A measuring tool for accurate haptic modeling in industrial maintenance training

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Abstract. In the context of training for industrial maintenance the capturing and modeling of interaction forces are important elements that allow to characterize the skills of users. This paper describes a device that can be used for acquiring such forces for later use in the context of a training system. The device has been designed for managing the force ranges and the precision required by typical maintenance operations and it can be easily adapted to different type of tools. The paper discusses also the calibration of the device and presents a case study in which actions from different users are being captured.

1 Introduction

Industrial Maintenance and Assembly is a very complex task. Usually, these tasks involve the knowledge of specific procedures and techniques for each machine. Each technique and procedure requires cognitive memory and knowledge of the way the task should be performed as well as fine motor "knowledge" about the precise movements and forces that should be applied. The dominant skills involved in these tasks are cognitive, and they reflect the operator's ability to obtain a good representation of how to perform each of the steps of a task and the correct order to perform them, which is reflected in their hierarchic organization. But, in many cases , assembly and disassembly operation may involves also motor-control skills which importance is often underestimated. Example of such skills is the capacity to undertake precise movements and controlling the forces applied, especially during the manipulation of delicate parts, in which potential damage can occur when adverse force/movement is applied. For this very reason a multimodal industrial maintenance and assembly platform is in development [1] in the scope of the EU project SKILLS with the intention of providing an efficient and accurate training system for the transfer of skills involved in such specific tasks.

In order to faithfully replicate the interaction user-machinery within the virtual world, i.e. in a way perceptually equivalent to the real maintenance job, there was the need of capturing exact forces and torques profiles exerted during the performance of a skilled maintainer. This is less trivial that it may appears as, to the best of our knowledge, there are not on the market universal force measuring tools suiting the range of usages normally involved in assembly and disassembly. To achieve a good data recording of possible interaction forces exchanged during assembly a unique measuring tool was then developed and the preliminary evaluation of recorded data is presented here. This allows to build efficient haptic rendering model for the contact during operations like screwing with a screwdriver or tightening with a wrench.

Next section will present related work in the topic. After, a discussion of the device realization and calibration is presented. In section 5 a setup that shows the usage of the tool is depicted and retrieved data are analyzed to show capabilities of the device. Last section introduces future works and summarizes the conclusions.

2 Related work

In [2] is explained that the repeated performance of tasks develops a motor memory. The creation of such motor schemes involves a gain in performance [3] such that the preservation of the exact motor components involved to execute a task is essential for developing skills. To replicate the correct motor actions in a virtual reality training platform a precise haptic modeling of the interaction is essential. Some specific works exists that have analyzed the tool handle shape and how it influences performance for instance in the specific case of a screw driving torque task [4]. It is indeed demonstrated that a discrete number of injuries occurring at the hand can be avoided if the hand tools were ergonomically well-designed [5]. Other ergonomics studies focus on the quantification of the forces applied with or by hand tools [6]. In particular the paper from McGorry describes a device for measuring gripping forces and the moments generated by a hand tool.

The present paper starts from this studies and develop a new force measuring tool capable of streaming force and torque values to a remote computer for later analysis.

3 Device

The device (Fig. 1) has been designed to be used in industrial maintenance tasks where different operations and tools are involved. Therefore it is composed of a base that can be plugged with different tools. Since the most common operation is screw driving, as a first step the device has been equipped with a screwdriver and with a wrench (Fig. 1). According to [7] maximum values of torques in screw driving task carried out with a screwdriver do not exceed 6 Nm. The maximum diameter of screws, tightened by means of a wrench in the target application [1], is 8 mm. Thread calculation formulas and empirical relations for screw driving tasks [8] lead to consider 36 Nm be the maximum bending moment applied. These values have been used for the design of the device.

The base is composed of three parts (1-3 shown in the right side of Fig. 1): the handle, the sensing system, and the electronics.

Fig. 1. The assembled device with wrench tool (left) and the components (right)

1. **Handle.** It has two functions: it provides a shield for the sensors, and it is the interface for the user. For the accuracy of the measurement the user should grasp only this part of the device.
2. **Sensing system.** It is composed of strain sensors and of an interface where sensors are attached. This system can read bending moments in the range ±36 Nm and torques in the range ±6 Nm. It is not sensible to normal stress if forces are less than 150 N (both in tension and compression). The resolution is 0.2 Nm for the bending moment and 0.2 Nm for the torque. Sensors employed are Vishay uniaxial strain gauges, whose main feature is the low hysteresis. The interface where the sensors are attached is the part 2 shown in Fig. 1: on the shaft two full Wheatstone bridges (A and D) are mounted to measure out deformation due to bending, whereas between the shaft and the circular external ring three ribs house two further bridges (B and C) for the torque sensing. On the opposite side of the ribs is the tool interface, tools are mounted on by means of two screws.
3. **Electronics**. It is composed of three parts housed by the large cylindrical cover:
   – Board with instrumentation amplifiers, it is mounted directly on the sensors' interface in order to minimize risks for strain gauges movements. Amplifiers employed are Burr Brown INA2141 whose gain G is set to 100.
   – Battery, mounted on a plate framed to the cover. The battery is charged without disassembling the device thanks to the socket on the cover.
   – Board with microcontroller and transmission module. The microcontroller is the PIC 18F4420 manufactured by Microchip, data are coded with 10 bits resolution. Data are sent to the PC via Bluetooth, transmission frequency is 300 Hz.

4 Device Design and Calibration

4.1 Design

The main specification for the design is the measurement of force and moment applied by the user in screw driving with a wrench and the measurement of torque applied when screw driving with a screwdriver. The sensors' interface has been designed to measure both bending moments and torque, without being sensible to direct stress. The material chosen for this part is the AISI 630(17-4 PH), stainless steel commonly used in strain gauges' applications. The sensors' interface is divided in three zones: the tool interface, the shaft for measuring bending moment, and the cylindrical base, that is used to house the amplifiers, to measure torques and to assemble the handle.

Bending Moment. For the shaft design the user is supposed to grasp only the handle. Shaft transversal section is an l by l square. Pressure on the handle is modeled by means of a force **F** and a moment **M**. According to Fig. 2 **F** is supposed to be directed along y and applied at a distance d from the element origin. Components of **F** along x and z are not considered: F_x does not produce strain where strain due to F_y is maximum, F_z produces a negligible strain that is anyway erased thanks to the strain gauges' placement. Distance d is fixed because the handle dimension does not allow to vary too much the position of the hand. Moment **M** is supposed to be directed along x, strain due to M_y is zero where sensors are placed, strain due to M_z is supposed to be negligible. According to Euler-Bernoulli beam equation the strain, in the $(Oxyz)$ system,

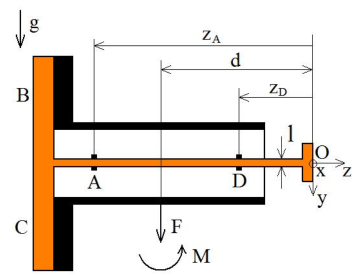

Fig. 2. Free body diagram for bending moment load condition. The uppercase letters A–D refer to the strain gauges, while the tool attachment is the point O.

at a given point P is:

$$\varepsilon_P = \frac{M_P \, z_P}{E \, J} \tag{1}$$

where

$$M_P = M - F(z_P + d) \quad \text{and} \quad J = \frac{l^4}{12} \tag{2}$$

Two values of M_P are needed to obtain F and M. Given M_A and M_D, F and M result

$$F = \frac{M_D - M_A}{z_A - z_D} \tag{3}$$

$$M = M_D \frac{d + z_A}{z_A - z_D} - M_A \frac{d + z_D}{z_A - z_D} \tag{4}$$

For the accuracy of this indirect measurement points A and B should be as far as possible. Therefore bridges have been placed at about $2\,l$ distance from changes of section in order to avoid geometrical nonlinearity effects and, at the same time, to maximize the distance among sensors.

Torque. Since nonlinearity effects cannot be avoid,strain of the ribs has been estimated with FEM. In Fig. 3 (a) the strain due to torque is shown (amplified). There are four zones where strain gauges can be attached. Since these zones are

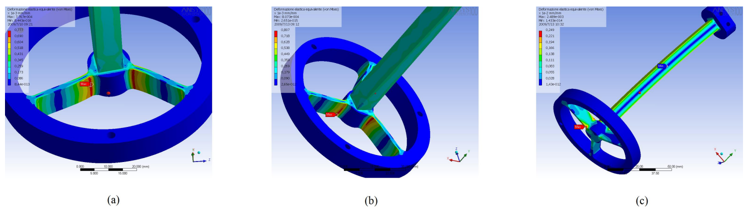

Fig. 3. Equivalent strain (Von Mises) for (a)pure torque, (b)torque and direct stress, and (c)bending moment

very narrow one redundant Weathstone bridge has been mounted. Load conditions investigated are pure torque, torque/direct-stress , and bending moment in order to verify respectively that:

1. Strain is large enough to be accurately measured.
2. Direct stress does not affect the measure.
3. Strain due to bending moment is not critical.

Figure 3 shows results of analysis, torque is 6 Nm, bending moment is 36 Nm and normal force is 150 N. All loads are applied to the tool interface. The three points are verified: strain is about 800 $\mu\varepsilon$ under pure torque condition; strain varies less than 3% when compression is applied; strain is less than 1200 $\mu\varepsilon$ (sensors' fatigue limit) in all conditions.

Inertial Properties. The device has been designed to work in real tasks, hence it is necessary that it is perceived as commonly used tools as much as possible. Among the variables that affect this perception, the size and the inertial properties have been considered in the design of the instrument. The materials of the handle, of the tools and of the cover for the electronics have been chosen in order to place the center of gravity of the instrument as close as possible to the center of the hand, to minimize mass and to minimize the moment of inertia respect to the axis n shown in Fig. 2. The handle diameter is the same of the screwdrivers involved in the target application, the length allows a human hand to completely grasp the handle. Tools are interfaced with the sensors interface by means of two screws. Holes are dimensioned and placed in order to keep contact between the interface and the tool, in this way backlash is always avoid.

4.2 Calibration

Assumptions and design analyses results were verified by means of a calibration. The device was loaded under three different conditions: bending moment, pure torque, and compression. Figure 4 shows the schemes for the first two conditions. In each case the handle was blocked by means of a clamp. Force were applied

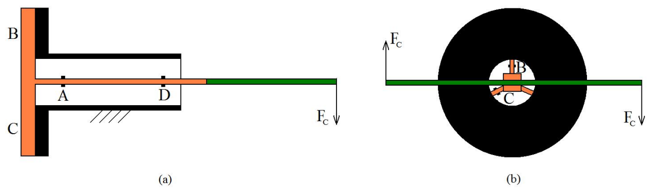

Fig. 4. Calibration layout for the conditions (a)Bending moment and (b)Pure Torque. The uppercase letters A–D refer to the strain gauges, while F_C is the applied force.

by means of calibrated weights, the uncertainty on the load (moment or force where the sensors are placed) is less than 3%. The system was loaded in the range ±6 Nm for pure torque, ±21 Nm for bending moment, and 150 Nm for compression. Load steps were 0.5 Nm for torque, 3 Nm for bending moment, and 20 N for compression. After each step load was set to zero to verify hysteresis and the trials were repeated three times to assess the reliability of the measure. Both torque and bending moment sensors' response is linear ($R^2 > 0.997$ in all cases), hysteresis was not appreciated. Output O_P available for each sensor is

$$O_P = O_P^0 + \Delta O_P \tag{5}$$

where ΔO_P is:

$$\Delta O_P = 1024\, GF\ G\, \varepsilon_P\ =\ k_p\, M_P \tag{6}$$

and O_P^0 is the output due to bridge offset. This value depends on the tool mounted and it must be recorded at the beginning of the measuring session. Table 1 shows values of k_p for each sensor:

Sensor	A	B	C	D
k_P [1/Nm]	11.19	17.19	17.38	10.50

Table 1. Constants k_P of each sensor

5 Acquisition System and Data Analysis

To analyze the capabilities of the developed tool a simple evaluation test has been performed. The test requires the user to perform a sequence of release and tightening of bolts with the wrench tool as follows: first release and tightening of a bolt parallel to the ground and then the tightening of a bolt perpendicular to the ground. The users were asked to perform the task with the right arm and with not specific timing requirements. We selected 7 voluntary users, all male and right handed, aged 23-30.

During the task we recorded the interaction forces using the device and the motion by means of a motion capture system. In particular a VICON MX-20+(OMG plc, UK) infrared motion capture system, configured with 7 cameras each having a resolution of 2 megapixels, was employed. The VICON system uses infrared strobes mounted around the cameras to track the position of retro-reflective 6-mm markers running at 200Hz with a resulting position resolution less than 0.5 mm. We used a configuration of 7 markers, of which 3 were placed over the device and 4 over the user: front chest, left and right shoulder and right elbow. Figure 5-left displays the phase diagram relative to forces and torques

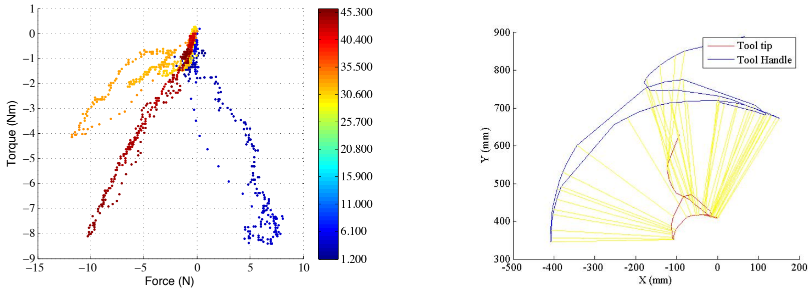

Fig. 5. Single user interaction during the task. Force/Torque plane (left) during the execution of the three subtasks with color as time. Motion of the handle (right) during vertical tightening projected over the plane parallel to the ground.

during the execution of the three subtasks. From this plot it is visible the separation of the single movements performed during the task. It is then possible, from the acquired data, to perform a segmentation and to distinguish each step of the complete task. Figure 5-right shows instead the last subtask performed by one of the user as recorded by the motion capture system. To perform correctly this step with a correct movement we expected the users to produce an action of pure flexion, with minimal torque. Figure 6 presents the distribution of torques for every user, showing only half of them performed the task as expected, resulting in a mean of the average torques of $0.1Nm$. However, all of them exerted a peak force of $-10N$ to tighten the bolt.

6 Main Conclusions and Future work

The capturing of interaction forces poses several challenges because of portability and ranges of forces, in particular in domains like industrial maintenance. In this

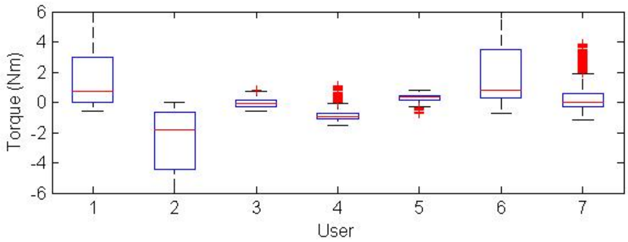

Fig. 6. Plot of torque values generated by the 7 users during the third subtask.

paper we have presented a device for capturing and discussed the design decision, integrating a first stage of evaluation. Future work will focus on the modeling of the interaction force in specific tasks, and the integration of the device in the context of an augmented reality training system. The other future challenge is in the haptic rendering of the interaction force using a haptic interface.

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