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# An Innovative Torque Sensor Design for the lightest Hydraulic Quadruped Robot

H. KHAN\*, F. CANNELLA, D G. CALDWELL

and C. SEMINI

Department of Advanced Robotics, Istituto Italiano di Tecnologia Via Morego 30, 16163 Genova, Italy \*E-mail: hamza.khan@iit.it http://www.iit.it/en/advanced-robotics.html

High-performance legged robots that are required to navigate on unstructured and challenging terrain benefit from torque-controlled joints. High-fidelity torque measurements are crucial for proper joint torque control. Commercially available torque sensors are expensive and often hard to integrate into compact and light-weight robot leg designs. Custom-made sensors on the other hand often suffer from asymmetric behaviour with respect to direction of rotation or poor linearity, especially for small and compact applications. This work is motivated by the need to achieve reliable torque measurements for the newly developed, small-size hydraulically actuated quadruped robot MiniHyQ. The main contribution of this work is the development of a new innovative design of a strain gauge based torque sensor with a high degree of linearity, symmetry, and scalability (both in dimension and measuring range). Furthermore, the glueing and wiring of the strain gauges are easy thanks to the geometry of the sensor that allows direct access to the mounting surfaces, even in compact dimensions. We show the design's symmetric (clockwise and counterclockwise rotation) and linear behaviour through virtual prototyping and experimental tests. Furthermore, we show how a small-scale instance of the sensor design is successfully installed on the MiniHyQ robot.

Keywords: Quadruped Robot Design; Torque Sensor; Strain Gauge based Sensor.

### 1. Introduction

In order to advance research faster, legged robots must become more manageable. So that dynamic experiments can be performed faster and more easily. The simplest way to achieve this goal is by reducing the size and weight of the robot. Currently, it is still area of great interest for designers to build a portable highly dynamic and versatile quadruped robot to run fast in all terrains. One of the key points of a successful of this kind of  $\mathbf{2}$ 

locomotion is to improve the joint compliance: passive or active. The first one is based on decoupling actuator and the driven link from the using an elastic element,<sup>4</sup> while the second one depends on the feedback of force and torques. Even if the active one requires a more complex control, it for sure reduces the mechanical complexity and permits greater performance. To implement the compliance  $controllers^5$  it is necessary the measurement of the torque at each robots leg joints. The development of torque sensor for robot has been of great interest for decades, as the commercially available torque sensors are expensive, need extra space in joints and difficult to customize. Thus, a variety of sensors were designed and developed for robotics systems with acceptable performance by different researchers.<sup>9</sup> It gets more complicated when it is needed to be customized for smaller and compact applications. Nevertheless a torque sensor with all the requirements together (as the linearity, the symmetrical behavior in both the clockwise (CWR) and counterclockwise (CCWR) rotations, high noise-to-signal ratio and temperature compensation) rarely were designer.<sup>10,13</sup> Last, but not least, the strain gauges installation is one of the issues that affects the shape of the sensors and their performances. In this paper a new design of torque sensor that collects all the aforementioned characteristics is presented. The virtual prototyping design (in particular the finite element analysis) was used to reach the final shape and the experimental set up was built to test the performances.

# 2. Related Work

Considering the advantages of flexible joints (the compliance permits, for instance, to make safer the human robot interaction, the energy harvesting and to move in unstructured environment, in particular the uneven terrain), in the last decades the robotic research began to deal with the compliant joints. Consequently, the control moved from the rigid joint to the fully sensorized joints based on the applications of torque sensors as Visher et al. and Aghili et al.<sup>1,12</sup>; as well as more recently Wolf et al.<sup>14</sup> have shown. In particular, Tsetserukou et al. classify the torque sensors in three categories: electrical, optical and based on electromagnetic phenomena.<sup>11</sup> Considering that in this paper we will apply the aforementioned torque sensor to a hydraulically quadruped, the high stresses and shocks push to take in account only the first ones and essentially them that are associated with strain gauges. Further developments were targeted towards the human-robot interaction,<sup>7</sup> the motion stabilization<sup>6</sup> or miniaturization.<sup>3</sup> Till now, despite to the different applications, the basic design was not improved too much,

because the non linearity and the non symmetrical behavior (in CWR and CCWR) was not guaranteed.<sup>2</sup>

# 3. Why Compact Torque Sensor is needed for MiniHyQ Robot ?

To the authors best knowledge, MiniHyQ is the lightest and smallest hydraulic quadruped robot that has been built so far. It is shown in comparison of existing hydraulic quadruped robots (Table 1). MiniHyQ is around 3 times lighter than most of the existing hydraulic quadruped robots. It has almost 30% higher joint torque density (robot mass to joint torque ratio) and 40% wider joint range of motion in leg-sagittal plane comparing to HyQ.<sup>8</sup> MiniHyQ is fully torque controlled, measured directly at

Name	Mass (offboard, onboard pump)	Dimensions (LxWxH)	DoF ( per leg) , Joint Torque Controlled
SCalf	78kg, $123$ kg	$1.1\mathrm{m}\ge 0.49\mathrm{m}\ge 1\mathrm{m}$	3, Yes
HyQ	75kg, $98$ kg	$1 \text{m} \ge 0.5 \text{m} \ge 1 \text{m}$	3, Yes
Baby Elephant	90kg,130kg	$1.2\mathrm{m}\ge0.6\mathrm{m}\ge1\mathrm{m}$	3, No
BigDog	N.A,110kg	$1.1 \mathrm{m} \ge 0.4 \mathrm{m} \ge 1 \mathrm{m}$	4, Yes
JINPOONG	80kg,120kg	$1.1m \ge 0.4m \ge 1.2m$	4, No
RLA-1	60.2kg,N.A	$1.1m \ge 0.67m \ge 1m$	3, No
LS3	N.A	bigger than BigDog	3, N.A
Wildcat	N.A	N.A	3, N.A
Spot	N.A,74kg	smaller than BigDog	3 , N.A
MiniHyQ	24kg,35kg	$0.85m \ge 0.35m \ge 0.77m$	3, Yes

Table 1. A comparison of Hydraulic Quadruped Robots

the joint. MiniHyQ's each leg has three active joints. Two of its joints use linear cylinder with in series load cell to measure joint torque. Its Hip Flexion/Extension(HFE) joint (third joint) uses rotary motor which provides constant joint torque of 60 Nm at 20MPa. It is needed to find a compact and high performance torque sensor which fits in the desired limit space shown in Fig 2(b).

#### 4. Torque sensor design

#### 4.1. Design Evolution

In order to find compact solution due to limited space, we started with scaling down and investigating the traditional strain gauge based designs.

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Fig. 1. MiniHyQ (a) picture of robot and (b) CAD model of HFE joint, it shows where custom designed strain gauges based torque sensor is fitted.

Four spokes based Torque Sensor It is classic example of strain gauge based torque sensor. The main drawback of this design, due to four spokes it is not easy or possible to glue and wire strain gauges on it. It provides reasonable output but it is not feasible for compact applications.

**Two spokes based Torque Sensor** Design with two spokes, seems promising for gluing strain gauges and symmetric output. But due to size constrains, it was not possible to bring peak strain or stress in middle of spoke to act like beam. Even though it is brought in middle by changing spoke thickness and its round size, but in trade off it reduced horizontal flat surface less than 5mm (in our case recommended horizontal length for mounting strain gauge is minimum 5mm). So, both of the previous torque sensors already in use in the HyQ<sup>8</sup> were not suitable to be scaled. A new design was necessary.



Fig. 2. Traditional starin gauge based torque sensors (a) Four spokes and (b) Two spokes.

# 4.2. Final Design

The design of this torque sensor is the synthesis about three needs: the easy access to the maximum strain rate point to glue the strain gauges, the symmetry and linearity of the sensor response. That was reached re-designing the former torque sensors with four wings equal in geometry, as shown in the Fig. 3; moreover, the half bridge strain gauge was mounted in two opposite wings of the sensor to sum two opposite signals; that guarantees the symmetry during both CWR and CCWR load application, because the possible difference between the tension/compression are canceled, as shown in the Fig. 4.



Fig. 3. (left) The 3D design of the torque sensor; (right) the half bridge strain gauge positions.

#### 5. Results

The symmetric behavior in both the rotations (CWR and CCWR) and its linearity are designed by virtual prototyping design (in particular Finite Element Analysis) and tested performing the experimental tests.

## 5.1. Virtual Prototyping Design Results

The model (built with 50000 elements, with 39NiCrMo3 material) permitted to simulate the torque sensor design performance; so the numerical model was built and the simulation were launched. The loads and the constraints were the input data. It is shown in the Fig. 4 (a), (b) and the outputs were the strains of surfaces where the strain gauges should be glued, as shown in the Fig. 4 (c), (d). The two results are similar in distribution and in values; moreover there is a wide area where to glue the strain gauge with low gradient. Also the stress was checked: 200MPa, that is lower of than 450MPA the yield point.

# 5.2. Experimental Results

The torque sensor was machined and the full bridge strain gauges was easily glued on the both sides, to maximize the signal and to compensate the temperature, as shown in the Fig. 5(a). To verify the design performances, an experimental test was carried out loading the torque sensor with a force in order to reproduce the working conditions. The torque was applied with





Fig. 4. **a**) and **(b**) loads a couple of forces, in red) and constrain (the blocked shaft, in blue) of the Finite Element Model. **c**) and **d**) the strain contours of the upper surface.

a beam and the masses hanged on its ends, as shown in the Fig. 5(b). The applied torque is defined as  $\tau = m * g * b$  where g is the gravity acceleration. The obtained relationship between the torque input and strain gauges output is linear, symmetry and with good sensitivity, as shown in the Fig.6.



Fig. 5. a) physical model of the torque sensor equipped with strain gauge. b) the test rig with schema of applied forces (in black) and arm length (in white) that created the applied torque (in yellow).

The obtained relationship between the torque input and strain gauges output is linear, symmetry and good sensitivity, as shown in the Fig. 6.

#### 6. Discussion and Conclusion

The Fig. 5(a) shows that the strain gauges installation is easy to do, because the surfaces have not any obstacle to be reached, despite the small size of this sensor. The experimental tests results permit to highlight the torque sensor performance: there are linearity and the symmetrical behavior, as

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Fig. 6. Experimental results of torque sensor while varying torque CWR and CCWR.

shown in the Fig. 6. Thus the final design satisfies the requirements for the robotic application. In fact, this torque sensor will be easily used in the same way in CWR and CCWR, because it does not needs any adjustment in the control. Moreover even the temperature it is compensated thanks to the full bridge strain gauges installation. So a new design of the torque sensor is presented and all the characteristics are elucidated. The requirements for being used in the robotics (arms and/or leg) are satisfied. To do that, a Finite Element Model was built and the experimental tests were carried out in order to measure the performance: in particular the symmetric and linear behavior. Moreover this design is compact and it permits the easy access to the surfaces for installing the strain gauges.

**Future Works** The future work envisages the optimization of the shape and the material in order to increase the sensitivity and to reduce the size. This will be generalize and a tool will be provided for designers to help easily customize this an innovative according their desired requirements.

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