Optical HMI with biomechanical energy harvesters integrated in textile supports

G De Pasquale¹, SG Kim², D De Pasquale¹

¹ Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, Italy
² Mechanical Department, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Boston, USA

E-mail: giorgio.depasquale@polito.it, sangkim@mit.edu, daniele.depasquale.87@gmail.com.

Abstract. This paper reports the design, prototyping and experimental validation of a human-machine interface (HMI), named GoldFinger, integrated into a glove with energy harvesting from fingers motion. The device is addressed to medical applications, design tools, virtual reality field and to industrial applications where the interaction with machines is restricted by safety procedures. The HMI prototype includes four piezoelectric transducers applied to the fingers backside at PIP (proximal inter-phalangeal) joints, electric wires embedded in the fabric connecting the transducers, aluminum case for the electronics, wearable switch made with conductive fabrics to turn the communication channel on and off, and a LED. The electronic circuit used to manage the power and to control the light emitter includes a diodes bridge, leveling capacitors, storage battery and switch made by conductive fabric. The communication with the machine is managed by dedicated software, which includes the user interface, the optical tracking, and the continuous updating of the machine microcontroller. The energetic benefit of energy harvester on the battery lifetime is inversely proportional to the activation time of the optical emitter. In most applications, the optical port is active for 1 to 5% of the time, corresponding to battery lifetime increasing between about 14% and 70%.

1. Introduction
The function of human-machine interfaces (HMI) is to transfer the analog commands imposed by the user’s body to machines. The majority of devices and systems developed are introducing some limitations to the user’s comfort and motion freedom because of the presence of cables or large batteries. Additionally, tedious and long calibration procedures are often required. The first HMI glove prototypes were proposed in the 1970s and 1980s, such as the MIT-LED glove and the Sayre Glove [1]. The Data Glove [2] (1982) was based on plastic tubes and light sensors to measure and store joint angles. The most recent devices were commercialized starting from the 1990s for virtual modeling, motion analysis and medical applications (CyberGlove [3], Humanglove [4], StrinGlove [5], etc). The HMI gloves proposed in the past have some common limitations: reduced comfort/performances due to wire communications, long calibration procedures, resistance to hand motions, and power supply based on cables or batteries. The glove introduced here, called GoldFinger, overcomes some of these problems by harvesting biomechanical energy from hands, by integrating advanced materials, by miniaturizing components, and by coupling the interface to standard textile supports.

The most diffused applications of HMI gloves are manufacturing, design and 3D modeling, robotics, medicine and health care, wearable systems management, sign language understanding and...
data management. In the manufacturing field, hand motion can replace computer peripherals to manipulate virtual objects. Practical examples are represented by gloves used to select interior furniture of cars through virtual reality programs (Daimler-Benz), to simulate maintenance operations on aircrafts (Boeing) [6], or to test the performances of astronauts and pilots [7]. Other applications are in the medical field, where gloves support rehabilitation of hand capabilities as motion, grip strength, and temperature sensitivity [8].

The invasiveness of HMI gloves generally represents a limitation to user’s hand motion and can reduce the portability of the device. Additionally, the fabric support may alter the sensors precision and accuracy, and the global measurement performances. The energy supply is usually provided through external cables or heavy batteries that additionally limit the user mobility. The next generation of HMI should include innovative features as high integration levels of sensors and electric connections with the fabric, energetic autonomy, good wearability and comfort of use, wireless communication and low cost.

In this paper, the design, prototyping and experimental validation of a HMI glove are presented. The device communicates by means of an optical port (LED) and integrates an energy harvesting system able to increase the battery charge with the fingers motion. The electro-mechanical conversion properties of the transducers were preliminary validated. Then, the electric power of the harvesting system installed to the glove was measured during the fingers opening-closing motion. The battery capacitance (160 mAh) can supply the optical port continuously for approximately 104 hours (including additional 11% power consumption due to circuitry losses). The energetic benefit of energy harvester on the battery lifetime is inversely proportional to the activation time of the optical emitter. In most applications, the optical port is active for 1 to 5% of the time, corresponding to battery lifetime increasing between about 14% and 70% [9].

2. Device description

The HMI glove, named GoldFinger, is represented in Fig. 1. The main features of the design are the energetic efficiency of the system, the integration of components (piezoelectric transducers, electric conductors and electric controls), the miniaturization of electronic components (including the power management circuit and the storage battery). An aluminum case situated on the back side of the glove is used to protect the electric parts against dust, wear and impacts. This kind of package is characterized by small dimension (55x46x10 mm$^3$), strength and lightness. The technical fabric of the glove provides elasticity and resistance to wear and water. Fabric-embedded wires are used to electrically connect the piezoelectric transducers to the circuit. The conductive wires (Fabrickit, electrical resistance = 0.3 Ω/m) have almost the same flexural deformability of the fabric.

![Functional components of GoldFinger.](image)
The optical port is controlled by the user through an electric switch integrated in the glove and made with conductive metalized nylon fabric (Statex, surface resistance < 0.02 Ω, abrasion resistance = 500,000 cycles, temperature range = –30 / +90 °C, thickness = 0.1 mm, specific mass = 77 g/m²), instead of using discrete electrical components. The conductive fabric is composed of a nylon support covered by three Sn/Cu/Ag layers. The optical port is made with a high efficiency LED L-383IDT (Kingbright, size = 9.6x5x2.5 mm³, forward voltage = 1.7 V, forward current = 2.5 mA, wavelength = 627 nm, capacitance = 15 pF).

The functional scheme of the device is reported in Fig. 2. The hand analog command sequence is sent to the receiver through the light emitter mounted on the fingertip. The optical receiver is an analog-to-digital converter (ADC) represented by a camera. Through the software interface, the light path and light on/off flashing sequence is tracked and converted in Cartesian coordinates and the microcontroller is programmed accordingly.

Figure 2. The device workflow.

3. Biomechanical energy harvesting
The harvesting system is made with four couples of piezoelectric transducers (Physik Instrumente, PIC252) integrated into the fabric in correspondence with the fingers joints, and in particular to the proximal-interphalangeal (PIP) joints of the 2-5 fingers. The transducer components are reported in Fig. 3a: they include the piezoelectric foil with two metalized surfaces connected to the electrodes and the polymeric package. The properties of the transducer are reported in Tab. 1. Laboratory tests also revealed good conversion efficiency and reliability under repetitive load cycles. The control circuit used to manage the harvested power and to control the optical port is reported in Fig. 3b.

4. Software interface
The software interface works in two steps, as shown in Fig. 2. In Step 1, the LED position is detected by filtering the environmental light and by selectively tracking the wavelength corresponding to the LED color. Depending to the light path and to the on/off switching, the command message is composed and converted to Cartesian coordinates. The analog optical instructions are then translated by the software to codified logic instructions that have been previously associated with the gestures. In
Step 2, the real-time programming of the microcontroller is provided by modifying the parameters of the flow of execution instructions.

The area of detectable movements is approximately 1 m$^2$, situated in the range 0.5-1 m from the receiver objective. The optical reader used is a camera that can record images in color (i.e., 24-bit RGB with 3 channels and 8 bits/channel) at 15 fps with a resolution of 640x480 dpi. Figure 4 shows the image captured by the camera (left) and the digitally processed image generated by the interface software during Step 1 (right). The actual position and status (i.e., on/off) of the light emitter is detected and saved by two Cartesian coordinates.

![Figure 4](image)

**Figure 4.** Software interface for light tracking and analog-to-digital commands conversion.

5. **Validation tests**

The electro-mechanical properties of the piezo transducers were preliminary validated in the cantilever mode by using a TIRA TV51120 electromechanical shaker. The output current and power were measured at variable resistance, and the resistance $R_{\text{opt}} = 216$ kΩ maximizing the power is obtained.

The following measurements were conducted with the transducers applied to the glove in their final configuration; more in detail, two transducers are coupled in opposite configuration for each finger to increase the output current. Finally, the glove has been equipped with four transducer couples and is then worn to run the tests, consisting in opening-closing fingers for 10 s. The output parameters of the open circuit voltage ($V_0$) and of voltage difference ($V$) across $R_{\text{opt}}$ are measured and stored during the fingers motion. The average instant power generated by the glove is

$$P_{\text{inst}}(t) = \frac{P_{\text{cumul}}(t)}{t_{\text{sam}}} = \sum_{T} P(T) \cdot \Delta t,$$

where $P_{\text{cumul}}$ is the cumulative power obtained as the sum of the instant power over time with $t_s$ the sampling times. The measured values of the cumulative power and of the average instant power are reported in Fig. 5.

![Figure 5](image)

**Figure 5.** Measured total output power generated by the glove (a) and average instant power (b).
From the experimental results, the total average power generated is 31.9 µW (6.6, 8.5, 8.5 and 8.3 µW for each finger, respectively). By considering the power consumption of the optical port (4.25 mW), the operative duty cycle of the system is 133.2. The power dissipated by the conditioning and leveling circuit is about 0.5 mW. Then, by including all of the sources of electric power consumption, the system duty cycle is approximately 146.5. With the reported duty cycle and without using batteries, the light emitter could be active for 30 s per hour. Then, the energetic performance of the harvester is suitable for increasing the battery charge and/or reducing the battery size. In particular, by using the GoldFinger glove instead of the gloves normally worn by operators, the lifetime of the battery of the GoldFinger is increased by the percentage reported in Tab. 2.

**Table 1.** Properties of piezoelectric transducers.

| Property               | Value | Dimension |
|------------------------|-------|-----------|
| length                 | 61    | mm        |
| width                  | 35    | mm        |
| thickness              | 0.4   | mm        |
| bending radius          | 12    | mm        |
| piezo layer thickness   | 100   | µm        |
| Young’s modulus         | 16.4  | GPa       |
| capacitance            | 150   | nF        |
| temperature range       | -20°F/+180°F | °C     |
| mass                   | 2.1   | g         |

**Table 2.** Duty cycle as function of the optical port activation.

| Optical port active time period (%) | System lifetime (hours) | Lifetime increase (%) |
|-------------------------------------|-------------------------|-----------------------|
| 1                                   | Battery only            | Battery and energy harvesters |
| 5                                   | 1047                    | 34450                 | 69.6 |
| 10                                  | 1047                    | 1126                  | 6.96 |
| 20                                  | 523.6                   | 542.5                 | 3.48 |
| 50                                  | 209.4                   | 212.4                 | 1.39 |
| 100                                 | 104.7                   | 105.5                 | 0.70 |

6. Conclusions

GoldFinger demonstrates the applicability of biomechanical energy harvesters to HMI and the possibility to increase the battery lifetime through the conversion of biomechanical energy. The prototype, characterized by small power consumption, small, compact and fabric-integrated components, is also improved by the wireless communication of the optical port. The wearability, comfort, low stiffness to bending and small battery size can sensitively increase the added value of this kind of devices for the future. The overall duty cycle provided by the integrated piezoelectric transducer is approximately 146.5 and it is able to increase the battery lifetime between about 14% and 70% in those applications where the optical port is used between 1% and 5% of the time.

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