A Visuo-haptic Sensor for the Exploration of Deformable Objects

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***Abstract*—We present a linear tactile sensor for grasping applications, which is based on a passive rubber foam material mounted on the fingers of a gripper and a low-cost camera pointed towards the actuator. This concept allows to visually measure local deformation, geometry and forces, without the need for costly dedicated sensors in the actuator. In an experiment, the geometry and deformation behavior of a deformable object (plastic bottle) is explored with the proposed sensor.**

1) Introduction: Autonomous grasping of partially unknown, deformable objects in human environments is a complex problem. In general it requires an object model, a grasp planner as well as visual and haptic feedback. The latter is needed during the grasping process to obtain the current state and provided by a dedicated laminar tactile sensor such as [1], which is mounted onto the fingers and measures local pressure/forces applied to the object. A haptic object model of geometry and deformation behavior (local stiffness) can be obtained by exploration, i.e. by acquiring grasp samples on the object surface. A two-finger gripper is sufficient for many objects and allows for relatively simple grasp configurations. Such models are essential for objects like bottles or cups which require substantially different grasping parameters, depending on their material (glass, plastic or paper) and the weight of their content. Geometric models can also be obtained visually, if the object is not transparent and the surface exhibits diffuse reflection. During a grasp, the desired grasping force and pattern are derived from the object model. The sensor feedback is used to adjust the forces and to verify the grasping pattern.

In this work, we present a visuo-haptic sensor, which relies on a passive and inexpensive deformable rubber foam material mounted onto the fingers of a gripper, as well as a low-cost camera which observes the fingers. A similar approach has been presented for a mobile platform in [2], [3]. Contact forces, local pressure and object deformation along the fingers are determined from visual measurements as well as from the known deformation characteristics of the foam. The position of the fingers is also determined visually. The sensor can be used for grasping with haptic (force) feedback, as well as for haptic exploration tasks. The proposed setup allows for very low-cost grippers, since dedicated sensors for position and force can be saved. Especially laminar force sensors are quite costly and require cabling through the robot arm. On humanoid robots, the system even takes advantage of existing cameras, since the head cameras can be pointed to the hand. Furthermore, the system offers compliance, due to the rubber foam, and provides coherent measurements between the haptic and visual modalities.

2) Visuo-haptic sensor: The setup of the proposed grasping system is depicted in Fig. 1: A two-finger gripper with a linear driver is equipped with strips of rubber foam on the inside of the fingers. The foam is the passive part of the sensor; when the gripper closes, it comes in contact with the object and deforms depending on the local pressure. Cameras (one for each finger) are mounted above the gripper, such that they observe the top side of the fingers and the top surface of the foam material. To prevent occlusion of the foam by the object, they are located slightly outside of the grasping range. Visual

This work has been supported, in part, by the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC Grant agreement no. 258941.

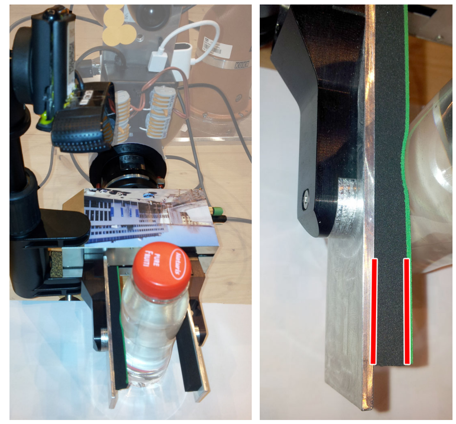

Fig. 1. *Left:* The proposed sensor consists of one or two low-cost webcams (top-left) and passive rubber foam strips on the fingers of a gripper (bottom). *Right:* Detailed view of the foam strip with its front painted in green. The deformation in the contact region at the center is measured visually using the camera. In the lower part, the red lines indicate the locations of the two contours tracked by snakes (reference and front).

snakes are used to track the two long contours on the top side of the foam – i.e. the reference contour r_i between the metallic finger and the foam, as well as the front contour s_i between the foam and object (or an artificial internal edge, see below). Distances are converted from the 2D image to world coordinates [in meters] by the intrinsic camera parameters and by a projection onto the plane spanned by the finger's major axis and its motion axis. The absolute position of the finger is known from r_i, and the current deformation δ along the front contour s is calculated by $\delta_i = (s_i - r_i) - (s_i^{ref} - r_i^{ref})$. The reference configuration ref is obtained during initialization, see below. Since the stiffness of the rubber foam is also known, object deformation and the applied pressure can be obtained simultaneously.

The deformation characteristics of foam materials are well-investigated [4] and generally expressed by a non-linear relation between normalized strain (compression) and stress (pressure $[Pa]$). We measure the strain-stress curve of the used rubber foam as outlined in [3] and approximate it by a third-order polynomial f, which yields the local pressure applied to the object. The curve obtained for rubber foam is more linear compared to plastic foams and has a slope of $0.08\frac{MPa}{1}$ in its central region. The total force applied to the object is obtained by integration over the pressure using f, the normalized deformation $\frac{\delta}{w}$ along the front counter s and the material width/height w, h: $F = h\int_s f\left(\frac{\delta(s)}{w}\right) ds$,

Visual snakes [5] are a popular concept for tracking objects which are well-defined by their contours. The foam material has no visible inner structure, such that edge tracking is the obvious choice. Snakes consist of connected points i which move in the image to minimize an image-based energy term, which primarily makes points snap to image edges, see also [3]. Furthermore, the energy term has a smoothness component, which drags points by their neighbors, if local edges are weak. If strong edges are present in the object, points

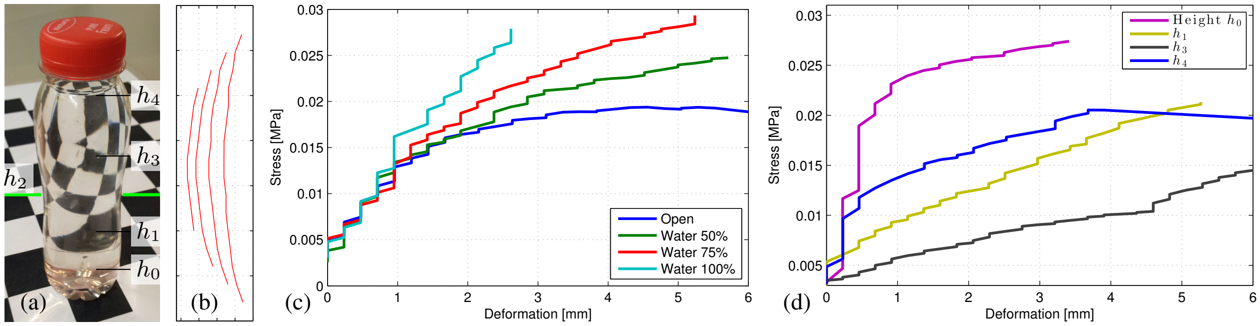

Fig. 2. *(a)* A transparent bottle (depicted in front of a chessboard pattern) is explored. Note the slight narrowing at half height (h_2, green line), which explains the low stiffness in this region. *(b)* Deformation shapes measured at the center of the bottle while increasing the pressure. *(c)* Stiffness at height h_2 with open cap or closed cap and varying levels of water inside. *(d)* Stiffness varies considerably along the height of the bottle (measured with open cap).

may jump off the foam contour. This is prevented by a component which penalizes any edge between r_i and s_i. The minimum of the energy term is searched iteratively in a local neighborhood along lines which are perpendicular to the contour in the reference configuration. This local 1D search makes points stay "in place" on the contour and ensures a low computational load for tracking.

The front contour s_i may be disturbed by strong edges in the object, as outlined in [3]. Therefore, an internal contour is added to the top surface of the rubber foam by applying a narrow color stripe in the front region, see Fig. 1 (right). The snake points s_i now snap to the edge between the black foam and the green stripe. Since this edge is constant, the localization accuracy of points s_i is improved. The effective width of the foam strip becomes smaller, and w must be adapted accordingly to account for the changed deformation behavior. Additionally, the color stripe is used to detect occlusion of the foam by the object. Pixels which are directly in front of s_i exhibit the appropriate (green) color, unless the foam is occluded. The corresponding points s_i are invalid in this case. Pixel colors are classified using a Gaussian mixture model, which is trained to the observed color stripe during initialization.

Initialization of snake points is performed on startup and whenever tracking is lost. For that purpose, the fingers are moved to a known reference position (e.g. by opening the gripper), and the reference snake points r_i are initialized at a regular spacing of e.g. $2mm$ between the two endpoints of the foam strip. The extrinsic relations between camera and foam strip are known from a geometric model up to a small error, or they are determined with a marker as in Sec. 3. By minimizing the energy term, snake points snap to the exact finger-foam edge. Next, the front snake s_i is initialized slightly in front of r_i and then pushed away from r_i. Points s_i will snap to the next edge, i.e. the front contour of the foam. This stable configuration is the zero-reference for deformation δ, which thus also considers deviations in the foam shape.

3) Results and Experiments: The proposed sensor concept is evaluated with a commercial two-finger gripper mounted on a Kuka lightweight arm. A strip of rubber foam with a cross section of about $1 \times 1cm$ is attached to each finger, and a single camera is mounted above the gripper to track one of the fingers. The system relies solely on visual data, therefore the dedicated position and force sensors in the gripper are not used. Initialization is performed using a reference template on the gripper (see photo in Fig. 1). An analysis of measurement accuracy is provided in [3].

In a first experiment, the stiffness and shape of a typical household object, a plastic bottle, is measured, see Fig. 2a. While the gripper is closed around the bottle at half height h_2, the deformation and applied pressure are recorded. Fig. 2b shows the deformed shape of the bottle at four different points in time. With increasing pressure (left to right), the entire surface retreats, the curvature decreases slightly and the contact area increases. The experiment is repeated with different levels of water inside the (closed) bottle. A closed bottle exhibits a tendency to preserve its volume – on compression, air applies an increasing counterpressure onto the inside surface. Most liquids prevent any volume change, such that compression must be compensated by an expansion in other areas. Fig. 2c shows the deformation-stress relations in the center of the contact region. They are equal for small deformations, since volume preservation is not dominant here. For large deformations, the bottle with 100% water is stiffest, since volume changes are prevented by the liquid.

In a second experiment, stiffness is evaluated at different height levels of the bottle by moving the gripper with the robot arm (haptic exploration). Stiffness of a thin-walled object exhibits a high dependency on the local geometry. Fig. 2d shows that the object is very stiff at the bottom and at the top. These are both convex regions, which provide most support. However, it can also be seen that there is a knee in the curves for $h_{3,4}$: Here, the surface bends to the inside and the support from the convex geometry is suddenly lost. Stiffness is low and almost linear near the center. A video of the haptic exploration is provided on http://www.lmt.ei.tum.de/goto/agm2014.

4) Conclusion: A low-cost tactile sensor for grasping tasks has been presented, which is based on a passive rubber foam and a low-end camera which measures positions and forces visually. In an experiment, the sensor is used for haptic exploration of a deformable transparent object. In future work, the performance of the sensor will be evaluated in a grasping framework. Furthermore, visual cues from the camera will be used to determine the reaction of the object and to decide if the grasp configuration is stable.

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