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3-D Printed Low-Cost Force-Torque Sensor

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Abstract—Force sensing is essential for many manipulation tasks and, more generally, for all robots physically interacting with their environment. While multi-axis force/torque sensors are readily available commercially, their cost and complex integration have so far limited a wide deployment. In this paper, we introduce a modular approach to design and integrating low-cost force sensors directly into 3D printed robot parts. Based on off-the-shelf optical sensors embedded into deformable structures, sensitivity and load capacity can be selected from a wide range. A working six-axis sensor, including electronics, can be built for less than 20 dollars, plus a few hours of 3D printing. We present tested example designs for sensors of different complexity, from a basic one-dimensional deflecting beam to six-axis sensors with custom shapes. We summarize the basic sensor layout geometries, explain key 3D printing and integration aspects, discuss sensor calibration, and describe our Arduino firmware and ROS-based drivers.

Keywords— Force and tactile sensing, force-torque sensor, optical force sensing, 3D printing, fused-filament fabrication (FFF), sensor calibration, LASSO, huber regression

I. INTRODUCTION

As noted by Cutkowski et al. [1], force and tactile sensing has been an active research area for robotics almost as long as computer vision, but it 'Always seems to be a few years away from the widespread utility.' As there can be little doubt about the central role of force and tactile sensing for human manipulation and many robot assembly tasks, the problem then is in the availability of suitable sensing technologies, their robustness, and, finally, costs.

In this paper, we propose and demonstrate a family of 3D printed force and torque sensors using off-the-shelf optical sensors. While the basic sensing principle is well-known, the mechanical alignment of multiple optical sensors required for multi-axis force and torque decoupling can be surprisingly difficult. We present and discuss simple and proven designs that can be built with common FFF/FDM (fused filament fabrication, fused deposition modeling) 3D printers. The contributions of this paper include:

A. A summary of optical sensors and the electronics required.

B. An overview of mechanical structures and sensor layouts for multi-axis force and torque decoupling, the associate editor coordinating the review of this manuscript

C. Proven example 3D printable sensor structures with user-selectable per-axis stiffness,

D. Planar proximity sensor configurations combined with printed grayscale patterns for six-axis decoupling,

E. A modular sensor concept that combines a fixed sensor carrier with different elastic ''hats'' of different stiffness,

F. Guidelines and structures for the critical mechanical alignment of multiple optical sensors,

G. A collection of 3D printed example designs with explanations of the design decisions and lessons learned.

II. LITRATURE REVIEW

Industrial 3-DOF and 6-DOF strain-gauge force/torque sensors are readily available in a wide range of sizes and maxi- mum forces [2], [3]. Such sensors are factory calibrated with low drift and noise, provide high mechanical stiffness and overload protection, and enable industrial robots for tasks requiring force or impedance control. Unfortunately, the costs of these sensors remain high, and the required precision amplifiers and electronics make integration into smaller and mobile robots a challenge. Regarding force and tactile sensing in general, a variety of sensor technologies have been studied to measure normal forces applied to a robot part or surface, including resistive and piezoresistive materials [4], [5], conductive rubber [6] and polymers [7], magnetic [8] and capacitive sensors [9], and several variants of optical sensing [10]. In addition to single sensors, array sensors have been proposed for most of the approaches, e.g. [11] [12]. The design of force and tactile sensors for robot hands capable of dexterous manipulation remains an unsolved challenge [13]–[15].

III. METHODOLOGY

A. Material, Components, Flowchart, Block Diagram, Theory

The basic circuit for optical sensor readout consists of just four components, with the emitter LED connected to a stable power supply via a series resistor that sets the LED current. Using another pull-up (or pull-down) resistor, the phototransistor current is easily converted to a voltage that can be measured directly by the built-in analog-digital converters of common microcontroller battery is used to give the power supply to water pumps automatically.

Exploiting this, our sensors are designed around popular microcontroller boards like Arduino [52] and Teensy [53]. These boards are readily available at low cost and come with full documentation and good software support, including bootloaders for reprogramming via USB. As the boards already provide high current digital output pins, multi- channel analog-digital converters, and standard serial communication interfaces, very few external components are required. The form factor of these boards is also small enough to permit integrating all electronics directly into the sensor housing, eliminating the need for expensive shielded analog cables between sensor and amplifier.

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IV. DESIGN

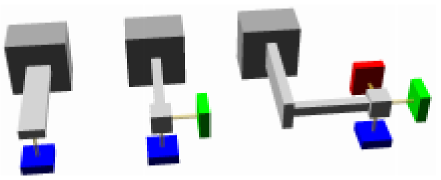

Fig. 1. 3axis Electronic accelerometer

Fig. 2. Phototransistor

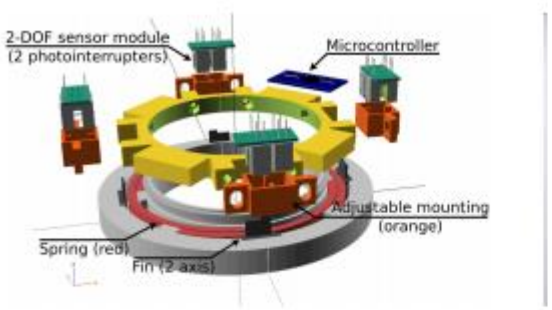

Fig. 3. Entire force torque sensor

V. COMPONENTS

The prototype comprises a total of 17 optical sensors, divided into two functional groups. The torque-sensing tool mount consists of a 3D printed standard 1/4-inch bit holder that takes any common screw bit. Compared to common metal-based tools, the maximum torque that can be applied to the screw bit is much lower, but still sufficient for light screwing tasks. The thin elastic levers are protected by robust overload end stops. The bottom face of the screw-bit holder features a printed grayscale pattern atop a set of five reflex- type optical sensors in a planar cross-type arrangement, measuring normal force and moments applied to the tool. The hexagonal grasp handle consists of six independent cantilevers with fixed supports on the upper and lower ends. Two reflex-type sensors are mounted on the inner core of the handle below each cantilever (a total of 6 × 2 sensors). The grasp faces deflect under finger contacts, measuring the total force applied to the cantilever and allowing for a rough reconstruction of the contact location on the grasp handle.

VI. WORKING

The (well known) principle of the proposed force sensors is based on elastic cantilever structures, where the deformation under load is measured in turn by contactless optical sensors. We first review the characteristics of the optical sensors and list the basic geometries for multi-axis decoupling. We discuss the design of cantilever structures with axis-specific stiffness and explain the use of spiral springs as the key elastic elements in our force sensors.

A stable power supply is essential for the proposed application, as the forward current of the LEDs (and, therefore, emitted light) increases steeply with applied voltage. Most Arduino-style boards support dedicated external power sup- plies but can also be run as USB bus-powered devices. While convenient, requiring only a single cable for power and data communication, USB power from a PC may significantly limit sensor accuracy, as the voltage may change over time due to power management and the activity of other devices on the USB bus. If the additional communication latency can be tolerated, a USB hub powered by an external high-quality power supply provides a working solution. The typical voltage drops across an infrared LED is about 1.2 V, so that two or three LEDs can be connected in series at 3.3 or 5 V supply voltage. Given typical forward currents in the range of 5. . .20 mA, total current consumption for a sensor with eight LEDs is about 80 mA for continuous operation. When necessary, e.g. for battery-operated devices, the LEDs can also be pulsed, reducing average power according to the duty-cycle. Also, it may be possible to share the signal outputs of multiple phototransistors, reducing the number of required A/D converter inputs. Multiple factors limit sensor resolution, mainly the onboard A/D converter, the voltage swing generated by the optical sensor, and the stability of the power sup- ply. If necessary, custom circuit boards can be designed with multi-channel high-resolution A/D converters.

VII. RESULTS & DISCUSSION

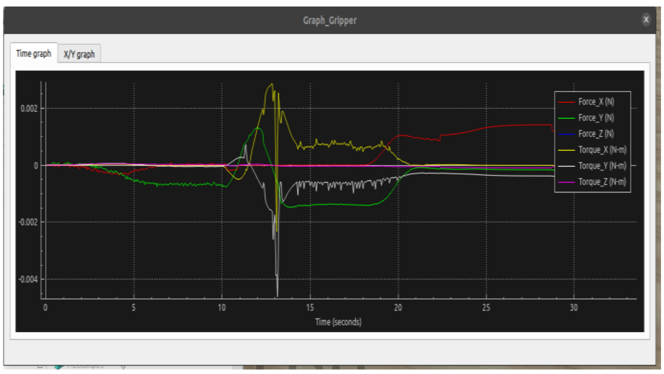

Fig. 4. Force Torque output from the simulation

For now, we are done with the simulation, and the above image is the result of force torque output from the simulation.

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VIII. LIMITATIONS

The cost is low, but the quality of 3D printing is very limited, and the accuracy is not consistent. The structure has a low caliber payload as well.

IX. FUTURE SCOPE

I am working on a hybrid manufacturing approach, where the optical sensors and electronics components are automatically inserted and connected during the 3D printing process. We use a modified printer with an integrated pick and place system and a dispenser for conductive silver paste to print wires. Printing both the structural and electronic parts of custom sensors would significantly facilitate the assembling step.

X. CONCLUSION

In this paper, we introduced a design approach for low-cost 3D printed force/torque sensors based on optical proximity or photo-interrupter sensors. While the basic design principles are widely known, creating functional multi-axis sensors can be quite tricky, as precise alignment of all components and careful consideration of 3D printing quirks and defects are needed. We presented a set of workable example designs, ranging from a simple 1-DOF force sensor to fully decoupled six-axis F/T sensors of different shapes.

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