A Reliable Low-Cost Foot Contact Sensor for Legged Robots

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***Abstract*— In an unstructured environment, fast walking legged robots can easily damage itself or the crowd due to slips or missing desired contacts. Therefore, it is important to sense ground contacts for legged robots. This paper presents a low-cost, lightweight, simple and robust foot contact sensor designed for legged robots with point feet. First, the mechanical design of the foot is proposed. The foot detects contact as it presses against the ground through the deformation of a layer of polyurethane rubber, which allows the compressive displacement of the contact foot pad to trigger the enclosed sensor. This sensor is a binary contact sensor using pushbutton switches. The total weight of the foot contact sensor is 82g, and the cost of manufacturing one is less than $10 USD. Next, the effectiveness of the developed foot is confirmed through several experiments. The angle between the center axis of the foot and the ground is referred to as the contact angle in this paper. The foot contact sensor can reliably detect ground contact over contact angles between 30° to 150°. This prototype sensor can also withstand contact forces of over 80N for more than 10,000 steps.**

I. INTRODUCTION

In a structured environment, many legged robots can walk well without any contact sensors as ground contact can be inferred from joint torque measurements from the motors attached to legs. However, in an unstructured environment, fast contact sensing is crucial for many robotic tasks that require physical interactions. Especially in the case of performing force control, inaccurate contact detection can lead to situations where the robot's end-effector can act erroneously and damage its surroundings. For legged robots, having a contact sensor can provide the robotic controller with real-time information of slips, missteps or early touchdowns, and therefore prevent any potential damages. Therefore, reliability in sensing ground contact is the most important parameter in ground contact sensor design. More specifically, the sensor should be able to consistently sense the ground contact at different angles during the process of repeated touchdowns of the foot in dynamic walking situations. Additionally, the sensor should be lightweight. When considering the inertial effects of legged robots, the robot is often modeled as having a lumped mass on its body while having massless limbs in both bipedal walking [1] and quadruped gait planning controllers [2], [3]. As a part of the foot assembly of the robot, a more lightweight design of the ground contact sensor is desired for making the physical robot represent the mathematical model better.

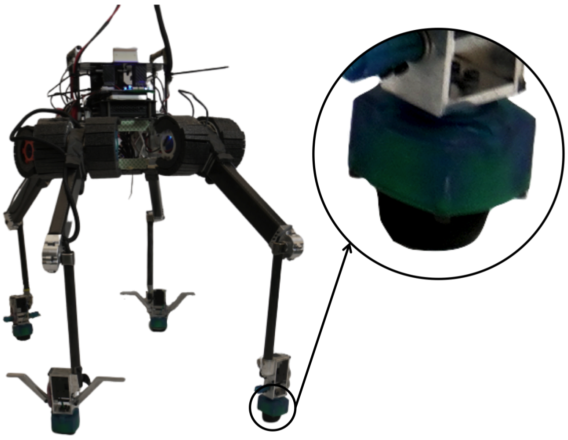

Fig. 1: ALPHRED. A quadruped robot, ALPHRED, with foot contact sensors attached. The weight of ALPHRED is 20kg, and therefore, the triggering force threshold for each foot contact sensor should be 50N or less.

When it comes to mounting sensors on the feet, many literature use force-torque sensors [4], [5] or tactile sensing arrays [6]. Conventional strain gauge based force-torque sensor is among the most popular choices for ground contact sensing, especially in bipedal robots using the Zero Moment Point walking method [7], [8]. In these cases, force-torque sensors are usually placed on the ankle joint of the humanoid robot as a structural component. These sensors have to be placed at a very precise location and require strong enclosures to protect them from external wear and tear. Although a force-torque sensor is capable of measuring direct force and torque at the ankle joint, they fall short in dynamic walking situations for quadrupeds with major shortcomings. As mentioned, the mathematical model of a legged robot becomes more accurate when the mass of each limbs is small. However, the force-torque sensors that can handle relatively large forces weigh a considerable amount, making the assumption of massless limbs very inaccurate. In addition, impacts to the foot assembly are very common in dynamic walking situations for legged robots, but force-torque sensors cannot adequately handle impact due to their high stiffness [9] and need re-calibration and often costly replacements after a number of impact cycles. Moreover, they are less suitable for robots with very small foot surface areas, and often have low signal to noise ratios.

Alternative tactile sensing technologies utilize optical, magnetic, resistive or capacitive sensors to measure con-

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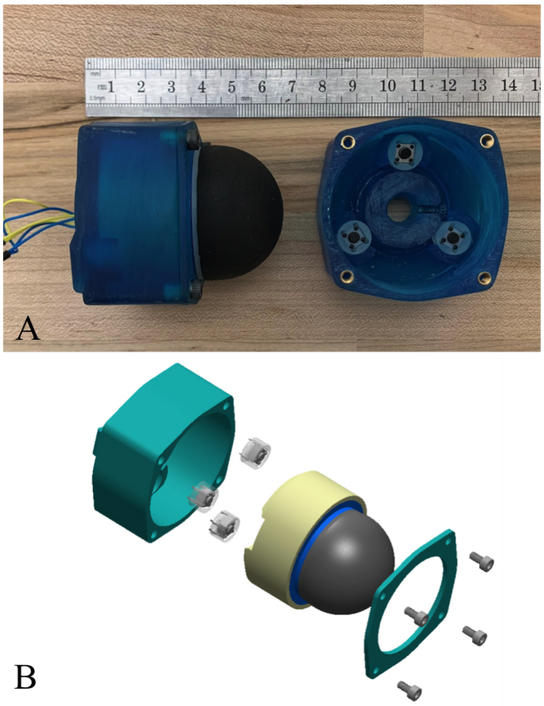

Fig. 2: A reliable low-Cost foot contact sensor for legged robots. (A) Completed foot contact sensor is shown on the left, and bottom view of pushbutton switch layout is on the right. (B) Rendered exploded view of the foot contact sensor.

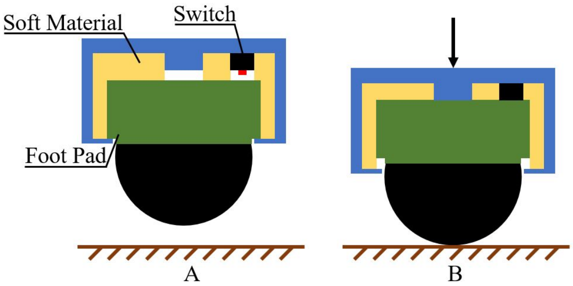

Fig. 3: Ground Sensing Mechanism. When the foot is in contact with the ground and a reaction force is applied to the foot, the soft material layer gets compressed and the foot pad triggers the switch (B). And when the foot leaves the ground, the soft material layer springs back and restores the sensor to is neutral state (A).

tact forces and pressure distributions [10]. These sensors are typically made in thin sheets that contain an array of sensors, and they are good at detecting contact locations. However, they are more suitable for small legged robots or in lower force applications [9], [10]. Other foot contact sensors that have also been developed include magnetic Hall-Effect based sensors [11] and barometric pressure sensors [9]. These sensors usually require additional complicated electrical circuits and can be more difficult to manufacture. In addition, the compactness of the foot is limited by the size of the sensors and the accompanying printed circuit boards (PCB). Our proposed foot contact sensor utilizes a simple and low-cost pushbutton switch. The structure of the sensor can be easily manufactured using 3D printing. Our foot contact sensor consistently exhibits high sensitivity to ground contact as well.

This paper is structured as follows: Section II discusses the design and fabrication of the foot contact sensor. Section III presents the experiment setup and results and Section IV discusses the data from the experiment. Finally, Section V presents the conclusion and future work.

II. FOOT DESIGN AND FABRICATION

The general design requirements for achieving dynamic tactile sensing are low hysteresis for good dynamic response, sensitivity aligned with force direction of interest, coverage and density, repeatability, maximum force or acceleration before saturation, packaging and robustness, and provisions for sampling and signal routing [12]. Our proposed foot contact sensor satisfies these criteria. The design principles and manufacturing processes are detailed in this section, while the performance of the sensor is validated in the next sections.

The sensing mechanism operates using the elastic deformation of a soft material. The entire foot contact sensor consists of three major functional components: a hard hemispherical contact foot pad, a layer of polyurethane rubber for compressive displacement under contact force, and an array of binary pushbutton switches for the detection of ground contact. When the foot is in contact with the ground, the reaction force from the ground pushes onto the foot pad, which compresses the layer of soft material and pushes onto the switches to trigger the sensor. When the foot is no longer in contact with the ground, the layer of soft material restores to its uncompressed height, thus disengaging the switches.

Although under-actuated and naturally unstable when operating with only with one or two feet as support [13], a point-foot design can provide normal force to the body of the robot at a wide range of contact angles, making it a good choice for dynamic walking and on unknown terrains. A point-foot also makes the contact dynamics of walking straightforward, as ground reaction force can be considered as concentrated at point of contact. As shown in Fig. 4, the point contact for our proposed foot design is provided by a hemispherical foot pad design. A Dunlop squash ball of 40mm diameter is cut open as the outer shell of the hemispherical contact foot pad. The rubber shell provides the foot pad with a good grip on the ground to prevent slipping in dynamic walking situations. On its interior, epoxy is molded to couple a hex bolt with the rubber shell and a 3D printed lid. Filled with hard epoxy, the foot pad does not experience significant deformation even under large loading, which validates the assumption of a point contact with the ground. With a hex bolt at its center, the foot pad can be used as a standalone component that can be fastened directly to the tibia of a quadruped or serve as a sub-component in the foot assembly.

In order to achieve triggering and releasing, the sensor must also have a compliant member that can deform elastically under force so it can restore to its original shape when said force is no longer applied to it. Some variations of a metal spring are usually used for this purpose as the linearity relationships between the applied force and its corresponding deflection can be used to infer the amount of contact force being applied. However, in dynamic walking situations, the feet of the robot hit the ground with an impact. Metal springs experience low damping losses and can cause the z-direction foot position to be harder to converge to a stable landing. On the other hand, soft materials, like rubber, exhibit spring-like and damper-like characteristics simultaneously. Although the non-linearity between compressing stress and strain in soft materials makes it more difficult to infer the ground reaction force, they are sufficient for binary ground sensor applications. A thin layer of Smooth-On ReoFlex urethane rubber is molded onto a 3D printed (Stratasys ABSplus) part, which couples with the hemispherical point foot.

During the locomotion of legged robots, the feet will experience cyclic loading with high-stress, so it is important to use appropriate material for the housing of the foot contact sensor. Due to its strong material properties, Tough Resin from Formlabs was used to print the housing. After post-curing, Tough Resin has an ultimate tensile strength of 55.7MPa and a tensile modulus of 2.7GPa. In addition, using the Formlabs stereolithography (SLA) 3D printer also provides higher resolution, as fine as 50 microns, and smooth surface finish.

For the binary sensing of the foot contact, miniature pushbutton switches are used. These tactile switches are low-cost and have a small footprint. As shown in Fig.5, an array of three pushbutton switches are placed radially symmetrically above the foot pad, each at a 120° to one another. The three switches are connected in parallel so that if any one of the switches gets triggered, the sensor identifies a ground contact.

Due to the simplicity and affordability of the electrical components of the sensor, most of the cost of producing the prototype were from the Tough Resin and the squash ball. The total cost of manufacturing one foot contact sensor was less than $10 USD. Also, because of the small footprint of the sensor, as well as the majority of materials being plastic, the total weight of the foot contact sensor is only 0.082kg. The lightweight nature of the foot contact sensor means the inertia of the foot assembly has a negligible effect on the validity of the massless limb assumption.

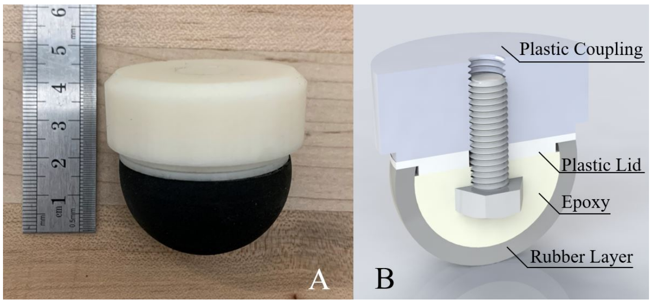

Fig. 4: Hemispherical Foot Pad (A) and its Section View (B). The axis of the hex bolt is referred to as the center axis of the foot, and the angle between the center axis and the ground upon contact is referred to as the contact angle.

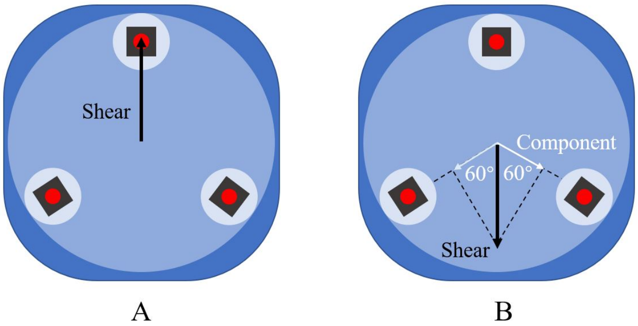

Fig. 5: Bottom View of the Placement of pushbutton Switches. The orientation of the foot contact sensor can influence the shear effect that acts perpendicular to the center axis of the sensor. However, this three-switch layout ensures that the minimum shear effect in (B) is still at least half as sensitive as in (A).

In early design iterations, only one pushbutton switch was placed on the center axis. Although this version of the sensor was able to detect ground contact in most cases, its sensitivity was strongly related to the foot's contact angle. As the ground contact angle deviates from 90°, the contact force required to sense ground contact grows rapidly, and the sensor was no longer able to detect ground contact at contact angles less than 45° or more than 135°. This limitation would greatly diminish the strengths of a point-foot design. On one hand, the component of force along the center axis decreases as the contact angle deviates from 90°. However, on the other hand, it is hypothesized that the shear effects that are perpendicular to the center axis of the foot contact sensor also contribute to the forces seen by the switches thus also affecting sensitivity. The foot pad experiences more displacement further away from its center when the foot contacts the ground at an angle, because there is more room for the soft material layer to deform. Therefore, a design embodying three pushbutton switches placed further away from the center axis is used. As shown in Fig.5, when we hold the magnitude and the direction of the contact force constant, this design ensures that the maximum shear effect caused by the contact force is at most two times the minimum shear effect caused by the contact force. Having more than three switches may further improve the consistency of sensitivity at different contact angles and foot orientations, but would reduce the room for the soft material layer. Preliminary testing of the three-switch design indicated significant improvement in detecting ground contact with large contact angles, and experiments were designed to investigate the relationship between triggering and releasing force threshold and the contact angle. This will be discussed in the subsequent sections.

For legged robots, the minimization of wiring is an additional advantage. With the three pushbutton switches connected in parallel, only two pins are required to use the foot contact sensor. For instance, one pin can be connected to an Arduino or any microcontroller's pull-up or pull-down pin, and the other pin to the ground. Then, as the foot makes contact with a surface and triggers the switches, the microcontroller can easily detect it. If the robot has a computer, the microcontroller can communicate with the computer through serial communication at a desired sampling rate as well. For the case of ALPHRED, we used a Teensy 3.5, through which the computer on ALPHRED could read all four foot contact sensor states via serial communication at a 1kHz sampling rate.

III. EXPERIMENT AND RESULTS

A. Test Setup

In order to characterize the performance specifications of the foot contact sensor design, the test stand, shown in Fig.6, was built. The main component of the test stand is a vertical linear rail and carriage. The foot contact sensor is attached to the carriage so that a vertical motion can be achieved by moving the carriage along the linear rail. The sensor can also be mounted at different angles, so it can touch the ground at different contact angles. A load cell is mounted under the foot contact sensor, which measures the ground reaction force when the sensor touches the ground. Above the linear rail, a DYNAMIXEL MX-28AR motor is mounted. A cam and follower mechanism is attached to the motor to convert the rotatory motion of the motor to a linear reciprocating motion of the carriage. The cam pushes the foot contact sensor onto the load cell and pulls it back up to simulate repeated steps of the robot. In this setup, we are able to repeatedly test the triggering and releasing of the sensor. Also, by slowly moving the cam, the force thresholds at which the foot contact sensor triggers and releases can be measured.

Two experiments are performed. In the first experiment, the foot contact sensor is repeatedly pressed onto and released from the weight sensor 10,000 times. The maximum contact force for each cycle is about 80N. We are especially interested in the critical loading conditions under which the foot contact sensor identifies the start and the end of ground contact. The contact force values of these two critical loading conditions are referred to as the triggering force threshold and the releasing force threshold, respectively. The values of triggering and releasing force thresholds are measured after every 500 cycles. This experiment aims to investigate the reliability of the sensor, as well as the consistency in sensitivity after repeated triggering and releasing.

The second experiment measures the values of triggering and releasing force thresholds at different contact angles to evaluate the sensor's consistency in sensitivity when the foot lands onto the ground at different contact angles. In this experiment, the foot contact sensor is rotated in a plane of rotation illustrated in Fig. 7(A). The location of pushbutton switches when the foot contact sensor is tested at different contact angles, as shown in Fig. 7(B). In the experiment setting, when the contact angle is less than 90°, the loading condition in shear plane is the same as Fig.5 (A), and when the contact angle is greater than 90°, the loading condition in shear plane is the same as Fig.5 (B).

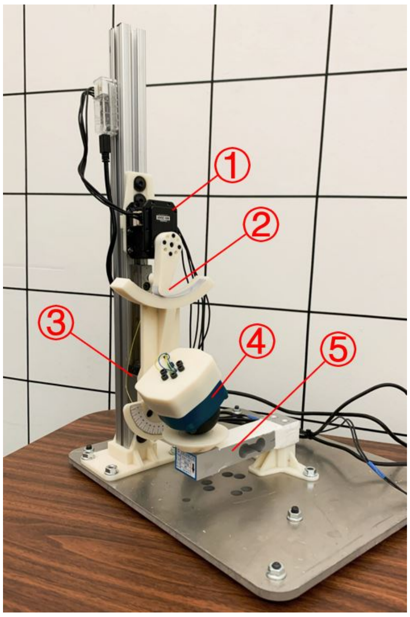

Fig. 6: Actual Experiment Setup. Major components of the experiment setup are: (1) DYNAMIXIEL MX-28AR motor, (2) Cam and follower mechanism, (3) Linear rail and carriage, (4) Foot contact sensor, and (5) Load cell

B. Results

In the first experiment, the foot contact sensor is able to sense ground contact in all 10,000 cycles. This result proves that the proposed foot contact sensor design can reliably detect ground contact, which is very important because failing to sense ground contact for even once means that the robot can possibly damage itself or become a safety hazard for the environment and the crowd.

Fig.8 plots the triggering and releasing force thresholds, measured after every 500 cycles, against the number of cycles. It shows that the force threshold of sensor triggering is consistently higher than that of releasing, but only by a very small amount. Therefore it is reasonable to conclude that the triggering and releasing force threshold for the foot contact sensor is approximately the same. Also, although a gradual creep in triggering and releasing force threshold due to repeated applied load is observed, the amount of increase is less than 2N after 10,000 loading cycles. Even when static posing with its weight evenly distributed on all four feet, ALPHRED still experiences a ground contact force of 50N on each of its feet, compared to which 2N is a relatively small amount. This means that the service life of our proposed foot contact sensor design is expected to be much longer than 10,000 cycles without major specification

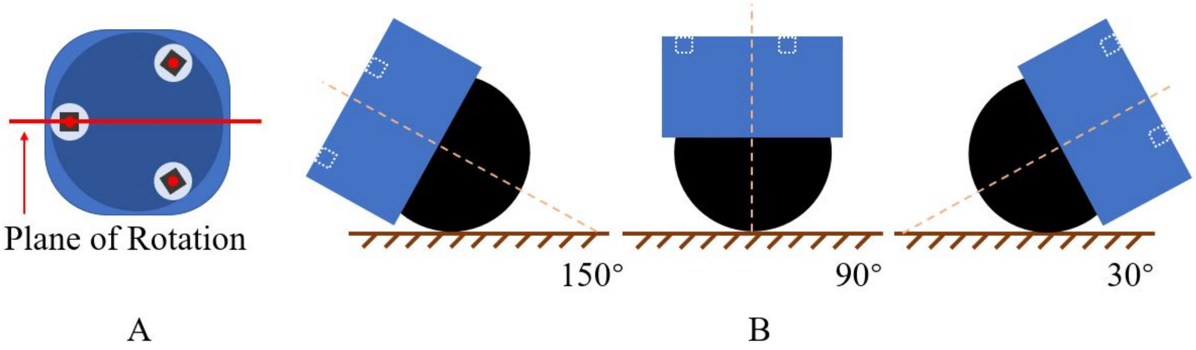

Fig. 7: Experiment for Different Contact Angles (A) Plane of rotation for the experiment (Bottom View). (B) Foot contact sensor in the plane of rotation for different contact angles, with white boxes indicating the location of pushbutton switches (Side View).

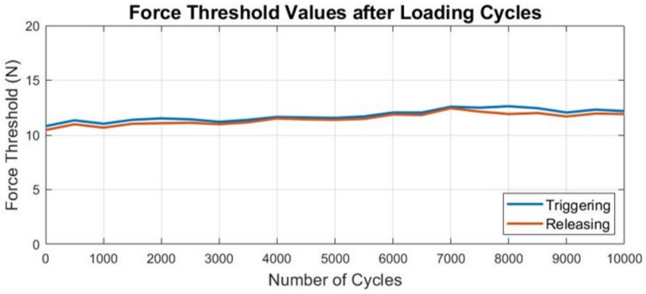

Fig. 8: Force Threshold Values after Loading Cycles. After each 500 loading cycles, the triggering and releasing force thresholds are measured. The plot indicates that the sensitivity of the sensor remains consistent after 10,000 loading cycles.

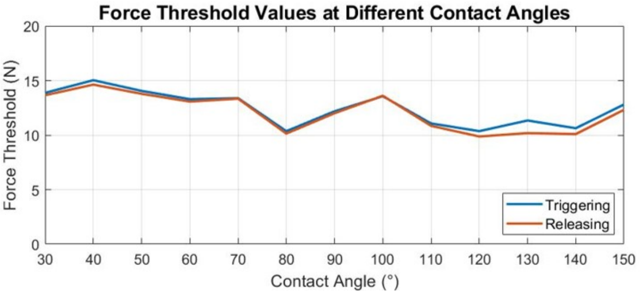

Fig. 9: Force Threshold Values at Different Contact Angles. The foot contact sensor is rotated about the center of the hemispherical foot pad for the measurement of force threshold values at different contact angles. The thresholds are measured for 10° angle increments. The plot indicates a relatively consistent range of force threshold values over a wide range of contact angles.

changes. Therefore, this experiment proves excellent sensing reliability of the foot contact sensor.

Fig.9 shows the triggering and releasing force threshold at different contact angles. Although the contact angles less than 90° have mostly higher force threshold values, no direct correlation is found between the contact angles and the force thresholds. Within a reasonable range of 30° to 150° ground contact, the maximum and the minimum force thresholds differ by less than 5N, therefore we can conclude that the values of force thresholds are not strong functions of contact angles, proving the foot contact sensor exhibits a high consistency in sensitivity at different contact angles.

IV. DISCUSSION

A. *Contact Angle Effects*

As discussed in previous sections, the arrangement of three pushbutton switches is hypothesized to result in a small discrepancy in sensing the shear effect of the ground contact force. Shown in Fig.5, the loading angles resulting in a shear in the direction shown in Fig.5 (B) is hypothesized to have reduced shear effect sensing when compared to loading situations that would result in a shear direction shown in Fig.5 (A) due to geometry. In correspondence to the experiment setup, the contact angles less than 90° are hypothesized to reflect more shear effects. However, the experiment data cannot validate said hypothesis. As shown in Fig.9, many contact angles are more sensitive to ground contact force when compared to their counterpart with the same angle difference to vertical, but not all. Manufacturing error may be one of the reasons why we are neither able to prove nor falsify the aforementioned hypothesis, as the subtle sensitivity difference in each of the three switches may result in different behaviors of the entire sensor under different loading conditions. Therefore, although the foot contact sensor exhibits consistent sensitivity at different contact angles, the effect of contact angles to the triggering and releasing thresholds remains inconclusive and improved manufacturing methods may be crucial for future verification.

B. *Dynamic Walking Problems*

In dynamic walking situations, the feet of the robot often experience high linear acceleration. As shown in Fig. 3, a high acceleration downwards of the end of the limb might cause the foot contact sensor to trigger false positive, as the foot pad would press into the soft material layer due to inertial effects. This is the reason why the mass of the foot

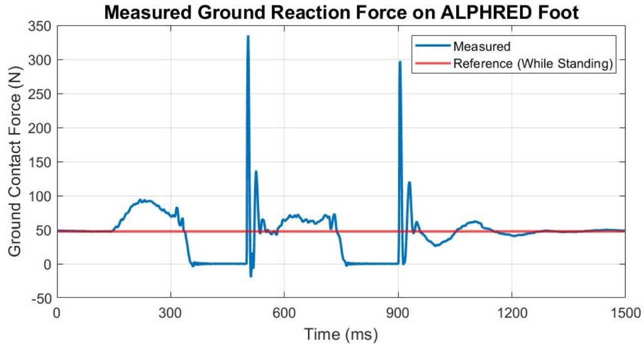

Fig. 10: Ground Reaction Force for Typical ALPHRED Walking Cycles Ground contact force on each foot is measured with a $1150\mathrm{Hz}$ sample rate while each foot experiences two steps. The red reference line shows the static loading condition when ALPHRED is standing still with 4 feet evenly distributing the weight.

pad is designed to be very small. The foot pad component with the soft material layer added weighs a total of $0.037\mathrm{kg}$. The triggering force threshold is about 12N, and by Newton's Third Law, the corresponding acceleration needed to trigger false positive is about 33 times gravitational acceleration, which is rare even in dynamic walking situations. In fact, properly working foot contact sensors do not appear to detect false positives on ALPHRED while walking or jumping. Nevertheless, the maximum acceleration along the sensor's center axis, over which false positives might be triggered, awaits experimentation to characterize.

As mentioned in previous sections, a significant impact on the foot assembly is expected in most dynamic walking scenarios. While the cyclical loading experiment conducted does indicate that the sensor can reliably sense ground contact for repeated cycles, the loading condition in the experiment is not representative of the impact that the foot assembly experience during dynamic walking. Fig. 10 shows the ground reaction force of ALPHRED's typical walking gait as experienced by the foot assembly. The foot assembly experiences a collision for about $10\mathrm{ms}$ with a peak impact force over 300N, which is more than 3 times the maximum force each foot would experience in any static instance. The impulse of foot touchdown is about $2\mathrm{N\,s}$ by integrating contact force over the duration of the impact. According to the recorded runtime of ALPHRED, the foot contact sensor has withstood over 50,000 stepping cycles without failure, exhibiting good performance both in mechanical durability and sensing reliability against repeated impacts. However, as shown by the experiment, the values triggering threshold and releasing threshold tend to have a slight increase over extended loading cycles, but the effect of loading cycles with high impact requires further investigation for a more accurate estimation of service life.

V. CONCLUSION

This paper presents a low-cost hemispherical foot contact sensor intended for applications in legged robots with point feet. The foot contact sensor is able to detect ground contact precisely and consistently for more than 10,000 cycles and can cover contact over a wide range of contact angles between 30° to 150° as well. This prototype foot contact sensor is lightweight and robust, and thus is suitable for locomotion in unstructured environments as it allows robots to detect events like contact and slippage.

Future work will focus on optimizing the design of the sensor and performing more investigation on the effect of contact angles and on possible false positive scenarios, such as observing the sensor's state under faster and higher force impacts. Impact cycle test and maximum impact test should also be performed, as the foot will experience high force impacts consistently during locomotion. In addition, the exploration of other materials with more damping characteristics may help to stabilize the transient sensor states while landing and improve the performance of the sensor, such as reducing the gradual creep behavior. However, it is important to note that the material needs to be carefully chosen so as to not reduce the sensitivity of the sensor.

REFERENCES

[1] S. Kajita *et al.*, "Biped walking pattern generation by using preview control of zero-moment point," *2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422)zz*, Taipei, Taiwan, 2003, pp. 1620-1626 vol.2. doi: 10.1109/ROBOT.2003.1241826

[2] Focchi, M., del Prete, A., Havoutis, I. *et al.* "High-slope terrain locomotion for torque-controlled quadruped robots." *Auton Robot* **41,** 259272 (2017).

[3] J. Di Carlo, P. M. Wensing, B. Katz, G. Bledt and S. Kim, "Dynamic Locomotion in the MIT Cheetah 3 Through Convex Model-Predictive Control," *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Madrid, 2018, pp. 1-9.

[4] K. Walas, Terrain classification using vision, depth and tactile perception, in *Proceedings RGB-D Adv. Reasoning Depth Cameras Conjunction RSS*, Berlin, Germany, 2013, vol. 27.

[5] A. Schmidt and K. Walas, The classification of the terrain by a hexapod robot, in *Proceedings 8th International Conference on Computer Recognition Systems*, 2013, pp. 825833.

[6] M. Hopflinger et al., Haptic terrain classification for legged robots, in *Proceedings 2010 IEEE International Conference on Robotics and Automation*, 2010, pp. 28282833.

[7] Jianxi Li, Qiang Huang, Weimin Zhang, Zhangguo Yu and Kejie Li, "Flexible foot design for a humanoid robot," *2008 IEEE International Conference on Automation and Logistics*, Qingdao, 2008, pp. 1414-1419. doi: 10.1109/ICAL.2008.4636375

[8] McGill, S. G., Yi, S. J., Yi, H., Ahn, M. S., Cho, S., Liu, K., et al. (2017). Team THORs entry in the DARPA robotics challenge finals 2015. *Journal of Field Robotics*, 34(4), 775801.

[9] M. Y. M. Chuah, L. Epstein, D. Kim, J. Romero, and S. Kim, "Bi-Modal Hemispherical Sensor: A Unifying Solution for Three Axis Force and Contact Angle Measurement," in *International Conference on Intelligent Robots and Systems*. IEEE, 2019.

[10] X. A. Wu, T. M. Hun, R. Mukherjee, and M. Cutkosky, "Integrated ground reaction force sensing and terrain classification for small legged robots," *IEEE Robotics and Automation Letters*, vol. 1, no. 2, pp. 1125-1132, July 2016.

[11] T. P. Tomo, S. Somlor, A. Schmitz, L. Jamone, W. Huang, H. Kristanto, and S. Sugano, Design and characterization of a three-axis hall effect-based soft skin sensor, *Sensors*, vol. 16, no. 4, 2016.

[12] M. R. Cutkosky and J. Ulmen, Dynamic tactile sensing, in *The Human Hand as an Inspiration for Robot Hand Development*. New York, NY, USA: Springer, 2014, pp. 389403.

[13] A. Shkolnik and R. Tedrake, "Inverse Kinematics for a Point-Foot Quadruped Robot with Dynamic Redundancy Resolution," *Proceedings 2007 IEEE International Conference on Robotics and Automation*, Roma, 2007, pp. 4331-4336. doi: 10.1109/ROBOT.2007.364146