

Development of a Wirelessly-Powered Wearable System for Finger Tracking

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Abstract—In this paper, the development of a system capable of tracking finger motion is presented. The proposed wearable tracking unit is placed on the finger and it is wirelessly powered without using cables or batteries, thus enhancing freedom of movement. The system is comprised by two sections: a measurement unit and a wireless power transfer apparatus. The measurement unit consists of an electronic board able to measure, acquire and transmit sensors signals; a stretch sensor and an inertial measurement unit are integrated on the measurement unit. Furthermore, the wireless power transfer apparatus is implemented by means of inductively-coupled resonant circuits. A prototype of the developed system is characterized by experimental tests. Results show the feasibility of the proposed approach. The measuring system can track finger movement with a sample rate of 30 Hz, while the wireless power transfer system demonstrates the capability of transferring 67.72 mW, necessary to power the measurement unit, at a maximum distance of about 8 cm.

Keywords — wireless power transfer, finger tracking, stretch sensor

I. INTRODUCTION

Tracking the motion of a human subject's hands and fingers is required for numerous applications in the biomedical, industrial, and commercial fields [1]. In particular, it can be used for implementing human-machine interfaces, robotic telemanipulation systems, augmented reality, and rehabilitation technologies [2]. Several methods have been proposed for this purpose, including camera-based optical systems [3], magnetic-field localization solutions [4], and inertial measurement units (IMUs) [5].

Camera-based systems provide accurate tracking information that is suitable for many practical applications. However, their main drawback is the requirement of line-of-sight and they typically maintain performance only in controlled illumination conditions. Short-range magnetic tracking systems, based on artificially-generated AC magnetic fields, have been proposed to overcome the requirement for line-of-sight conditions [6]. Nevertheless, such systems are affected by magnetic-field disturbances due to ferromagnetic and conductive materials in the environment [7].

On the other hand, systems based on data gloves are heavily used both in industrial and commercial contexts [8]. These systems are composed by a wearable device, usually equipped with inertial modules and stretch sensors applied near the interphalangeal joints. Data gloves-based systems

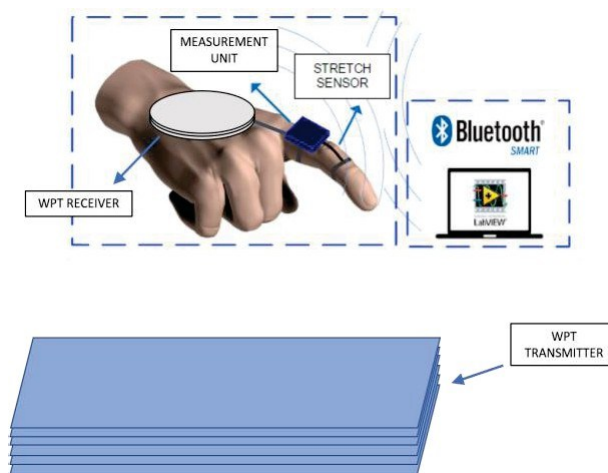


Fig. 1 – Architecture of the proposed system, showing the measurement unit and stretch sensor that are powered by a wireless power transfer subsystem.

permit to collect more reliable data than optical systems [9]. However, they can result in physical constraints for some movements, due to the presence of wires used for signaling and powering purposes. Conversely, wireless solutions avoid such constraints. To transfer data, protocols for personal area networking such as Bluetooth Low Energy are commonly employed. Besides, to transfer power, wireless power transfer (WPT) systems are widely investigated in the literature. In particular, inductive coupling of resonators is the preferred technology for developing medium-range WPT links [10]. A measurement methodology for characterizing WPT systems in terms of the amount of power delivered to the load and the efficiency is presented in [11].

The measuring system proposed in this paper is wearable, powered by a WPT device, and able to track the hand motions by means of a stretch sensor and an IMU. The measurement unit is integrated in small modules that can be applied to each finger autonomously. According to every specific need and usage case, the minimum number of modules can be used to reduce physical constraints. As an example, to control a pointer on a screen it is sufficient to track a single finger with one module. Instead, to manipulate physical or virtual objects, multiple modules can be worn on different fingers. In the following sections, the architecture of the proposed system is presented and experimentally characterized using a realized prototype.

II. ARCHITECTURE OF THE PROPOSED SYSTEM

The measuring system (shown in the top portion of Figure 1) is composed by two main sections. The first is represented by the measurement unit. The custom-developed main electronic board is equipped with all the peripherals and sensors needed to carry out the measurement operation and to transmit the retrieved data wirelessly. The second section is composed by a readout unit that receives and interprets the finger movements. In our implementation it is composed by a personal computer with Bluetooth Low Energy module and LabVIEW Virtual Instrument program. Furthermore, a WPT subsystem is used to provide power to the measurement unit. This subsystem is implemented using inductive coupling of LC resonant circuits. In the following subsections, the measurement unit and the WPT subsystem are described in detail.

A. Measurement Unit

Figure 2 reports the block diagram of the measurement unit.

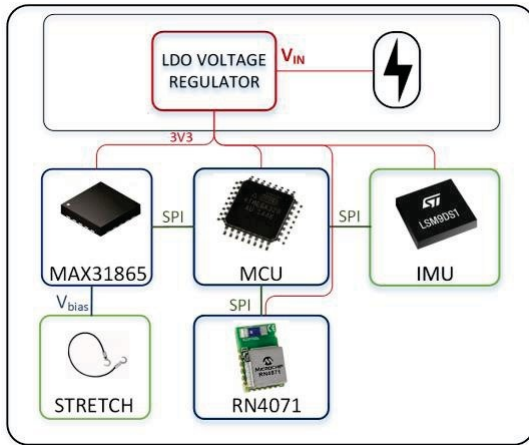


Fig. 2 – Block diagram of the measurement unit.

The core of the unit is an ATmega328P microcontroller, this device controls and supervises all the operations needed for the measuring process (peripheral diagnostics, sensors reading and wireless transmitting). The microcontroller is chosen for its low-power capabilities (picoPower technology from Atmel). Most of the on-board peripherals can be selectively turned off when not in use to reduce the overall power consumption. The chosen package is the smallest available (ML-32 pin, 5 x 5 mm).

The 3-D orientation of the board is retrieved through an IMU (LSM9DS1, produced by STMicroelectronics) which includes accelerometer, gyroscope and magnetometer. Since the PCB board is bound to the first phalanx, the IMU is used to measure the finger position and orientation. The angle between the first and the second phalanx is measured by a stretch sensor (from Image Scientific,) made by a conductive rubber that varies its resistance depending on the stress to which it is subjected. To couple this filament to the dorsal part of the finger, a pair of fabric rings were produced. The length of the stretch sensor can be chosen according to the specific length of the phalanges. The filament has a nominal resistance, in absence of stress, of about 395 Ω /cm. The stretch sensor resistance is measured by a specific integrated circuit, MAX31865 from Maxim Integrated.

The wireless communication channel is provided by a Bluetooth Low-Energy (BLE) module, RN4871 from Microchip, which guarantees low-power functionalities. The GATT roles (Generic Attribute Profile) are used to exchange data in accordance to the BLE protocol [12]; on the server side (measurement unit) four custom characteristics are defined to store sensors data from IMU and stretch sensor. At each measuring cycle, the microcontroller updates the data in the characteristics. After a Bluetooth connection between the two modules is established, on the client side (computer program) a subscription to the cited characteristics is done and the notification function is activated. Every time the microcontroller updates the data on the server side, they are automatically transferred to the client module. The update rate of the measurement unit is 30 Hz. The data transmission lasts about 1.7 ms, then the module reads the sensors for the following 31.1 ms. The board can be supplied directly with a stable voltage of 3.3 V or with an unregulated voltage from 3.45 V to 24 V thanks to an on-board low-dropout (LDO) voltage regulator (TPS71533, Texas Instruments). The average power consumption of the measurement unit is 67.72 mW. In Figure 3, the top and the bottom layer of the measurement unit are shown. The actual size of the board is 25 x 35 mm.

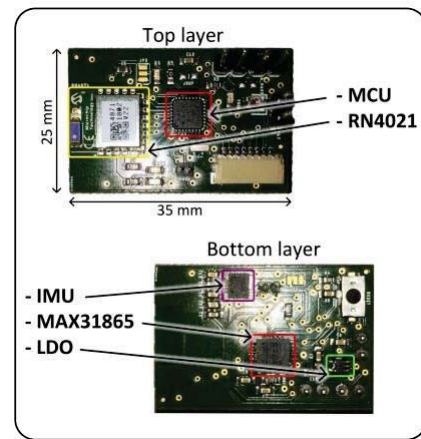


Fig. 3 – Representation of the fabricated PCB with the main components highlighted.

B. WPT Subsystem

The architecture of the developed WPT subsystem is shown in Figure 4.

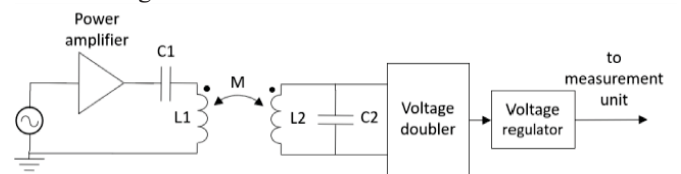


Fig. 4 – Block diagram of the WPT subsystem, based on series-parallel tuned resonant circuits. The WPT subsystem is used to provide power supply to the measurement unit.

The core of this subsystem is comprised of two mutually-coupled inductors, i.e. L_1 and L_2 . The custom-made transmitter coil L_1 is comprised of 15 turns of enameled copper wire, which is wound around a 25 cm x 20 cm wooden rectangular support. The receiver coil, L_2 , is a commercially-available coil, the WE 760308111, having an

inductance of 6.3 μ H, attached to a 5 cm-side square ferrite support. The dimension of the secondary coil is compatible with the usage on the back of the hand in the position illustrated in Fig. 1. The transmitter and receiver coils are connected to lumped capacitors to implement a series and parallel resonator, respectively. The resonators are tuned to the same resonance frequency of 108 kHz.

The transmitter resonator is driven by a sinusoidal signal at the resonant frequency, buffered by a power amplifier based on the OPA541 operational amplifier connected in the voltage-follower configuration. The receiver resonator is connected to a Greinacher voltage doubler circuit that converts the sinusoidal signal to a DC level. Then, a voltage regulator provides the required voltage of 3.3 V to the measurement unit.

III. EXPERIMENTAL TESTS

A. Standalone finger tracking system

A series of tests were performed on the measuring system to evaluate the overall functionalities. The first test is aimed at evaluating the behavior of the sensors with which the system is equipped. In the first test, the IMU has been used as an inclinometer to retrieve the pitch angle θ and roll angle Φ starting from the acceleration measured on the three axes. The values of the angles are obtained through the following equations:

$$\theta = \text{atan}\left(\frac{G_y}{\sqrt{G_x^2 + G_z^2}}\right) \quad (1)$$

$$\Phi = \left(\frac{-G_x}{G_z}\right) \quad (2)$$

The device has been bounded to a mechanical structure by which a known angle can be imposed. The comparison between the data retrieved from the accelerometer and the imposed known angle are arranged in Figure 5. The calculated coefficients of variation (R^2) are respectively 0,9985 and 0,9996 for the roll and pitch angles.

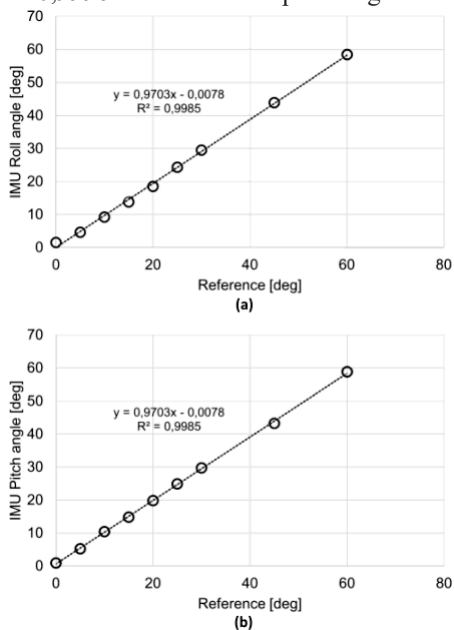


Fig. 5 – Measured inclination in terms of the reference with standard deviation for roll (a) and pitch (b) angles.

The second test performed is a characterization of the stretch sensor. The setup includes a digital multimeter HP34401A to evaluate the sensor resistance and an ARAMIS optical system (by GOM) that performs Digital Image Correlation (DIC). This device recognizes specific pattern on the tracked object surface and calculates the reciprocal distances between the points. When the sensor is stretched, ARAMIS system can calculate the overall lengthening. As it is reported in Figure 6 the sensor is characterized by a good linearity in the strain interval 0 – 10 %, the calculated gauge factor is 4.73.

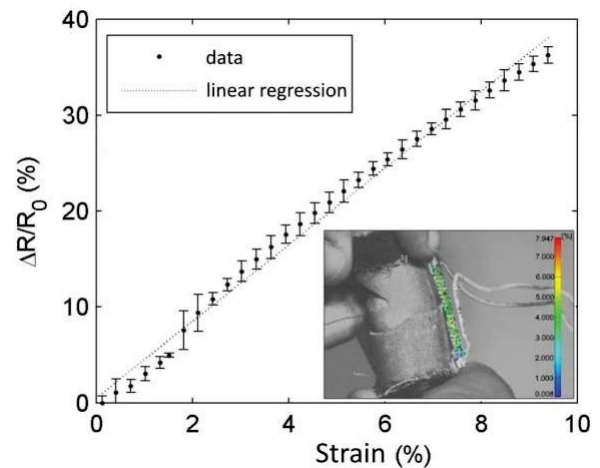


Fig. 6 – Stretch sensor characterization in the strain interval 0 – 10% ($R_0 = 300 \Omega$). The detail shows the ARAMIS GOM output.

A second set of tests was done to evaluate the capabilities of the system to recognize different objects when they are grabbed. Two different measurement units were applied to the index and middle fingers. Later, four different objects were grabbed and released (in the same way) for about 20 times. The results are reported in Figure 7. As the adopted objects have different diameters, they produce different combinations of flexion angles in the two fingers which is reflected in different resistance values. Since these combinations are nearly non-overlapping, the system can recognize the objects in the predefined set.

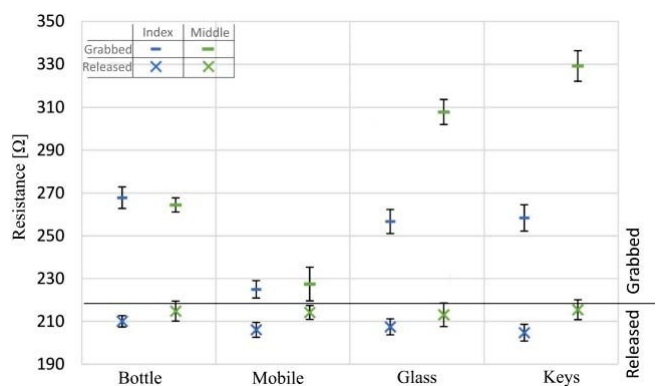


Fig. 7 – Resistance values for different grabbed objects retrieved from two fingers (index and middle finger).

B. Wireless Power Transfer tests

Further tests have been carried out to verify the compatibility between the WPT system and the measurement system. The board was connected directly to the 3.3 V output of the WPT system, bypassing the onboard LDO voltage regulator. The WPT system was turned on with a voltage supply of the power amplifier of $V_{DC} = \pm 12$ V, a zero-mean sinusoidal input signal with peak-to-peak amplitude $V_{pp} = 15.34$ V and frequency $f = 108.7$ kHz. The current in the transmitting coil was 1.088 A. The measurement unit was powered, connected to the readout unit in full measurement and transmission states. The test aimed to verify the maximum distance at which the WPT was able to supply the measuring system. Accordingly, the emitter surface has been ideally divided in nine areas and the output voltage (before the step-down converter) has been measured at different vertical distances. The test was repeated also for three different inclinations φ of the receiving coil ($\varphi = 0^\circ$, $\varphi = 30^\circ$, $\varphi = 45^\circ$). The setup scheme is reported in Figure 8.

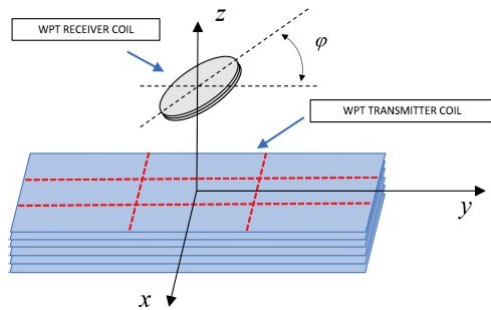


Fig. 8 - Setup of the WPT performance test. The dashed red lines denote the nine areas in which the surface has been divided.

As shown in Figure 9, in the first case ($\varphi = 0^\circ$), with a misalignment of 0° , the maximum distance reachable with the system in full operation mode is 8 cm, where the system was working correctly in all the nine areas. While increasing the distance to 9 cm, the device does not power on in any area.

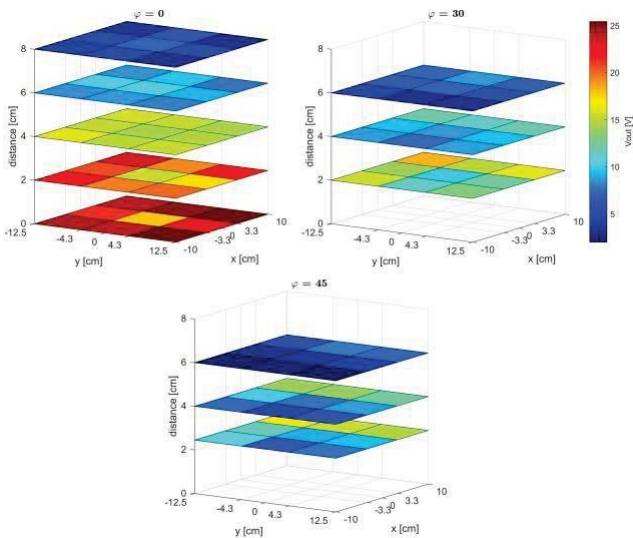


Fig. 9 – Output voltage of the voltage doubler in the WPT circuit at several positions above the transmitting coil.

In the cases with an angle formed between the two coils respectively of $\varphi = 30^\circ$ and $\varphi = 45^\circ$, the maximum distance decreases to about 6 cm. At this distance the system works in almost all areas except two in which the magnetic field is too weak. In both these areas the measurement board reaches the brownout limit and stops the transmission to avoid sending erroneous data.

To analyze the magnetic field radiated from the WPT transmitter coil, a simplified model has been modelled and simulated by a fullwave environment [14] adopting the finite element method (FEM) numerical simulator. The coil has been simulated as a single current loop with the profile of the real one, with constant current intensity of 1.088 A multiplied by 15, which is the number of copper wire turns, resulting in a total current of 16.32 A. The simulation has been performed at the operating frequency of 108 kHz. The B field RMS intensity has been evaluated along two different paths that cross the rectangular coil perpendicular to the long and short sides and intersect in the center of the coil. The two paths are evaluated at two different heights that shows the fast decaying of the field intensity. The results of the simulation, shown in Figures 10 – 12, have been compared with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) limits for the safety exposure of the public and workers at the frequency of 108 kHz [15].

We have observed that the emitted field B is compliant with the ICNIRP for workers exposure limit, which is $100 \mu\text{T}$ in the frequency range 3 kHz - 10 MHz, when the position of the receiver is higher than 40 mm from the coil plane.

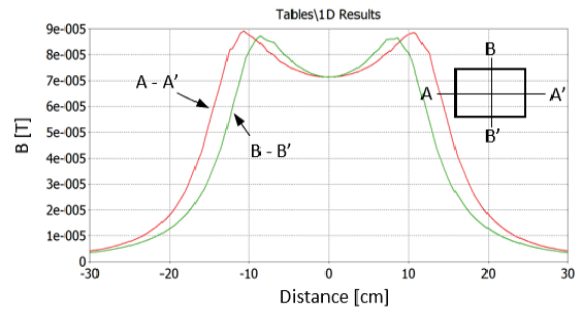


Fig. 10 - Simulated B field values on the paths at 40 mm height above the transmitting coil.

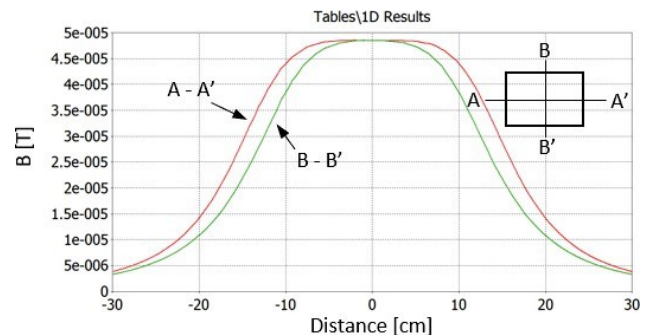


Fig. 11 - Simulated B field values on the path at 80 mm height above the transmitting coil.

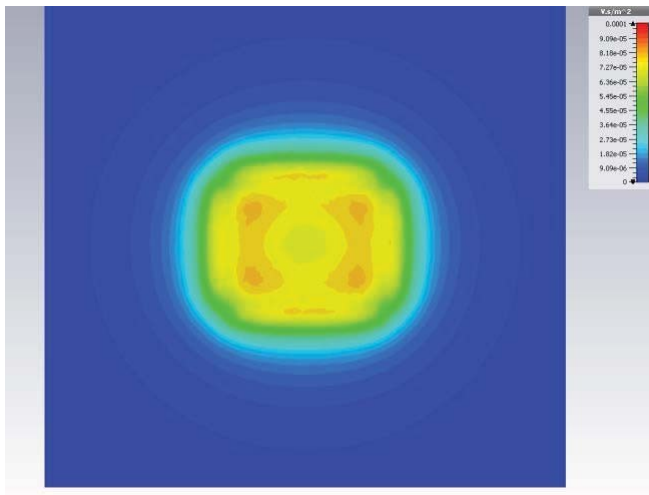


Fig. 12 - Simulated B field at 40 mm height above the coil.

IV. CONCLUSION

A research activity focused on the development of a wearable and wirelessly-powered finger tracking system was presented. The system architecture is based on a measurement unit worn on the finger and a wireless power transfer subsystem. Experimental tests performed on a prototype show that the developed system is able to track the extension and flexion of a finger and to transmit data via Bluetooth with an update rate of 30 Hz. The wireless power transfer subsystem is capable of supplying 67.62 mW to the measurement unit within an 8 cm operational range, which is suitable for several short-range finger tracking scenarios. To improve the performance of the wireless power transfer subsystem, future work should explore the usage of a receiving coil with a higher quality factor and the increase in the power of the WPT transmitter. Furthermore, the application of a supercapacitor or small battery in the measurement unit should be tested. Finally, the modification of the geometry of the WPT transmitting coil should be studied, to better cover the operational volume required by specific applications.

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REFERENCES

- [1] D. De Carli, E. Hohert, C. Parker, S. Zoghbi, S. Leonard, E. Croft and A. Bicchi, "Measuring intent in human-robot cooperative manipulation", 2009 IEEE International Workshop on Haptic Audio visual Environments and Games, 2009.
- [2] M. Zabri Abu Bakar, R. Samad, D. Pebrianti, M. Mustafa and N. Abdullah, "Computer vision-based hand deviation exercise for rehabilitation", 2015 IEEE International Conference on Control System, Computing and Engineering (ICCSCE), 2015.
- [3] T. Koivukangas and J. Katisko, "On the comparison of the accuracies of optical tracking and EMTS modalities of surgical navigators", 2010 5th Cairo International Biomedical Engineering Conference, 2010.
- [4] V. Pasku et al., "Magnetic Field-Based Positioning Systems," in IEEE Communications Surveys & Tutorials, vol. 19, no. 3, pp. 2003-2017, thirdquarter 2017.
- [5] A. H. J. Moreira, S. Queirós, J. Fonseca, P. L. Rodrigues, N. F. Rodrigues and J. L. Vilaca, "Real-time hand tracking for rehabilitation and character animation," 2014 IEEE 3rd International Conference on Serious Games and Applications for Health (SeGAH), Rio de Janeiro, 2014, pp. 1-8.
- [6] A. Moschitta, A. De Angelis, M. Dionigi and P. Carbone, "Analysis of simultaneous 3D positioning and attitude estimation of a planar coil using inductive coupling," 2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Turin, 2017.
- [7] V. Pasku, A. De Angelis, M. Dionigi, A. Moschitta, G. De Angelis and P. Carbone, "Analysis of Nonideal Effects and Performance in Magnetic Positioning Systems," in IEEE Transactions on Instrumentation and Measurement, vol. 65, no. 12, pp. 2816-2827, Dec. 2016.
- [8] L. Jhang, C. Santiago and C. Chiu, "Multi-sensor based glove control of an industrial mobile robot arm", 2017 International Automatic Control Conference (CACS), 2017.
- [9] B. Fang, F. Sun, H. Liu and C. Liu, "3D human gesture capturing and recognition by the IMMU-based data glove", Neurocomputing, vol. 277, pp. 198-207, 2018.
- [10] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljagic, "Wireless power transfer via strongly coupled magnetic resonances," Science, vol. 317, no. 5834, pp. 83-86, 2007.
- [11] A. De Angelis, M. Dionigi, P. Carbone and M. Mongiardo, "Characterization and performance measurements of mid-range wireless power transfer links," 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings (I2MTC), Taipei, 2016, pp. 1-5.
- [12] R. Heydon, Bluetooth Low Energy: The Developer's Handbook. Upper Saddle River, NJ: Prentice Hall, 2014.
- [13] Images Scientific Instruments Inc., «Flexible Stretch Sensors», <http://www.imagesco.com/sensors/stretch.pdf>.
- [14] CST microwave Studio, www.cst.com
- [15] International Commission on Non Ionizing Radiation Protection, "Guideline for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz to 100 kHz)", Health Physics, vol. 99, no 6, dec 2010.