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Composite Force Sensing Foot Utilizing Volumetric Displacement of a Hyperelastic Polymer

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Abstract—This paper illustrates the fabrication and characterization of a footpad based on an original principle of volumetric displacement sensing. It is intended for use in detecting ground contact forces in a running quadrupedal robot. The footpad is manufactured as a monolithic, composite structure composed of multi-graded polymers which are reinforced by glass fiber to increase durability and traction. The volumetric displacement sensing principle utilizes a hyperelastic gel-like pad with embedded magnets that are tracked with Hall-effect sensors. Normal and shear forces can be detected as contact with the ground which causes the gel-like pad to deform into rigid wells. This is all done without the need to expose the sensor. A one-time training process using an artificial neural network was used to relate the normal and shear forces with the volumetric displacement sensor output. The sensor was shown to predict normal forces in the Z-axis up to 80N with a root mean squared error of 6.04% as well as the onset of shear in the X and Y-axis. This demonstrates a proof-of-concept for a more robust footpad sensor suitable for use in all outdoor conditions.

I. INTRODUCTION

High speed running places great demands on the sensing capabilities of any robot, and this is especially true in the foot. As the sole interface between the robot and the ground, it is the only means with which a legged machine can generate reaction forces with its environment. In order to provide useful feedback and control, the ground contact model should be as accurate as possible. This means that the force sensor in the footpad should have a high dynamic range in both normal and shear for a complete picture of the reaction forces, all the while being tough enough to withstand the impact of repeated foot strikes during running. Indeed, durability is but one of a variety of functional requirements necessary from feet in general. The ability to adapt to asperities in the ground, absorb impacts, provide traction, and store and release energy are all important functions [1] [2]. Additionally, it has been shown that the viscoelastic properties of mammalian paw pads are critical in ensuring a desirable dynamic response under impacts such as those experienced during running [3]. This diversity of goals in an ideal foot presents a sensing problem that occupies a niche not readily addressed by off-the-shelf solutions.

Though tactile sensing has been the focus of much research within the field of robotics, current sensing methodologies are almost invariably designed separately from the robot itself, often utilizing standard components. This results in sensors that are ‘added-on’ to the robot instead of being built into the robot’s design, which can be problematic for a number of reasons.

The most conventional of approaches to force sensing fail to incorporate the compliance that is essential for successful interaction with terrain while running [3]. These methods have often taken a policy of separating a robot from its environment by placing the sensor directly between a robot and its foot. Reaction forces acting upon the machine are commonly rerouted and transmitted through the sensor to attain a measurement—which ultimately alters the original mechanics. The gold standard, a traditional force/torque (F/T) sensor, is one example of such a methodology that is commonly found in industrial robotics and humanoid robots used for research. ‘KHR-3 Hubo’ [4] and ‘LOLA’ [5] are two examples of humanoid robots that use a custom F/T sensor in each foot for sensing ground contact. The direct use of F/T sensors for force sensing in the foot makes the foot much more bulky, weighing the robot down. Similarly, ‘BIPMAN’ attempts to emulate the human foot, but still uses multiple off-the-shelf sensing solutions [2].

Furthermore, the broader approach of measuring the deformation of rigid structures, as is done in F/T sensors, is less than ideal despite the allure of linearity and repeatability in measurements. Such a method would require the need for sensors to be mounted far from the foot-ground contact with compliant mechanisms between the two or depend on a rigid contact surface with the ground that would likely result in chatter [3]. In fact, having the sensor anywhere in series with the robot, the sensor may respond with undesired dynamics.
such as out-of-phase non-collocated modes like chatter during actuation. This poses problems for the controller, and may cause instabilities in the system [6].

Compliant sensors take a different approach but often encompass many concerns significantly removed from those required from the demands of running. Scalability, adaptability to curved surfaces, low power consumption, and cost aim to maximize the sensors’ utility in a wide range of applications as a “artificial skin” [7][8]. Phan et al. demonstrated the use of capacitive skin sensors to monitor the collisions and impact of a robot arm [9]. Likewise, tactile sensors for human gait analysis within medical studies seek to fill a similar niche but are constrained by the need to interface with existing footwear and measure many more parameters than are required for robotic running. As a result, the subsequent design integrates many different types of sensors and supporting hardware irrelevant to simply measuring ground reaction force and touchdown [10]. While this and other similar solutions are well suited for retroactively fitting robots with the ability to sense touch or comprehensively measuring physiological parameters, there is still much to be desired when considering the dynamic requirements of the footpad on a running, quadruped. It is desirable to extract only the essential measurements and minimize the demand put on the control system, which must compute in real-time during running.

Given the aforementioned challenges in matching off-the-shelf sensors to a very specialized application, designing the sensing solution in tandem with the robot can result in great advantages. For example, the musculoskeletal humanoid ‘Kojirō’ innovatively utilizes joint-angle sensors found in mobile phones in its spherical joints [11]. Another good example of this is seen in the custom-built strain sensor developed by Park et al. for use in their active soft orthotic device [12]. This is combined with their hyperelastic pressure sensor [13] to form a soft artificial skin with conductive liquid metal channels capable of multi-modal sensing [14]. Similarly, the exoskeletal end-effectors embedded with optical fiber Bragg grating sensors allowed Park et al. to integrate sensing while minimizing the bulkiness of hardware [15]. Wettels et al. have created a high performance biomimetic tactile finger (BioTac) with an incompressible conductive fluid surrounded by the elastomeric skin of the fingertip [16]. In this manner, they are able to use an array of electrodes to detect the deformations of the fingertip membrane. Further design of the skin texture enhanced the response of the finger [17]. Similarly, the technique of Electrical Impedance Tomography (EIT) is utilized by Alirezai et al. in the creation of a highly stretchable tactile distribution sensor [18]. By drawing inspiration on the above examples, it is proposed here the fabrication of a novel integrated force sensor with applications in a running robotic quadruped.

Due to the current limitations in sensing technologies, there is a need for a light-weight resilient force sensor for use in a running quadrupedal robot. In this paper, we will introduce a light-weight force sensor integrated into the foot of a running robotic quadruped that serves a dual purpose. The fabrication technique allows for a compliant footpad that will grip to most ground surfaces without wearing out quickly. The footpad also integrates an array of Hall-effect sensors and magnets which enables it to detect ground contact and shear. The design, construction, and characterization of the force sensor are further elaborated in later sections.

II. SENSING METHODOLOGY

The integrated, volumetric displacement force sensor utilizes the novel approach of sensing the deformation of a soft, elastomeric padding into an array of rigid wells, as depicted in Fig. 1. Small magnets are mounted onto the padding, which allows the proximity of the elastomer’s surface to be sensed by Hall-effect sensors placed above these wells. As the wells are part of a single elastomer, any shear on the foot will affect the individual wells and magnets differently. This results in a change in the Magnetic Flux Density (MFD), which is then recorded via the Hall-effect sensors. Using neural networks to calibrate the system once, the MFD is related to the measured normal and shear forces. The geometry of the base of the footpad is intentionally curved so as to amplify the differences in the wells and to avoid simple shear from occurring. A photo of the monolithic foot structure, the rigid well insert, and Hall-effect sensors mounted onto a printed circuit board (PCB) are shown assembled and disassembled in Fig 2, along with the cross-section of a completely monolithic iteration.

A. Sensor Design

In order to measure force, it must be converted into a quantity that can readily be measured as a signal. The deformation of the soft elastomer within the paw pad was chosen as the sensing mechanism. This required no additional mass to the foot but rather hollowing out wells in the rigid, plastic structure of the top of the foot while inserting small magnets and Hall-effect sensors into the structure. The chosen mechanism incorporates the compliance necessary to facilitate successful interaction with terrain, and minimizes need for additional weight or components, and allows for a monolithic and robust structure. The presented sensor strives to attain a greater level of integration within a compliant structure in order to preserve the original design intent and promote dynamics favorable to running while measuring ground reaction forces as close to the foot-ground interface as possible.
Fig. 2: Assembled and disassembled force sensor. Components depicted are (A) outer “skin” of woven fiberglass embedded in polyurethane rubber, (B) soft silicone rubber to form “padding” inside “skin,” (C) outer plastic for mounting and structure, (D) magnets mounted on top of silicone rubber, (E) ABS rigid well insert and (F) array of five Hall-effect sensors. In the bottom, cross-sectional view, a completely monolithic prototype was used, casting the outer wall and rigid wells (C & E) as a single piece of Task® 4 plastic.

B. Foot Design

This current foot design has gone through multiple design iterations and has demonstrated robust performance with our MIT Cheetah, a quadrupedal robotic platform intended to test high speed running (Fig. 3). The biomimetic design was inspired by the texture and shape of feline paws. This work serves to incorporate the volumetric displacement sensing principle into the current design to allow for force sensing.

Several aspects were incorporated into the design of the foot in order to promote successful interaction with the ground. Firstly, the tougher, outer “skin” of the foot was cast using a durable rubber, Vytaflex® 20, in order to withstand the wear and tear that repeated impact and loading would impose on the material. The rubber material provided a high coefficient of friction to generate sufficient forces tangent to the ground during contact.

Woven fiberglass was embedded within the outer, rubber layer to strengthen it against strain in the surface area of the pad. This resistivity to strain strengthens the pad to shear forces but keeps the foot compliant to forces acting normal to its surface. This directional compliance further facilitates the driving mechanism utilized by the sensor, as the soft elastomer is prevented from slipping out from under the foot due to shear, but uninhibited from being pushed up inside the rigid wells when loaded under normal forces. The compliant pad also lowers peak forces experienced by the foot and acts as a mechanical, low-pass filter for asperities in the ground. The compliance allows the foot to simply deform around smaller asperities in the ground that would trouble rigid structures.

Our design of having the volumetric displacement sensor integrated into the footpad means that the amount of mass in series after the sensing unit available to give rise to instabilities is minimal. Other unwanted dynamic effects are also avoided, such as noise due to inertial factors during periods of high acceleration. In the current design, only 35g of mass is present between the sensor and the ground.

C. Fabrication Technique

The sensor was fabricated by casting several different thermosetting polymers to one another. The monolithic design was chosen to promote robustness during impact, and minimize the size the sensing unit occupied. As an added bonus, since the sensor is completely encased in the footpad, it is protected from the environment and unlikely to fail. An illustrated overview of the process can be seen in Fig. 4.

The tough, outer “skin” of the foot was constructed by embedding woven fiberglass into a 2mm thick layer of Vytaflex® 20 polyurethane rubber of shore hardness 20A. After demolding, the skin retained the shape imposed by the casting process and was filled with Ecoflex® Supersoft Silicone rubber of shore hardness 00-10A, which was allowed to self-level.

A rigid, outer lining was cast on top of these rubbers using Task® 4 polyurethane resin of shore hardness 83D. The rigid lining provided structural integrity and allowed for a separate, ABS insert to be anchored onto the foot which imposed the rigid wells above the silicone rubber. The use of a separate insert allowed for rapid iteration on the geometry of the wells and greater ease in securing the magnets to the soft, silicone rubber. Ultimately, the ABS insert would be replaced by casting the well geometry directly into the Task® 4 once an optimal configuration had be conferred upon.

The final weight of the full prototype with ABS insert was 95 grams, while completely monolithic iterations
weighed only 60 grams once the wells were cast directly out of Task® 4 plastic.

D. Force-Deformation Relation

Due to the complexity in the geometry of the footpad and the elastomer, attaining analytical models through the use of hyperelastic material models is non-trivial. The total force can be estimated by assuming that the footpad is a rectangular block of elastomeric material with various material models such as Mooney-Rivlin [19], Arruda-Boyce [20] and Ogden [21]. These models are highly dependent on the quality of the experimental data collected. The difficulty is furthered with the presence of wells that the elastomer deforms into and the use of two different elastomers in each layer (Vytaflex® 20 and Ecoflex® 00-10). This makes it almost impossible to predict the change in height and orientation of the magnets in the wells.

Simulating the footpad deformations using a finite-element analysis package such as Abaqus™ was considered, but the resulting model was overly complex and took an unreasonable amount of time to solve for a set of initial conditions. Similarly, the accuracy of the model depends greatly on the material properties that are obtained experimentally. Hence, a more straightforward method was sought. In the end, the use of an artificial neural network (ANN) to directly associate the forces with the MFD was determined to be the best way to obtain the correlation. It offers the advantages of only requiring a one-time calibration procedure and is able to provide force feedback to the system in real-time.

A small 1 inch by 1 inch PCB was manufactured and populated with 5 single-axis Hall-effect sensors. The center sensor is an Asahi EQ-430L (S₀) and 4 Sentron CSA-1VG sensors (S₁, S₂, S₃, and S₄) surround it with the sensing axis aligned to the X and Y-axis as seen in Fig. 2. Each peripheral sensor is separated by a distance of 7.5mm from the central sensor and this orientation allows each sensor to pick up the slight changes in the MFD during ground contact. The overall change in the MFD can be summarized by the function below:

\[ S_{MFD}(t) = [S_0(t) \ ... \ S_1(t) \ ... \ S_4(t)]^T \]  

where \( S_i \) is the individually measured MFD of the \( i^{th} \) magnetic sensor. In this particular case, the MFD is the result of the coupled interactions of 5 magnets on the surface of the hyperelastic gel-like pad. The vector \( S_{MFD}(t) \) can be represented by either an analytical distributed multipole model [22] or through experimental field measurements.

This PCB is then mounted over the wells containing the magnets (Grade N42). As the magnets are connected by a monolithic piece of elastomer, any normal forces will cause the 4 magnets near the edges to rise by the same amount. However, in the case of shear forces, the wells along the outer edges deform by different amounts and these discrepancies are picked up by the Hall-effect sensors on the PCB. The loading conditions on the footpad are measured by a F/T sensor and can be represented as:

\[ F(t) = [F_x(t) \ F_y(t) \ F_z(t)]^T \]

This change in the MFD, \( S_{MFD}(t) \) is then parsed in MATLAB and the MFD and the applied forces are empirically correlated using the Neural Network Toolbox. A feed-forward neural network is created where an input-output relationship is mapped between the MFD as measured by the 5 Hall-effect sensors and the forces recorded by a F/T sensor. The Levenberg-Marquardt optimization network training function [23] then uses a back-propagation algorithm to update the weights and bias values of the neural network until the minimum mean squared error is obtained and the desired performance is realized. Note that the Levenberg-Marquardt algorithm or damped least-squares method is an example of a nonlinear regression algorithm. The Levenberg-Marquardt algorithm is given as:

\[ [J^TW + \lambda \text{diag}(J^TW)]\delta = J^T[W(F(t) - \hat{F}(t))] \]

where \( J \) is the gradient matrix, \( W \) is the weighting matrix, \( \lambda \) is the algorithmic parameter, \( \delta \) is the increment in each iteration, \( F(t) \) is the target force output from the F/T sensor and \( \hat{F}(t) \) denotes the force estimates of the ANN. This work on the use of artificial neural networks for force sensing is further elaborated on in the paper by Ananthanarayanan et al. [24].
III. EXPERIMENTAL RESULTS

A. One Axis Results

Preliminary results were generated with one-axis machine in order to assess the prototype’s potential in both normal and shear directions.

The footpad sensor was first clamped into the top jaws of an industrial materials-testing machine (Zwick Roell BX1-EZ005.A4K-000) with a manual 2-axis table loaded onto it. A 6-axis F/T sensor (ATI Industrial Automation SI-660-60) was mounted to the base of the materials testing machine which is capable of measuring up to 1980N in the Z-axis with a resolution of 0.25N. The footpad was lowered onto the F/T sensor until the desired normal force was reached. This experimental setup can be seen in Fig. 5. The data from the volumetric displacement footpad sensor and the F/T sensor are acquired through a National Instruments sbRIO 9642 connected through LabVIEW. This setup allowed for arbitrary normal loading conditions while shear in both the X and Y-axis is observed.

Using the above setup, the footpad was preloaded with a normal force using the materials testing machine and then the 2-axis table was then manually actuated by the researcher in both the X and Y-axis by 10mm. This is done at a rate of around 1.5 Hz. The results are shown in Fig. 6. The results show that there is a good correspondence between the MFD changes and shear in the X-axis but less so for shear in the Y-axis.

B. Combined Two Axes Shear Results

In order to get training data to feed into the neural network, accurate linear positioning of the footpad is required. This was achieved by using an industrial 3 axis CNC milling machine (HAAS Super Mini Mill 2). A mount was fabricated to attach the footpad directly to the quill and a separate mount for attaching the F/T sensor to the mill table. This experimental setup is shown in Fig. 7.

Training data was first collected by having the CNC milling machine run through a programmed training path with the footpad in contact with the F/T sensor. With a known normal load, the footpad was made to traverse 5mm in both the positive and negative directions along the X-axis. This was then repeated in the Y-axis. Finally, the footpad was made to follow a circular path of 10mm diameter about the origin. For verification, the more data was gathered with an arbitrary path. This path involved a diagonal motion of 5mm in each of the 4 quadrants of the X and Y-axis. This was then followed with 4 smaller circular paths of 5mm diameter along each of the positive and negative X and Y-axis. A qualitative depiction of the paths is shown in Fig. 8.

The results (Fig. 9) show that the neural network is able to predict normal forces in the Z-axis up to 80N with the greatest accuracy. The root mean squared (RMS) error is 4.83N. This represents a RMS error of 6.04%. This is followed by the Y-axis where shear forces of 40N are detectable, but the predicted force magnitude does not correspond with reality completely. The RMS error in this case is 12.90N. In the X-axis, similar performance is observed where shear forces of up to 40N are predictable, but the force magnitudes differ. The RMS error for the X-axis is 16.76N. Note that the noise levels in these graphs are much higher than the ones for the previous setup in Fig. 5. This is due to electromagnetic interference (EMI) from the CNC milling machine, and would inevitably improve in environments more natural to running. A Butterworth filter with a 10Hz cutoff frequency has been applied to the gathered signals to remove the EMI noise.
Fig. 7: Experimental setup with the CNC milling machine. The foot was mounted directly to the quill of the milling machine to ensure stiffness. The footpad made direct contact with the 6-axis force sensor during testing.

Fig. 8: Two-axes shear paths. The two paths were used to train the ANN. The furthest points on each sub-trajectory correspond to a radius of 5mm away from the center of each path. Both paths were run at several, set normal loads.

Fig. 9: Experimental results for correspondence between the predicted force and actual force. The blue line shows the actual force measured and the red line shows the neural network predicted force. The figures are in the order of X, Y and Z-axis from top to bottom respectively.

IV. DISCUSSION

The proposed design offers a method to marry two distinct goals in foot design for running applications: promoting favorable dynamic performance and extracting an accurate measurement from ground reaction forces. Both can be accomplished in a robust manner while minimizing weight and number of parts by integrating them completely. In order to do so in a manner that does not severely restrict design space, the mechanical considerations of the footpad and the considerations given to the mechanisms utilized by sensor are effectively decoupled through the use of the ANN. Thus, the dynamic response can be designed and achieved first while sensing is attained once the physical structure is established. In the specific case of the MIT Cheetah, a proven foot using this fabrication structure had already been developed and utilized in currently running experiments (Fig. 3). The end goal is to have sensing capabilities were efficiently integrated to the structure with minimal addition of hardware.

The experimental results show that the footpad sensor is able to detect normal loading conditions with sufficient accuracy and to identify the onset of shear in both the X and Y-axis. These results present a promising proof-of-concept on a novel mechanism to sense ground reaction forces while utilizing an inherently compliant interface with the terrain. However, several aspects of the design are readily available for improvement within subsequent iterations as well.

1. Collecting additional training data may further fine-tune the ANN parameters and will allow us to minimize the errors in the force sensing. Only one group of trajectories, repeated at varying normal loads, was used to produce the current correlation. There might be some load history dependence (e.g. creep effects) which needs to be investigated further. Specifically, impact tests may prove to be the most relevant training method for running and would provide more telling information such as response time. Unfortunately, the existing experimental setups do not readily allow for such tests to be conducted.

2. The placement of the magnets, especially the direction of the poles should be modeled to achieve an optimal MFD that would give the maximum change in response to stress and shear. Arranging the
magnets in the manner of a Halbach array might give rise to greater sensitivity [25]. This has the advantage of maximizing the magnetic field on the side facing the Hall-effect sensors. It also minimizes any stray fields on the ground-facing side, reducing the potential for interference from unintended sources. The size and shape of the magnets can be optimized as well.

3. In order to significantly improve the measurement of shear forces, alternative well geometries can be easily explored by 3D printing different ABS inserts. Rather than completely vertical extruded cuts, incorporating wells that travel some distance along the X and Y axes may increase sensitivity and accuracy to shear forces.

4. By varying the material properties of the hyperelastic gel-like pad, different force sensitivities can be achieved. This can be incorporated into the current ‘2 pad’ design (Fig. 3) where a single footpad will have 2 gel-like pads of different stiffness. The will allow the footpad to have a wider dynamic force range.

V. CONCLUSION

This paper presents a proof-of-concept dual purpose footpad with integrated force sensing capabilities. The design of the footpad makes use of the strengths of 3 different polymers to give a footpad that is durable under repeated ground impacts while still being compliant enough to offer good traction. The volumetric displacement sensing principle utilizes a hyperelastic gel-like pad with embedded magnets, which allows normal and shear forces to be detected indirectly without the need to expose the sensor. A one-time training process using an artificial neural network is all that is necessary to relate the normal and shear forces with the volumetric displacement sensor output. The volumetric displacement sensor is able to detect normal forces up to 80N with a RMS error of 6.04% and the onset of shear forces in both the X and Y axis. This is a robust footpad sensor suitable for use in all outdoor conditions. Upon further refinements, this footpad is intended for use in the MIT Robotic Cheetah to detect the occurrence of ground contact and the forces involved.

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