A Robust Shear-Based Optical Tactile Sensor for Quadruped-Mounted Manipulation

Assylkhan Seitzhanov[1], Jabrail Chumakov[2,3], Zhanat Kappassov[2]

***Abstract*—Vision-based tactile sensors (VBTS) work well on the benchtop, but mobile manipulation on legged robots brings unstructured contact, incidental collisions and field debris that existing sensors do not handle well. Gel-based and marker-based VBTS wear directly on the sensing surface, so replacement and recalibration become a bottleneck in the field. We use an optical tactile sensor whose shear-based principle and layered construction separate signal quality from surface wear. The dyed sensing layer sits behind a replaceable transparent cover and never touches the object. This work looks at the sensor's design from a field-deployment angle, ties its characterization results to mobile use, and describes its integration as the tactile frontend of a quadruped-mounted robot arm.**

I. Introduction

Tactile sensing gives robots access to contact forces, surface geometry, and slip that vision alone cannot provide. VBTS are now the dominant approach, largely because a single camera recovers rich contact information at low cost [5], [6]. GelSight [2] and its derivatives, including DIGIT [3] and GelSlim [11], recover surface normals from the deformation of a reflective elastomer. TacTip [4] amplifies surface normals through a biomimetic pin array in a soft dome. All of these sensors make the same architectural choice. The sensing transducer sits on the same surface as the object that contacts them., so abrasion accumulates directly on the sensing element.

Mobile manipulation on legged robots changes the operating envelope. Body sway during locomotion transmits unplanned loads through the arm, the sensor may brush against the terrain during approach, and field use exposes the sensing surface to debris absent from benchtop studies. Gel-based sensors accumulate scratches on the elastomer that encodes the tactile signal, and marker-based sensors drift as embedded features shift under repeated loading [9]. Replacement cycles on the order of a few hundred contacts are acceptable in a lab, but impractical in the field.

NUSense [1] takes a different route (Figure 1B). A transparent, mechanically passive cover sits over a dyed sensing layer, so only the cover is exposed to contact, and only the cover is replaced under wear. The sensing transducer is isolated from the wear surface, and this is the property we exploit for mobile deployment. In what follows, we present NUSense's design from the perspective of field-deployed tactile sensing and describe its integration as the tactile frontend of a quadruped-mounted robot arm.

[1]Institute of Smart Systems and Artificial Intelligence, Nazarbayev University, Kazakhstan.
[2]Robotics Department, Nazarbayev University, Kazakhstan,
[3]Freedom Holding Corp.
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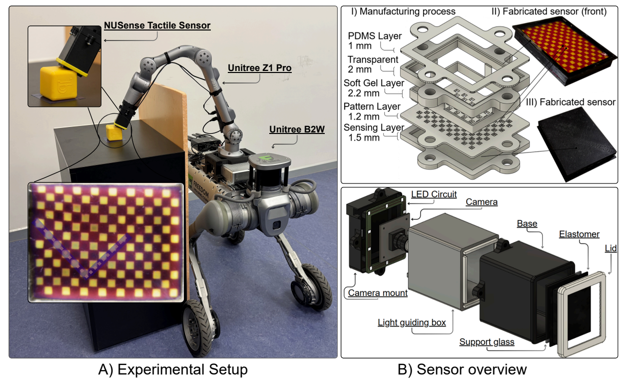

Fig. 1. Overview of the NUSense sensor and its integration on a quadruped-mounted manipulator. (a) Experimental setup: a 6-DoF manipulator mounted on a quadruped platform, with NUSense at the end-effector contacting a test object, (b) **Top:** Sensor overview — (I) exploded view of the multi-layered soft pad with per-layer thicknesses, (II) front view of the fabricated elastomer showing the red–yellow checkerboard pattern, and (III) assembled sensor. **Bottom:** Hardware assembly: camera, LED circuit, light-guiding glass, 3D-printed housing, and replaceable elastomer pad.

II. Sensor Overview

A. Shear-Based Sensing

NUSense measures shear strain in a dyed silicone layer using a wide-angle camera that images the layer from below (Figure 1B). A normal load on the soft pad produces tangential displacement in the sensing layer via the Poisson effect, and the distortion of a colored grid quantifies this shear. Following [1], a B-spline surface is fitted to control points extracted from quadrilateral markers that are surface fitted in the undistorted image, and the shear strain of a contact is computed as a scaled L2-norm between the loaded and reference surfaces,

$$\gamma_{\text{ss}} = \alpha \sum_{i=1}^{K} \left\| \mathbf{s}_i - \mathbf{s}_i^{\text{ref}} \right\|_2 , \tag{1}$$

where $\mathbf{s}_i$ and $\mathbf{s}_i^{\text{ref}}$ are sample points from the loaded and reference surfaces, K is the number of sample points, and α is a scaling factor. The full derivation is given in [1]. The useful property for this application is that γ_{ss} aggregates displacement across the full sampled surface rather than tracking individual markers, so local contrast loss or grid distortion does not cause severe signal degradation.

B. Layered Architecture

The NUSense soft pad is a stack of four silicone layers (Figure 1B). From the glass outward, a PDMS adhesion

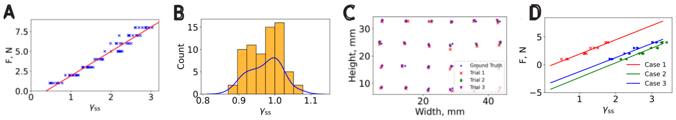

Fig. 2. NUSense characterization. (a) Force calibration with a linear fit over 1–8 N. (b) Peak shear strain distribution over 70 repeated 8 N contacts. (c) Contact localization across 24 indentation points. (d) Three-case damage robustness test with fresh pad, replacement pad, and intentionally cut pad. Data from [1].

layer bonds the stack to the optical window, a clear soft gel (Techsil RTV27905) couples loads to the sensing layer, the dyed sensing layer (Sorta-Clear 18 with yellow and red pigments in a checkerboard pattern) produces the visible shear response, and a transparent cover of the same material shields the interior.

Several properties of this stack matter for mobile deployment. The sensing layer never contacts objects, so scratches on the cover do not disturb the dyed markers. The cover itself is mechanically passive, and the shear computation in (1) depends on marker displacement rather than optical quality of the cover, so degradation of cover clarity translates into gradual noise rather than signal loss. Cover replacement also does not require disassembling the sensor, which brings field maintenance down from a full sensor swap to a few minutes of work.

C. Fabrication

The sensing layer is produced in a two-step cast. Yellow-pigmented Sorta-Clear 18 is poured into a patterned mold, and after curing process, the red-pigmented phase fills the complementary grid regions to produce a 12×9 checkerboard. The soft gel layer (2.2 mm) and the transparent cover are cast in sequence on top, and a thin PDMS layer bonds the stack to a Plexiglas optical window backlit by surface-mounted LEDs. The effective contact area is 50×38 mm, with the elastomer at the camera's 55 mm focal length. Complete fabrication details are given in [1].

III. Experimental Characterization

Four properties reported in [1] are directly relevant to mobile deployment.

Force response. A round-tip indenter (5 mm radius) and a flat-tip indenter compress the pad to 8 N and 3 N respectively, and a linear fit

$$F = 3.09\,\gamma_{ss} - 1.14 \quad (2)$$

holds over 1–8 N (Fig. 2A). This range covers typical gentle-object interaction forces, and the linearity means force can be recovered by a single affine transform without per-contact recalibration.

Repeatability. Seventy repeated 8 N contacts at the sensor center produce a peak-γ_{ss} distribution with coefficient of variation below 4% and no visible drift (Fig. 2B). The dyed sensing layer's optical response does not migrate under repeated loading of the cover above it.

Contact localization. Across 24 indentation points on a 6.4×7.0 mm grid at 6 N, contact location estimated from the shear centroid has an RMS error of 0.50 ± 0.09 mm (Fig. 2C). Sub-millimeter precision on a 50×38 mm pad is enough for grasping and tactile exploration.

Robustness under cover damage. A fresh pad, a replacement pad, and a pad with the protective cover deliberately cut are tested over 1–4 N contacts (Fig. 2D). All three cases produce force-correlated γ_{ss} with closely matching slopes, and they differ only in bias. A NUSense sensor with a damaged cover is therefore still functional, not merely replaceable. Force estimates can be recovered by rebiasing the fit, and full recalibration is only needed once the damaged cover is swapped out.

IV. System Integration

NUSense is attached to the end-effector of a Unitree Z1 Pro robot arm through a 3D-printed adapter that orients the sensor contact surface normal to the arm's approach direction (Figure 1A). The sensor frame is calibrated with respect to the robot base using a standard eye-in-hand procedure, so contact centroids estimated in the sensor frame can be expressed in base coordinates. The arm is mounted on a Unitree B2-W quadruped robot via a custom-fabricated adapter, and the combined system operates as a mobile manipulator.

Several aspects of mobile operation map onto specific sensor properties. Locomotion-induced body sway transmits unplanned loads through the arm during contact, and NUSense's linear response over 1–8 N tolerates these transients. The end-effector may also brush against ground or obstacles during approach, and the replaceable cover absorbs this wear rather than the sensing transducer. Cover replacement in the field is done without recalibrating the camera intrinsics or disturbing the sensing layer geometry, keeping maintenance overhead low.

Planned experiments include contact-driven exploration of unknown objects during combined locomotion and manipulation, comparison against a gel-based baseline under matched workloads, and an evaluation of the cover-replacement cycle under realistic field abrasion.

V. Conclusion

NUSense's core design choices of shear-based sensing, a mechanically isolated dyed sensing layer and a replaceable protective cover match the requirements of field-deployed tactile sensing. The characterization data from [1] are consistent with this assessment. The sensor is linear, repeatable, localizes to sub-millimeter precision and retains a force-correlated response even when the cover is damaged. Limitations of the underlying sensor model, namely the isotropic pad assumption, elastic-regime operation, and reduced sensitivity below 1 N, carry over to this application. Work in progress addresses quantitative validation on the mobile platform.

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