# Towards a new terrain perception for humanoid robots

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***Abstract*— In this work we tackle the problem of estimating the local compliance of tactile arrays exploiting global measurements from a single force and torque sensor. Experiments have been conducted on the feet of the iCub robot [1], sensorized with a single force/torque sensor, an inertial unit and a tactile array of 250 tactile elements (taxels) on the foot sole. Results show that a simple calibration procedure can be employed to estimate the stiffness parameters of virtual springs over a tactile array and to use this model to predict normal forces exerted on the array, based only on the tactile feedback. This prediction is further exploited to improve the estimation of the total feet state by fusing it with inertial and force/torque measurements in an Extended Kalman Filter. This multimodal sensor fusion is relevant when implementing whole-body controllers for robots in non-rigid non-coplanar contacts.**

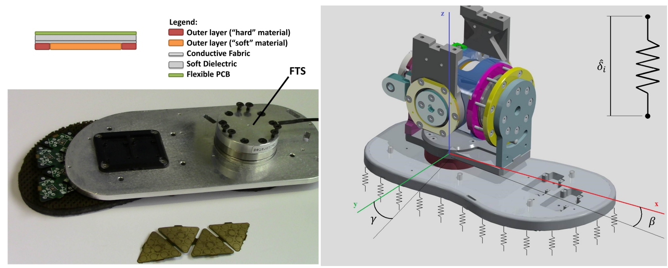


Fig. 1. On the right: foot sole with its relative sensorized skin. On both feet are glued 25 PCB triangles of 10 taxel each plus 2 temperature sensors. The FTs that we exploit for our tests is fixed directly on the metallic foot sole. On the left: the discrete model of the skin. Each taxel is associated to a linear compression spring, the local measure of compression for the elastic fiber is provided as an integer value ranging from 255, in case of undeformed skin, to 0 in case of fully compressed.

## I. INTRODUCTION

During locomotion the most important haptic informations are represented by the contact forces between terrain and robot feet. These forces have a great relevance in stabilizing the robot because it is through these forces that the robot can actuate the underactuated degrees of freedom, like the Center of Mass (CoM) position and the floating base orientation. Starting from the simplifying assumption of rigid contact between the robot feet and the ground we developed a whole-body algorithm to control the robot posture and follow a desired CoM trajectory [2]. To further improve our algorithm, i.e. considering also non-rigid contact, we need to advance the robot capability in sensing the ground characteristics. Humans, for instance, during locomotion exploit the rich haptic information coming from feet to coordinate muscle reflexes, while the Central Nervous System (CNS) modulates the gait pattern to compensate for changes in terrain compliance [3].

Along this research line, we recently proposed a methodology to improve the perception of the terrain [4]. Instead of focusing on novel algorithmic strategies, we rather exploited a novel sensor: the distributed pressure sensors (also known as the artificial skin [5]) integrated under the iCub feet. As described in Section II the major outcome of this work is a "stiffness matrix", that we are currently using to improve the estimation of the contact wrench and the changes in orientation of the iCub feet, as it will be briefly discussed in Section III.

## II. SKIN CALIBRATION

The robot skin is a compliant distributed pressure sensor composed by a flexible Printed Circuit Board (PCB) covered by a layer of three dimensionally structured elastic fabric further enveloped by a thin conductive layer. The PCB is composed by triangular modules of 10 *taxels* which act as capacitance gauges. Figure 1 shows a particular of the skin glued under the foot sole together with the Force/Torque ensor (FTs) mounted on the iCub ankle.

The skin has been modeled as a discrete system composed by a set of parallel springs (one over each taxel) connecting the foot plate and the contact surface (see Figure 1). In order to perform the skin calibration and obtain the values for the local stiffnesses of each spring, we formulated an optimization problem based on a Constrained Least Square (CLS). We estimated the local stiffness of skin patches over taxels by manually stimulating the artificial skin with a probe. By exerting normal forces on the sole of the foot we collected a first dataset that was then split into a training and test set. To further assess the validity of the estimated parameters, we collected a second dataset in remarkably different conditions. During these set of acquisition the robot was standing in an upright position with the foot on a hard spherical surface (spherical cap). Results are shown in Figure 2.

## III. IMPROVING FOOT STATE ESTIMATION

We exploit the devised stiffness matrix of the skin and corresponding prediction of the applied normal forces to improve the state-estimation of the individual iCub feet. In particular, thanks to an Extended Kalman Filter (EKF), the measurements of the skin are fused together with the readings of the Fts and of an Inertial Measurement Unit (IMU). The state $x$ vector for this EKF is given by the following:

$$x = [v^B \quad \omega^B \quad f_o^B \quad \mu_o^B \quad f_c^B \quad \mu_c^B \quad \phi^B]^T \qquad (1)$$

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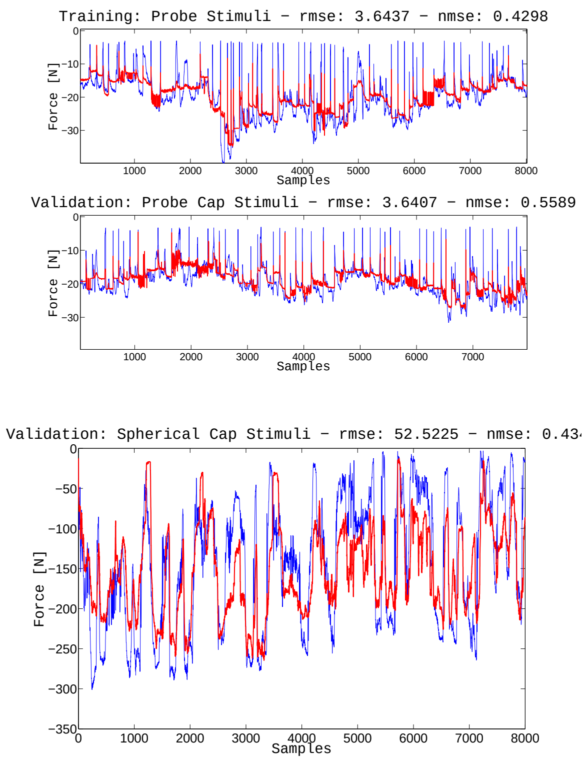


Fig. 2. Measured (red) and estimated (blue) force1. The global force is obtained as the sum of the product of the taxel measurements and the estimated associated spring stiffnesses. On the top: the training and test data set. On the bottom: the spherical cap testing data set.

Where $v^B$ is the linear velocity of the foot (with $B$ accounting for body coordinates), $\omega^B$ its angular velocity, $f_c^B$ and $\mu_c^B$ the contact forces and torques, $f_o^B$ and $\mu_o^B$ are all the other forces and torques acting on the foot, while $\phi^B$ is the foot orientation.

The corresponding measurement vector is given by the following:

$$y = [h_{imu} \quad h_{ft_o} \quad h_{ft_c} \quad h_{skin}]^T, \tag{2}$$

where each component is defined as follows:

$$\begin{aligned} h_{imu} &= [(\dot{v}^B - mg^B(\phi^B)) \quad \omega^B], \\ h_{ft_o} &= [f_o^B \quad \mu_o^B], \\ h_{ft_c} &= [f_c^B \quad \mu_c^B] \\ h_{skin} &= [\hat{f}_{c_z}^B], \end{aligned}$$

where $h_{imu}$ consists of measurements from a foot-mounted IMU returning proper acceleration and angular velocities, $h_{ft_o}$ and $h_{ft_c}$ are the FTs measurements from the upper leg and the foot respectively, an $h_{skin}$ is obtained from the skin as explained in the calibration section.

The results of this procedure are represented by the estimation of both the orientation of the foot, as well as the internal and external wrenches it is being subject to. As an example, in Figure 3 we show the final estimated contact wrenches for a single foot.

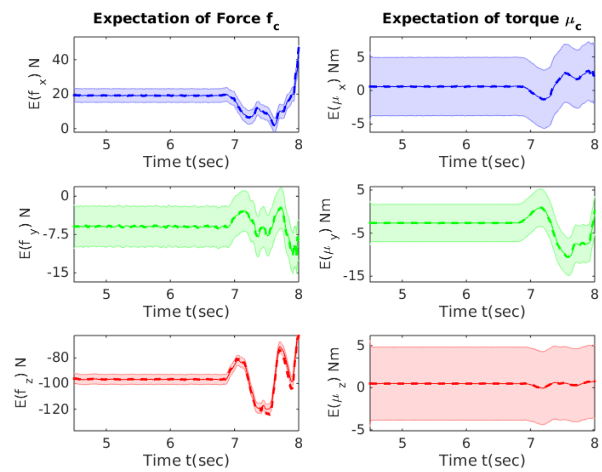


Fig. 3. Predicted contact wrench with skin under the feet during a backward tipping experiment.

## IV. Conclusions and Future Work

In this work we presented an approach to estimate the orientation and the contact forces of a robotic foot. The novelty of our technique resides in the exploitation of an artificial skin composed by a tactile array glued under the robot feet. Validation experiments have been conducted on the feet of the iCub humanoid. Results show that a simple procedure can be used to calibrate the tactile array and to generalize the obtained calibration in quite different scenarios. Eventually the data of the artificial skin are fused together with force/torque and inertial measurements to improve the state estimation of the iCub feet.

## ACKNOWLEDGMENT

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