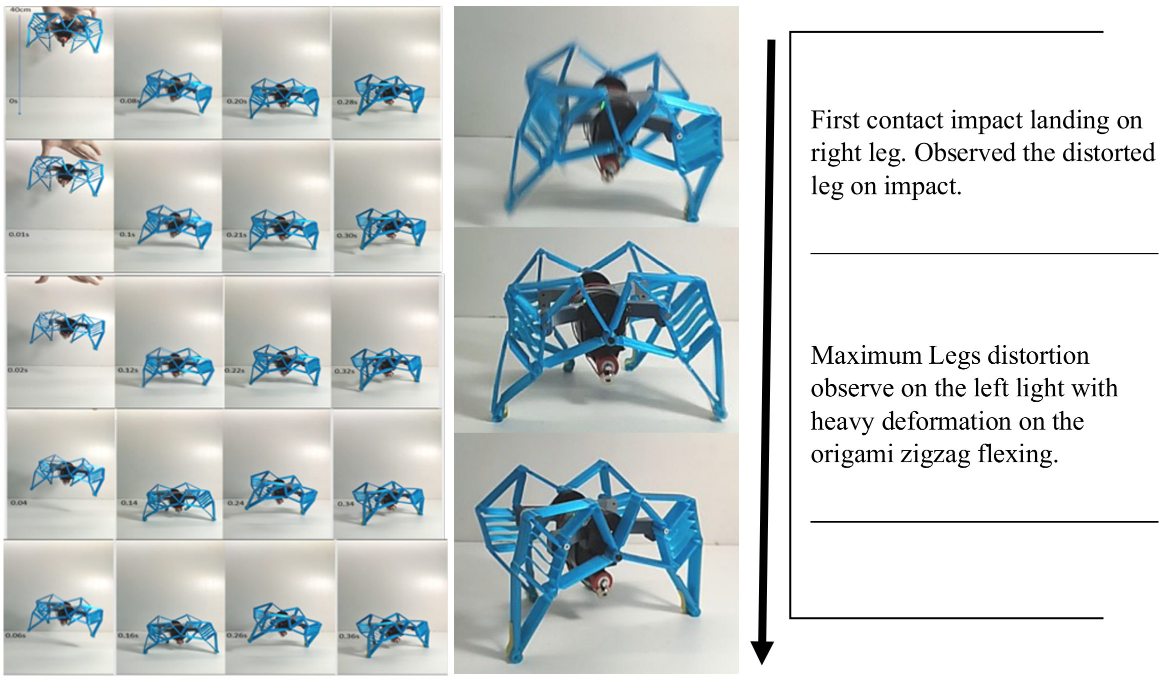


FIGURE 15. The free-fall drop test of the 3D Print-in-place Soft Origami Legged Robot (3DSOLR)

In contrast, the Rigid Legged Robot has rigid legs and is connected by screws and joints, which has little compliance properties. As a result, on the 2nd drop test, the rigid legs ultimately gave way, with broken hinges and parts, as shown in Figure 16.

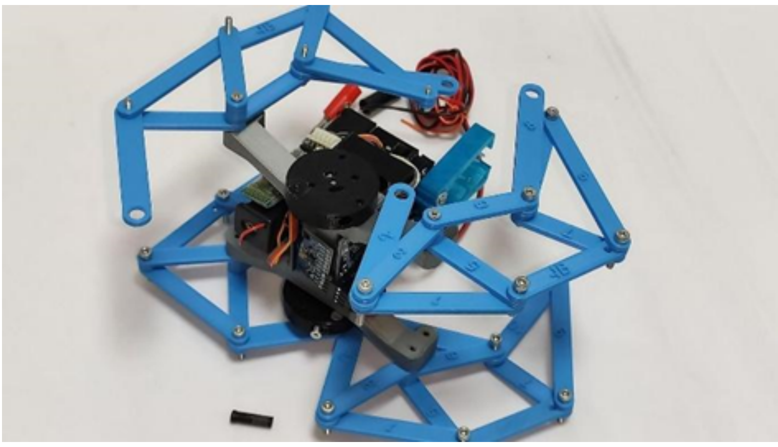


FIGURE 16. Aftermath of Rigid Legged Robot on 2nd drop test

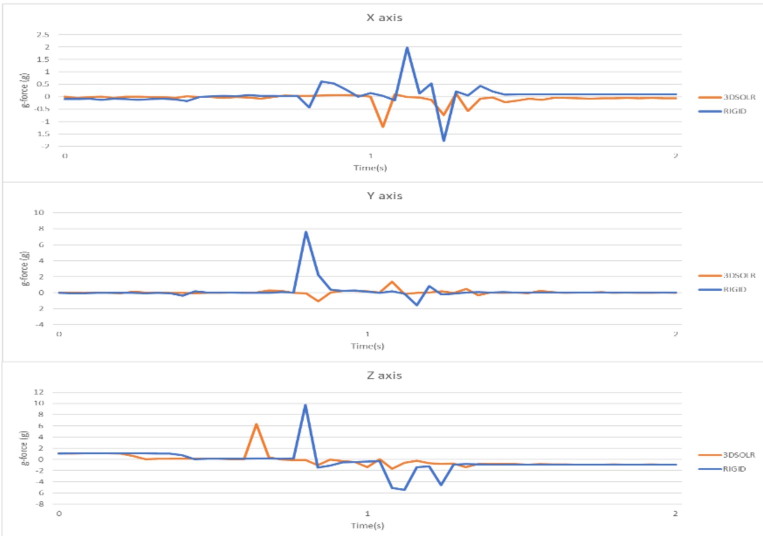


FIGURE 17. X, Y, Z acceleration data of the drop tests for 3DSOLR and Rigid Legged Robot

From the Figure 17, Rigid Legged Robot measured higher acceleration in short duration compared to 3DSOLR which measured lower acceleration. This is primarily due to its soft origami legs with rebounced and compliant characteristics.

The 3DSOLR carried another embedded processor, ESP32 CAM. This is a tiny board that is able to process images from its onboard camera for object classification. Figure 18 showed the flow chart of the software.

FIGURE 18. Software Flowchart with ESP32 CAM that forms the AI Object Detection with command for Robot manipulation.

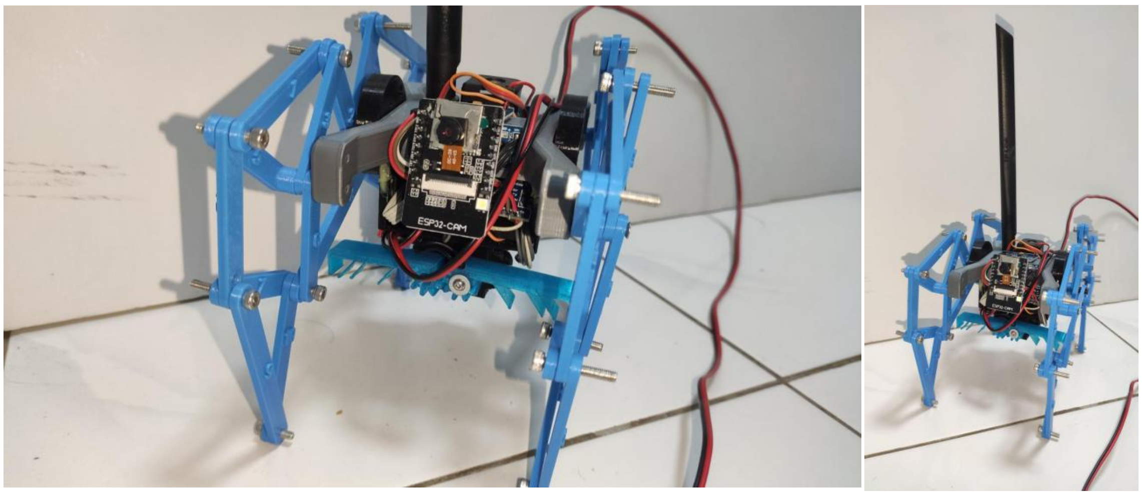


FIGURE 19. ESP32 CAM mounted in front of the 3DSOLR and visible on the right is the 2.4GHz antenna for WIFI connectivity on the Rigid legged Robot.

The ESP32 CAM used custom inference from Edge Impulse using Mobilenet V1 96x96 image pixels, as shown in Figure 19. The custom inference algorithm uses 998 images with an 80/20 split for training and testing (as shown in Figure 20) and training of the MobilenetV1 resulted in 95.5% accuracy (as shown in Figure 21).

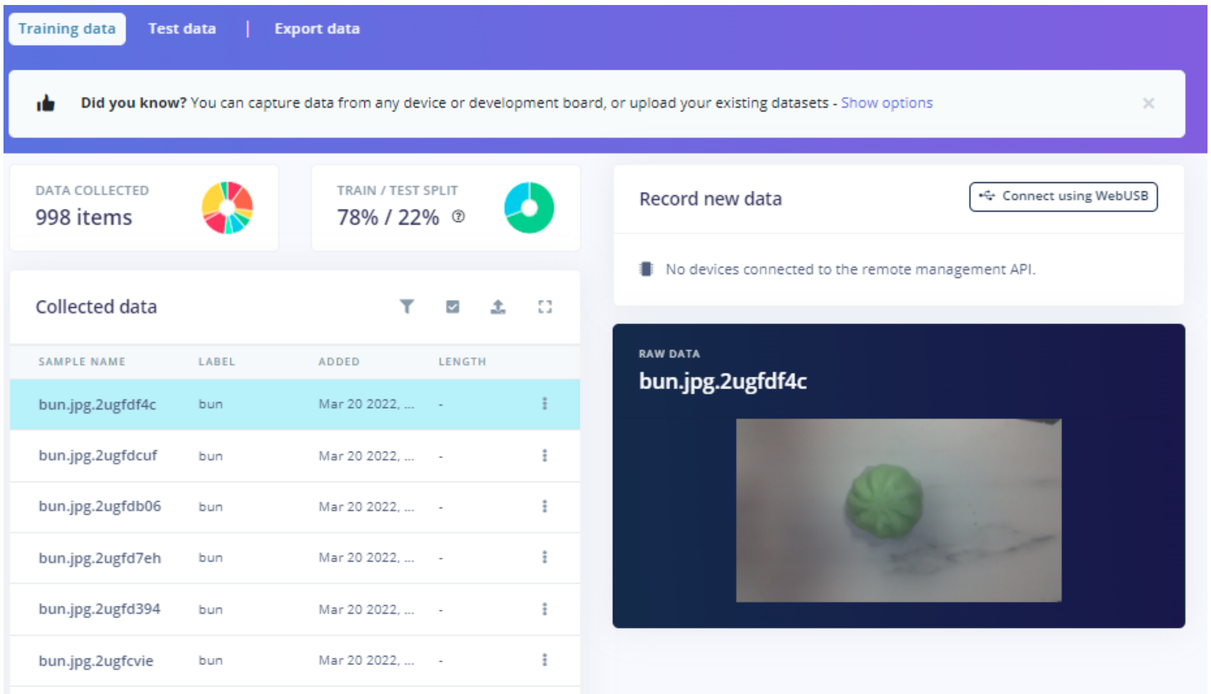


FIGURE 20. Training and testing in Edge Impulse using Mobilenet V1 96x96 image pixels.

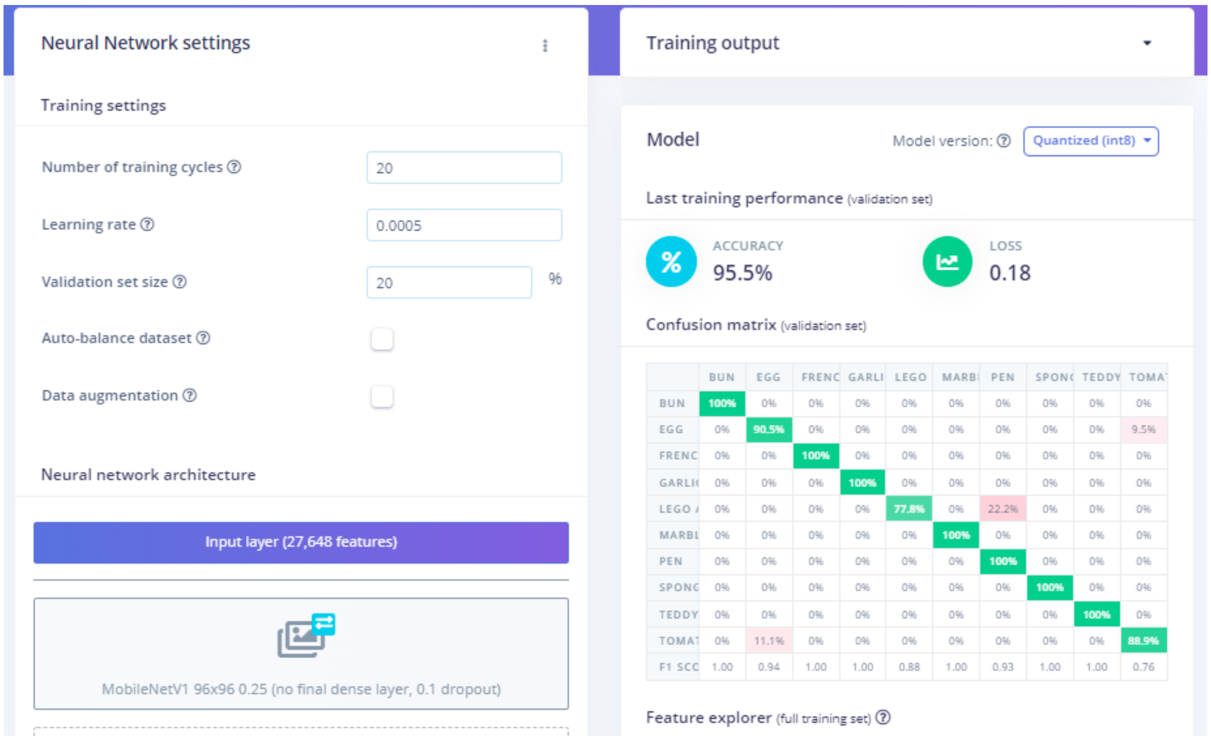


FIGURE 21. Object classification accuracy of the MobilenetV1.

We have compared our 3DSOLR with other four-legged robot designs in Table 3 below and the images of the robots KOTETSU and Scout-I is shown in Figure 22.

TABLE 3. Summary of published performance reports of four-legged robots against 3DSOLR

Name of the Robot	Dimensions (m) [L: Length(m); W: Width(m); H: Height(m)]	Gait	Speed (m/s)	Weight (kg)	Leg Material	DOF	Number of actuators	Actuator
KOTETSU	0.34 x 0.19 ~ 0.25 x 0.35 (L x W x H)	Walk	0.200	5.20	Aluminum	3/leg	3/leg	Electric
SCOUT -I	0.2(L)	Walk, Run	-	1.20	Aluminum	1/leg	1/leg	Electric
SCALF - 1	1 0.4 0.68 (L W H)	Trot	1.8	123	Aluminum	3/leg	3/leg	Hydraulic
Star1ETH	0.6(L)x 0.49(l)	Bound	1	23	Aluminum	3/leg	3/leg	Electric
Rigid Legged Robot	0.18 x 0.12 x 0.14 (L x W x H)	Theo Jansen walking gait	0.097	0.22	PLA	Limited	1/leg	Electric
3DSOLR	0.18 x 0.13 x 0.14 (L x W x H)	Theo Jansen walking gait	0.067	0.23	TPU	limited	1/leg	Electric

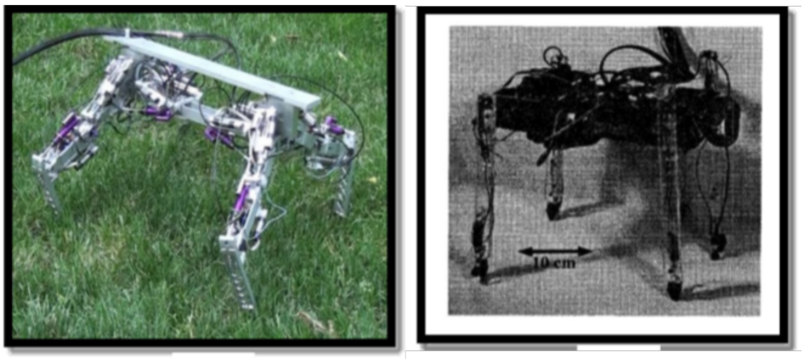


FIGURE 22. KOTETSU (left) and Scout-I (right)

CONCLUSION

Aiming at the limitations and complexities of the multi-motor control of a quadruped robot, we proposed a 3D print-in-place soft origami leg structure scheme of single degree of freedom linkage quadruped robot. The robot mechanism consists of four soft origami flexible legs driven by two DC motors and was inspired by the rigid joint Theo Jansen legged robot. The design of the soft origami legs was analyzed with Finite Element Analysis (FEA) using ANSYS software before 3D printing. During the mobility test, 3DSOLR achieved a maximum speed of 6.734cms^{-1} and it survived the drop test. 3 axis acceleration data were recorded during the tests and analyzed using Fast Fourier Transform (FFT) for better understanding. The 3DSOLR is lightweight, semi-autonomous using two Hall effect sensors and a wireless Bluetooth module. Being 3D print-in-place using TPU increases its durability while having flexibility, simplicity and safety. It also equipped with a soft gripper and artificial intelligence (AI) capability with ESP32 CAM onboard which has object classification using custom Edge Impulse neutral network MobileNetV1 96 x 96. These features made the robot suitable to be used in social robotics and rescue robotics applications. The transmitter program was implemented in Bluetooth serial communication using MIT App Inventor 2 smartphone apps. A microcontroller Arduino ATMEL was used as the main controller and coded in Arduino IDE.

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Biswal, P. & Mohanty, P. K. 2021. Development of quadruped walking robots: A review. *Ain Shams Engineering Journal 12*(2): 2017–2031.

Bowen, L. A., Grames, C. L., Magleby, S. P., Howell, L. L., & Lang, R. J. 2013. A classification of action origami as systems of spherical mechanisms. *Journal of Mechanical Design*, 135(11). DOI:https://doi.org/10.1115/1.4025379.

Cao, J. Q., Li, B. & Yuan, W. F. 2015. Design and Analysis of Quadruped Single Drive Mechanical Horse Mechanism. *Machinery Design and Manufacture*, *4:* 228–232. DOI:https://doi.org/10.19356/j.cnki.1001-3997.2015.04.062.

Chen, J. P., San, H. J., Wu, X. & Xiong, B. Z. 2021. Structural design and gait research of a new bionic quadruped robot. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. DOI:https://doi.org/10.1177/0954405421995663.

Ghanari, A., Babalasi, M. & Veisinejad, A. 2019. Design, mechanical simulation and implementation of a new six-legged robot. arXiv:1902.03547 (cs)

Hirose, S., Yoneda, K., Arai, K.. & Ibe, T. 1991, June. Design of prismatic quadruped walking vehicle TITAN VI. *Fifth International Conference on Advanced Robotics 'Robots in Unstructured Environments*, 723–728. DOI:https://doi.org/10.1109/icar.1991.240685.

Hutter, M., Gehring, C., Bloesch, M., Hoepflinger, M. A., Remy, C. D. & Siegwart, R. 2012. Starleth: A Compliant Quadrupedal Robot For Fast, Efficient, And Versatile Locomotion. *Adaptive Mobile Robotics*, 483–490. DOI:https://doi.org/10.1142/9789814415958_0062.

Hutter, M., Gehring, C., Jud, D., Lauber, A., Bellicoso, C. D., Tsounis, V., Hwangbo, J., Bodie, K., Fankhauser, P., Bloesch, M., Diethelm, R., Bachmann, S., Melzer, A. & Hoepflinger, M. 2016, October. ANYmal - a highly mobile and dynamic quadrupedal robot. *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. DOI:https://doi.org/10.1109/iros.2016.7758092.

Liu, J., Tan, M. & Zhao, X. 2007. Legged robots — an overview. *Transactions of the Institute of Measurement and Control 29*(2): 185–202.

Majidi, C. 2014. Soft Robotics: A Perspective—Current Trends and Prospects for the Future. Soft Robotics, 1(1): 5–11. DOI:https://doi.org/10.1089/soro.2013.0001.

Park, H. S., Floyd, S. & Sitti, M. 2009. Roll and pitch motion analysis of a biologically inspired quadruped water runner robot. *The International Journal of Robotics Research 29*(10): 1281–1297. DOI:https://doi.org/10.1177/0278364909354391.

Park, H.-W., Wensing, P. M. & Kim, S. 2017. High-speed bounding with the MIT Cheetah 2: Control design and experiments. *The International Journal of Robotics Research 36*(2): 167–192. DOI:https://doi.org/10.1177/0278364917694244.

Raibert, M., Blankespoor, K., Nelson, G. & Playter, R. 2008. BigDog, the Rough-Terrain Quadruped Robot. *IFAC Proceedings Volumes 41*(2): 10822–10825. DOI:https://doi.org/10.3182/20080706-5-kr-1001.01833.

Rosa, F., Bordegoni, M., Dentelli, A., Sanzone, A. & Sotgiu, A. 2017. Print-in-place of Interconnected Deformable and Rigid Parts of Articulated Systems. *Procedia Manufacturing*, *11:* 555–562. DOI:https://doi.org/10.1016/j.promfg.2017.07.149.

Ruan, Q., Yao, Y. A. & Wu, J. X. 2019. Analysis and experiments on a novel smoothly moving low-DoF multilegged robot. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *234*(1): 302–317.

Rus, D. & Tolley, M. T. 2018. Design, fabrication and control of origami robots. Nature Reviews Materials, 3(6): 101–112. DOI:https://doi.org/10.1038/s41578-018-0009-8.

Rygg, L. A. 1893. *Mechanical horse* (US491927A). United States Patent and Trademark Office.

Schenk, M. & Guest, S. D. 2011. Origami 5: Fifth International Meeting of Origami Science, Mathematics, and Education (AK Peters/CRC Recreational Mathematics Series). In Origami Folding: A Structural Engineering Approach (1st ed., pp. 291–304). A K Peters/CRC Press. DOI:https://doi.org/10.1201/b10971.

Semini, C., Barasuol, V., Goldsmith, J., Frigerio, M., Focchi, M., Gao, Y. & Caldwell, D. G. 2017. Design of the Hydraulically Actuated, Torque-Controlled Quadruped Robot HyQ2Max. *IEEE/ASME Transactions on Mechatronics 22*(2): 635–646. DOI:https://doi.org/10.1109/tmech.2016.2616284.

Semini, C., Tsagarakis, N. G., Guglielmino, E., Focchi, M., Cannella, F. & Caldwell, D. G. 2011. Design of HyQ – a hydraulically and electrically actuated quadruped robot. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, *225*(6): 831–849. DOI:https://doi.org/10.1177/0959651811402275.

Seok, S., Wang, A., Chuah, M. Y., Hyun, D. J., Lee, J., Otten, D. M., Lang, J. H. & Kim, S. 2015. Design principles for energy-efficient legged locomotion and implementation on the mit cheetah robot. *IEEE/ASME Transactions on Mechatronics*, *20*(3): 1117–1129.

Siew, F.Y., Azrul, A.M. & Firdaus, M.H. 2017. Aggregate impact on dynamic behavior of concrete using finite element method. *Journal of Engineering*, Special Issue 1:69-76.

Vinayak. 2006. Intuitive Design and Gait Analysis for a Closed Loop Leg Mechanism of a Quadruped with Single Actuator. In M. O. Tokhi, G. S. Virk, & M. A. Hossain (Eds.), *Climbing and Walking Robots* (pp. 303–310). Springer. DOI:https://doi.org/10.1007/3-540-26415-9_36.

Yan, C., Shi, K., Zhang, H. & Yao, Y. 2022. Simulation and analysis of a single actuated quadruped robot. *Mechanical Sciences* 13(1): 137–146.