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# Evaluation of NFC-Enabled devices for heterogeneous Wearable Biomedical Application

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***Abstract*—Biomedical systems that aim at monitoring parameters over a long period of time will require non-invasive wearable devices. A wide range of applications, including continuous workers monitoring or daily monitoring of patients, is expected to exploit wearable devices, each one characterized by different requirements. Such devices will adopt a design that minimizes discomfort and does not limit users' mobility to allow round-the-clock wearability. In order to ensure a significant reduction in the size of wearable devices, the next generation of this technology will need no batteries or at least very small ones. In this paper we analyze the use of Near Field Communication (NFC) for ultra-low-power communication in wearable devices for biomedical applications. Our goal is to verify whether NFC technology can support the heterogeneous requirements of different biomedical use-cases. For this purpose, we will first provide a review of the current state of the art in NFC-Enabled solutions. Then, we will evaluate NFC capabilities through a set of experiments, using off-the-shelf devices. We will pose particular focus on the energy harvesting capabilities to evaluate the feasibility of designing battery-less devices. Our results show that NFC adoption in different biomedical applications is possible, as they can ensure proper reading frequency and distance. Finally, we further demonstrate this through a proof-of-concept implementation: an NFC-based sensorized glove for work safety that is able to monitor the external temperature in a continuous manner.**

***Keywords—Near Field Communication, Biomedical applications, continuous monitoring.***

## I. INTRODUCTION

The most recent improvements in computing and communication technologies have allowed the definition and development of a new generation of miniaturized embedded devices. Following the lines drawn by the Internet of Things (IoT) paradigm, these devices can be integrated seamlessly into the Internet, thus shifting to a new Internet of Nano Things including the majority of physical objects around us [1].

The extreme reduction in size and weight of those connected devices enabled the creation of commercial devices, such as smartwatches, fit bands or textile integrated sensors. Such devices can be worn by humans for long periods without, or with minimal, discomfort, thus enabling uninterrupted monitoring in many applications. *Health care* are a consolidated market as many applications already exploit wearable devices to sense and process biomedical signals to track the general wellbeing by monitoring physiological parameters like heart rate or temperature, during daily activities. On the other side, *Smart industry* is a market in rapid expansion: industrial applications are exploiting wearable devices [2] specifically designed with the goal of improving workers' safety, for instance by monitoring workers movements and alerting them when entering in a dangerous area. In addition to safety, wearable devices are currently used to improve human-machine interactions as they can be exploited to create a simpler and more natural interface, e.g. by employing gesture recognition.

The boundaries of wearable technology are expected to be pushed even further by future technological improvements, possibly leading to a level of miniaturization such that implantable non-invasive devices could be introduced to the market. In this perspective, subcutaneous devices would need to be powered by energy-harvesting sources, e.g. heat of the human body, to be able to work without batteries. As a result, a more accurate healthcare monitoring of daily activities will be then possible [3].

Near Field Communication (NFC) is expected to play a crucial role in this context as enabling technology to create low-cost and energy efficient sensors [4]. NFC is a short-range communication technology that can ensure two-way interaction between devices in short distance with minimum energy consumption. The power consumption, in particular, is minimal so it enables the design of devices based on energy harvesting, i.e. devices without batteries powered by external sources, e.g. body thermal energy or the energy scavenged from the NFC wireless signal itself.

In this paper, we present an analysis of NFC technology in order to assess whether it is ready to support the heterogeneous requirements of different biomedical use-cases. To this aim, we first highlight the current status of NFC-enabled solutions for biomedical applications by reviewing the literature to derive the features of different available. Then we focus on two specific biomedical applications, namely smart industry and smart health, and for each one we derive a set of expected requirements. Consequently, we carry out a performance evaluation of the off-the-shelf NFC devices currently available in the market by means of real experiments in order to assess if the technology is ready to meet the requirements of biomedical applications. In our experiments, we have considered commercial NFC devices powered through energy harvesting to evaluate their battery-less capabilities. Our results show that NFC, even in the battery-less configuration, can ensure the proper communication frequency and distance for both smart industry and smart health use-cases. To demonstrate this possibility in the smart industry application, we built a proof-of-concept prototype for work safety monitoring. The prototype is a sensorized glove with an NFC temperature sensor that measures continuously the temperature of worker's hand to potentially detect dangerous situations.

This study is an extended version of a conference paper [5]. In particular, this work extends our conference

TABLE 1 COMPARISON OF NFC-ENABLE SENSORS

| Reference | Type of sensor | Passive | Flexibility | Size | Energy Consumption | Read Distance | Standard |
|---|---|---|---|---|---|---|---|
| **[20]** | Temperature, Humidity | Y | N | 180x50 mm | 3 mW | 21 mm | ISO 15693 |
| **[21]** | Temperature, 3-axis acceleration | Y* | N | 85.6x53.98x4.8 mm | 6.1 mW | 5-12 mm | ISO 14443 |
| **[22]** | Temperature | Y | N | 25x25mm | - | 20mm | - |
| **[23]** | Temperature | Y* | Y | 40x25 mm | - | 100mm | ISO 15693 |
| **[24]** | pH, Temperature | Y | N | 60x30mm | 5 mW | - | - |
| **[25]** | pH | Y | Y | - | - | 40mm | ISO 15693 |
| **[26]** | NaCl concentration | Y | Y | 25x60mm | - | - | ISO 15693 |
| **[27]** | Multigas (oxygen, carbon dioxide, ammonia) | Y | Y | 80x70 mm | 8.5 mW | - | ISO 15693 |
| **[28][29]** | Color sensor, pH | Y | N | 90x50 mm | 9.9 mW | 21 mm | ISO 15693 |

contribution by introducing a detailed state of the art review, by enriching the set of experiments and by presenting additional results obtained through a proof-of-concept implementation of a biomedical application that exploits NFC. The experimental section, in particular, has been extended by considering additional communication scenarios that complete our analysis.

The paper is structured as follows. In Section II. we present some background on wearable biomedical applications while in Section III we have analyzed the different type of NFC-Enable sensors. Section IV. presents the two use-cases we consider in this paper, namely Smart Factory and Smart Health. Then, in Section V. we analyze the requirements of each application in terms of device and communication capabilities and in Section VI. we present the results of our experiments and we analyze them with respect to the requirements highlighted in Section V. Finally, in Section VII. we show our prototype, a sensorized glove for temperature monitoring in work environments and in Section VIII we draw our conclusions about this preliminary study.

## II. Background

Smart wearable devices can monitor the wearer and/or his/her surrounding environment parameters. The sensed data can be stored, transmitted and locally/remotely elaborated to provide feedback to the wearer or to others (caregiver, physician, etc.). Wearable interfaces and smart textiles have been developed to enable continuous long-term monitoring of health (heart rate, respiration, biomarkers), physical performance (bodily movements, gait analysis, activity tracking, rehabilitation), as well for enabling human machine interaction [6]-[9]. Despite the large amount of research activities already carried out, smart wearables solutions failed to reach the expected potential. The recently published European Commission report on *smart wearables* has identified technological and non-technological barriers that have to be addressed to enable the uptake of such technologies [10],[11]. The main technological barrier has been identified in the integration of silicon-based (hard) electronic components into textiles or other conformable substrates. Indeed, each wearable sensor, even if developed in a flexible/stretchable/conformable fashion (e.g. breathing [12],[13] and posture [14]-[16] textile sensors), has to be connected to dedicated hardware that - at least - power the sensor and amplify, convert and transmit the acquired data. In terms of transmission protocols, Bluetooth low energy is the reference technology in wearable healthcare systems, as it is crucial in reducing the device dimensions and increasing the battery life [17]-[19]. As the common trend is to “hide” and “embed” sensing functionalities into daily life tools (e.g. watches, bracelets, garments), the way a sensor is powered poses particular problems. Even by exploiting low power transmission protocols such as Bluetooth low energy, sensor powering leads to several limitations: batteries in contact with the body, recharging of many devices, safety and wash-ability.

NFC is a standards-based short-range wireless connectivity technology that enables communication between devices using the 13.56MHz RFID band. Nowadays an increasing number of smartphones are equipped with NFC and

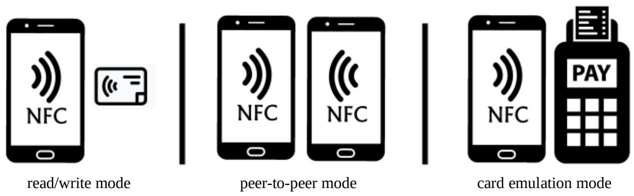


Fig. 1 From left to right, read/write mode, peer-to-peer mode, card emulation mode

the number of devices provided with NFC is expected to increase. In NFC communication there are two different components, the Tags and the Readers, which differ in the features and functions they perform. The Tags are passive devices with reduced dimensions that have the task of sharing information with the reader when in communication range. Readers are active devices that are able to read and write to passive nodes and usually have greater computing power and continuous power. The communication among Tag and Reader can exploit an energy-harvesting mode, which allows the Tag to operate in a battery less mode.

An NFC device can operate in the following three modes, shown in the Fig. 1. The first is the “reader/writer” mode in which the device operates as a reader that is able to communicate with tags or cards. An example of this use case is a device that reads a smart business cards to open a website, whose address is memorized on the tag. The second is the “Peer-to-Peer” mode in which two NFC devices communicates directly to exchange data. This mode is used for instance to easily exchange contact data between smartphones. The last one is the “Card Emulation” mode, in which the NFC device operates like a tag (e.g. a card) and communicates with another reader device. Typical use cases are the emulation of credit cards to perform money transactions or the emulation of tickets for public transport.

## III. Literature review

The technological progress and the introduction of NFC integrated circuits on the market have led to the possibility of developing low-cost portable battery-free sensors. This progress combined with the increase in the number of mobile devices equipped with NFC has created great interest in the scientific community. Consequently, different types of NFC-based sensors have been proposed in literature. In Table 1 we report the most significant research activities grouped by the type of sensor considered. For each work we report the following information: (i) whether the sensor is completely passive or semi-passive[1]; (ii) whether the sensor includes a flexible design; (iii) the dimensions of the board; (iv) an estimate of the energy consumed; (v) the maximum reading distance; (vi) the NFC standard adopted in the design. We focus on the above-mentioned parameters, because each biomedical use case requires a different set of characteristics from the sensor.

The authors of [20] created an NFC sensor that measures temperature and relative humidity using only the power obtained from the magnetic coupling received from a smartphone. The proposed system measures these parameters in a distance range between 8 and 21 mm depending on the smartphone model. In [21] the authors developed a programmable NFC platform, NFC-WISP. This platform can store energy in a tiny battery, which can be used to make measurements even when the sensor node is not in proximity of the reader. The authors configured this platform with an E-ink, a 3D accelerometer and a temperature sensor to achieve a possible monitoring application, e.g. in food transport at controlled temperatures. In [22], an implantable battery-less temperature sensor for continuous reading of external devices is proposed. This sensor has small size (25mm × 25mm) and the antenna is printed on a thin biocompatible plastic substrate to be planted during surgical operations on patients. In [23] a bio-patch to monitor temperature through NFC is presented. The system is designed to have a 1.5V tiny battery to use when the NFC reader is not in the communication range to save data in memory. In order to better adapt to the human body during installation, the prototype was implemented using a flexible substrate. To eliminate possible contact with the user's skin, this bio-patch is encapsulated in the gauze and installed with sanitary adhesive to ensure that it has good contact with the skin. The sensor allows the collection of data for 24 hours taking a sample every 15 minutes. In [24] the authors proposed a battery less chronic wound monitoring system powered and readable through NFC. To monitor chronic wounds flexible pH sensor and a negative temperature coefficient thermistor as a temperature sensor, which are attached directly on the dressing, are used. In [25],the manufacture of a battery-free and flexible pH sensor for wound monitoring is shown. This sensor is designed to have a good sensitivity in the physiological relevant range between pH 4 and pH 10, with a response in less than 28 seconds after the pH is increased or decreased. This sensor is also designed to be extended with other potentiometric sensors that can be used to measure the variation of ions, such as sodium and potassium relevant in the context of wounds. In [26], the authors demonstrate the possibility of creating a flexible patch NFC adhesive sensor for monitoring sweat biomarkers with the size of a typical band-aid. This sensor can read a dynamic range of 20 mM to 70 mM and 96% accuracy in the detection of $Na^+$ concentration. In [27], a multiple gas sensing NFC tag is developed. This device is completely passive and can measure different parameters like oxygen, carbon dioxide, ammonia, relative humidity or temperature. The measurements can be read through a smartphone and the collected data is shown in a smartphone application with an update rate below 1 s. This tag can be exploited in many applications where it is important to monitor gases in the atmosphere such as in dangerous workplaces. In [28], the authors present a color-based system to classify fruit ripening using a battery-free NFC tag and a commercial smartphone. The system is based on low-cost commercial integrated circuits, estimating a price of $5 per tag compared with a cost of 600-1000$ for a professional colorimeters or spectrometers, thus enabling widespread use of this type of instrumentation. The system is very simple to use, as the end-user interfaces with a smartphone application. In [29], the same system it is used to measure pH using pH-sensitive paper strips.

From the analysis reported above and the data shown in Table 1, we can conclude that not all the characteristics related to the sensors are always considered. In other words, each implementation focuses only on a limited subset of the characteristics. In this context, it is clear that an experimental study that analyzes the suitability of NFC for biomedical applications is still missing.

For this reason, in this paper we first present an initial analysis of the requirements that a heterogeneous wearable biomedical application using NFC should have, by considering two specific use cases as examples. Following our analysis, we assess the performance of NFC in order to verify that this technology can satisfy such requirements. Compared with related work, this paper does not aim at proposing a novel solution, instead, it focuses on assessing the performance of the technology via real experiments that involve commercial devices. Some of the previous work partially focused on assessing the performance of the technology, however, they focused only on specific aspects, such as maximum distance [25] or energy consumption [22].

## IV. Use cases

A wearable tag is composed of one or more sensors to provide physical measurements, a minimal circuitry with a microcontroller to read and pre-process data and the NFC interface. Those elements are seamlessly integrated on the body layer (in contact with or close to the human body). The wearable tag could be battery less, thus exploiting the NFC coupled with an energy harvesting circuitry. A reader will interrogate the tag to retrieve the sensed data and/or to provide some data like a command or a setting.

In this paper, we will specifically consider two different use cases, the Smart Factory and the Smart Health. We selected these two use cases as they have different properties on processing sensor data. Considering the use case of the Smart Factory we need to realize a real-time monitoring of

[1] A semi-passive device is a device that even though it has a battery it mainly operates in passive mode except when it is far from the reader, in this way the sensor can collect data in a continuous manner, even when it is away from the reader.

TABLE 2
SUMMARY OF THE REQUIREMENTS

| Class | Name |
|---|---|
| **Usability** | Size |
| | Weight |
| | Flexible |
| | Energy consumption |
| **Integration** | Monitoring frequency |
| | Preprocessing |
| **Communication** | Transmission Frequency |
| | Average latency |
| | Max communication distance |
| | Antenna alignment |

some parameters to prevent accidents in the workplace. In the Smart Health, instead, the system has to collect the data and analyze them subsequently to extrapolate relevant information. In the following we describe the use cases more in details:

- Smart Factory*:* wearable tags [19] are worn by workers in order to improve safety, e.g. to detect when a worker enters in a dangerous area (e.g. moving close to a dangerous machinery or touching a surface with a high temperature), or to monitor his/her wellbeing, e.g. by monitoring posture and tracking movements in repetitive tasks or detecting accidents such as falls. To this aim, the wearable reader may be placed in the center of the body, e.g. the pelvis area. A possible combination of sensing tags could be: a) e-textile sensor in a t-shirt (e.g. [30]) able to detect back flexion and to prevent dangerous postural behaviors; (b) sensing tags in work gloves detecting temperature and or force interaction with the environment; (c) heart rate tracker on the chest; (d) inertial measurement unit at the pelvis to detect movement of the center of mass (i.e. falls, posture, physical activity). Note that, in cases (a), (c) and (d) the reader to tag distance is almost constant, while in case (b) the distance may have consistent variations, which poses significant challenges on how to handle the information flow.

- Smart Health: for example, spatial-temporal gait characteristics are highly correlated to subject's health and well-being. Several studies reported that a modification in gait patterns is an early indicator of cognitive impairment caused by a neurodegenerative disease [31],[32]. Other studies have shown that the abnormal gait patterns can be associated with a higher risk of falling [33],[35]. In this case, the sensing tag, with inertial or e-textile sensors, could be seamlessly integrated in a sock or in a shoe to detect foot contact pressures and foot/ankle orientation during gait. The wearable reader could be applied on the trousers or directly in the shoe. Also, in this scenario the distance between the wearable reader and tag could be almost constant or variable depending on the site of integration selected. Moreover, the variation of such distance could be useful to extract information about specific events of the user gait cycle.

## V. REQUIREMENTS

In this Section, we analyze the requirements of the NFC devices that can have an impact on the application feasibility. We start by identifying three main classes of requirements, namely those related to usability, from the point of view of the user, to integration, from the point of view of the application, and to communication. An experimental evaluation of a subset of these requirements will be discussed in Section VI. A summary of all the requirements and their class is provided in Table 2.

### *A. Usability Requirements (towards wearability)*

One of the main factors that prevents the diffusion of wearable devices is their usability. This means that devices should seamlessly fit into dresses without requiring (or requiring small) modifications, possibly keeping the dresses washable. In addition, devices should not impair or limit user's movements, thus they should be comfortable to wear. We can translate this high-level user needs into the following physical requirements:

- Devices should be small and have low weight. A reduced size allows the device to be easily included in the dress without significant alterations. A small weight reduces the possibility of impairing user's movements. In addition, for some applications the device should be flexible in order to be non-invasive for the user.

- Devices should have a low energy consumption to limit the need for either recharging or frequent battery replacement. This requirement can be either satisfied by reducing the power consumption of the various elements of the device, or by exploiting alternative power sources, such as energy harvesting.

### *B. Integration Requirements*

The use cases presented in Section IV exploit sensors to measure biomechanical and physiological parameters, and eventually extracting a synthesis of the movement and the overall health status of the user. The obtained values will be then collected and used, for example, to reconstruct the actual movements, possibly comparing them against reference values. To this aim, it is crucial to obtain a reconstruction of the movement as close as possible to the real one. We thus identify the following two requirements:

- The monitoring frequency of the sensors within the device should be high enough to allow a continuous flow of information. Please note that this does not pose a requirement on the *delivery latency* of the sampled data, but only on how frequently the data is measured

- The ability of the device to perform preprocessing of the sampled data before transmission can significantly reduce the amount of data to be transmitted by performing data aggregation or filtering. This can possibly have a positive impact on reducing the power consumption.

### *C. Communication Requirements*

The data collected by the sensor must be forwarded to a device that has sufficient resources to process and store the data, such as a smartphone or an embedded computing system installed in proximity. This is due to the limited resources available on the wearable tag sensors that lack of sufficient processing and storage capabilities. Different types of applications can have different communication requirements, i.e. requirements on the communication reliability, e.g. in term of packets lost, or in the transmission efficiency, e.g. the maximum number of samples that can be transmitted per unit of time. Furthermore, based on the communication technology adopted different communication distances can be covered. For these reasons we consider the following communication requirements:

- **Minimum transmission frequency**, for applications that perform continuous monitoring of a specific physical measurement and need to exchange data in a continuous manner.
- **Maximum average latency** for all the applications that require real-time data collection, where data is received with a maximum latency.
- **Maximum communication distance** to ensure reliable communication for applications that involve mobility of the sensors due to specific movements or gestures of the users.

## VI. Performance Evaluation and Field Testing

In this Section, we present a performance evaluation of commercial NFC-based devices, to assess the feasibility of implementing wearable devices for biomedical application based on such communication technology. To this aim, we specifically consider the impact of energy harvesting, to assess how using this power source impairs the regular operations of the sensors and its overall performances.

### *A. Experiment Setup*

Our experimental setup is composed of off-the-shelf NFC devices from STMicroelectronics. It includes two modules: a Tag and a Reader. For the Tag we used the STEVAL-SMARTAG1 NFC card, shown in Fig. 2. This sensor-tag platform is an NFC-enabled sensor node characterized by small dimensions (4x4x0.5 cm) and is a good candidate for prototype implementation. This device is equipped with inertial and environmental digital MEMS sensors, an STM32 microcontroller and a dynamic NFC tag for communication with NFC readers. These features make this board particularly useful for deployment in field researches and data-collection. The STEVAL-SMARTAG1 board includes the following components and features:

1. The main component is its STM32L031K ultra-low power ARM Cortex-M0+, a very low power microprocessor with a CPU frequency of 32 MHz . The device has an 1 Kbyte EEPROM and 8 Kbytes of RAM in order to store the data collected or processed by the microprocessor. An extensive set of peripherals is also included, e.g. 12-bit ADC, 2 comparators, 1 low-power 16-bit timer, 3 general purpose 16-bit timers, 1 RTC, 1 SysTick, 2 watchdogs, I2C, SPI, USART and a low-power UART.
2. The first sensor is a LIS2DW12 3-axis MEMS accelerometer, ultra-low power that is capable of measuring accelerations with output data rates ranging from 1.6 Hz to 1600 Hz. This sensor can be configured to recognize for single/double tap, freefall, wakeup, portrait/landscape, 6D/4D orientation detections.
3. The second is an LPS22HB ultra-compact piezo-resistive absolute-pressure sensor with range 260-1260 hPa. The device includes a sensitive element and an IC interface that communicates via I2C or SPI from the application-sensitive element. This sensor can used for example as a digital barometer.
4. The last sensor is a HTS221 capacitive digital sensor for humidity and temperature. It includes a sensing element


Fig. 2 Tag: NFC STEVAL-SMARTAG1 4 ×4 ×0,5 cm

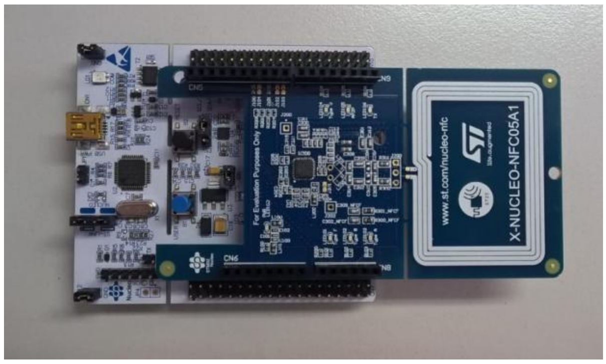


Fig. 3 Reader: Nucleo STM32L476RG and X-Nucleo-NFC05A1 12,8×7 ×3 cm

and a mixed signal ASIC to allow measurement reading through digital serial interfaces. The sensing element consists of a polymer dielectric planar capacitor structure capable of detecting humidity variations. The HTS221[2] can measure relative humidity from 0%-100% rH with a sensitivity of 0.004% and 3.5% accuracy. It can also measure temperature from -40 to 120 degrees C, with a resolution of 0.016°C with ±0.5 °C accuracy between 15 and +40 °C.

5. STLQ015 150 mA, ultra-low current linear voltage regulator. Input voltage ranges from 1.5 to 5.5 V. The device features a quiescent current which is just 1.4 µA at maximum output current. In addition, the device includes short-circuit constant-current limiting and thermal protection.
6. ST25DV64K 64 Kbit dynamic NFC/RFID tag, NFC Forum type V with I2C interface. The tag can work both in fast transfer mode and energy harvesting. The device has 64 Kbit EEPROM and offers two interfaces: the first interface is an I2C serial link to the microcontroller, the second interface is a RF link, which is activated when the device acts as a contactless memory powered by energy harvesting.

[2] https://www.st.com/content/st_com/en/products/mems-and-sensors/humidity-sensors/hts221.html

As for the reader, shown in Fig. 3, the Nucleo card STM32L476RG together with the nucleo expansion board X-Nucleo-NFC05A1 are used. The STM32 Nucleo-64 board is a low-cost embedded system for rapid prototyping. The board does not require any separate probe as it integrates the ST-LINK debugger/programmer. It is popular among makers for the large library of examples provided by the manufacturer.

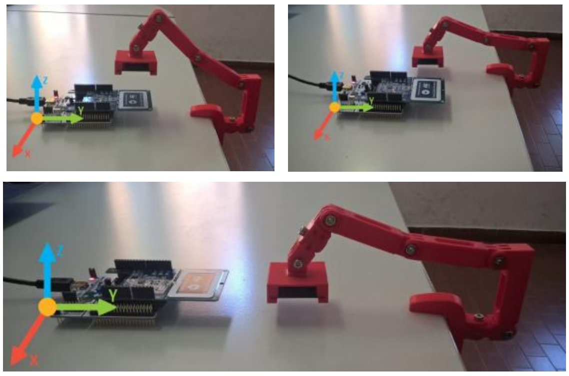

Fig. 4 Configurations of experiment 1: varying distance on the z-axis (top left), on the x-axis (top right) and on the y-axis.

The X-NUCLEO-NFC05A1 is an NFC card reader expansion for the STM32 Nucleo-64 boards, based on the ST25R3911B. The ST25R3911B manages frame coding and decoding in reader mode for standard NFC applications. In addition, the automatic antenna tuning technology (AAT) allows operations near metal parts and/or in changing environments.

The ST25R3911B supports ISO/IEC 14443 Type A and B, ISO/IEC 15693 (single Subcarrier only) and ISO/IEC 18092 communication protocols. It also supports the detection, reading and writing of NFC Forum Type 1, 2, 3, 4 and 5 tags. It contains a low power capacitive sensor, which can be used for ultra-low power wake-up without switching the reader field on.

Both the Tag and the Reader have been reprogrammed with customized code, realized modifying the program template provided by ST. Particularly, the initial code of Tag has been modified to store the sensor data in a predefined memory location, while the tag was activated by NFC beam from the reader. Instead, the reader code has been modified to connect with NFC type 5 tags and to carry out 1000 reading of the memory location containing the information saved by the tag. The time required to realize 1000 readings has also been measured using a timer and the number of unsuccessful readings has been also computed by analyzing the log of the reader collected through the serial port. To collect information and control the experiment, an Asus K550JX notebook has been used with the following specifications: Intel Core i7-4750HQ Processor, 12 GB RAM, 500 GB SSD, NVIDIA GeForce GTX 950 2 GB, running Windows 10. The two cards have been programmed using the SW4STM32 IDE, which is based on ECLIPSE.[3]

*B. Experiment description*

Using our testbed, two different types of experiments were carried out:

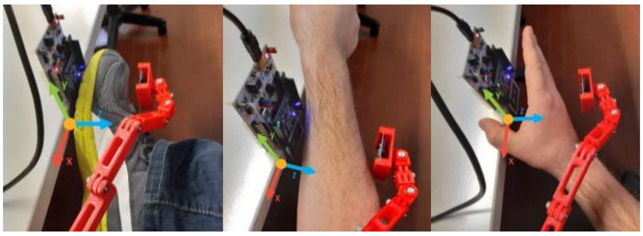

Fig. 5 Configurations of experiment 2.A: presence of different body part between reader and tag system with a fixed distance on the z-axis: a foot (left), an arm (center) and an hand (right)

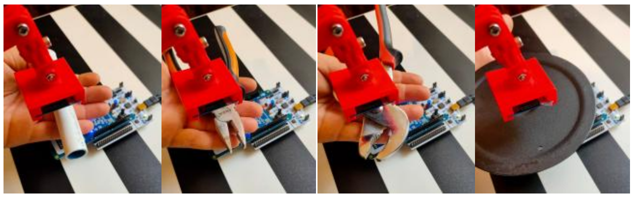

Fig. 6 Configurations of experiment 2.B: fixed distance on the z-axis and with presence of different metal objects from left to right hydraulic hose, an universal plier, a pump pliers and a iron plate

1. *NFC performance evaluation:* we focused on evaluating various communication performance indicators such as distance limits, the maximum communication frequency and the number of reception errors. These measurements were obtained in various experimental configuration, obtained by varying the Tag-Reader distance with respect to the X, Y and Z axes, and its angle on the x axis, as we show in the Fig. 4. Experiments are executed in battery and in energy-harvesting modes.

2. *Obstacle disturbance evaluation*: we analyze how an obstacle placed between the reader and the tag can influence the communication. To examine a possible degradation of the performance, we employed two different types of objects: body parts and metal objects. We evaluate the results in terms of communication delay, maximum communication frequency and number of errors.

In order to ensure experiment repeatability and precision, we designed and produced an *ad-hoc* adjustable 3D-printed support, with the Tevo Tornado printer. Its aim is to maintain the tag and the reader at a precise distance. We use a digital caliber, Tacklife model DC01, to precisely position and hold it at the desired distance.

To run the first set of experiments on NFC performance evaluation, we setup 4 different scenarios, which we show in Fig. 4. Particularly, in this set of experiments the reader and the tag are aligned following two coordinates that are already fixed, meanwhile we vary the distance of the remaining free coordinate. To summarize, we performed the following set of experiments:

1. We set the tag-reader distance on the x and y axis to zero and we vary the tag-reader distance in the z-axis from 10mm to 102mm.

[3] https://www.st.com/content/st_com/en/products/development-tools/software-development-tools/stm32-software-development-tools/stm32-ides/sw4stm32.html

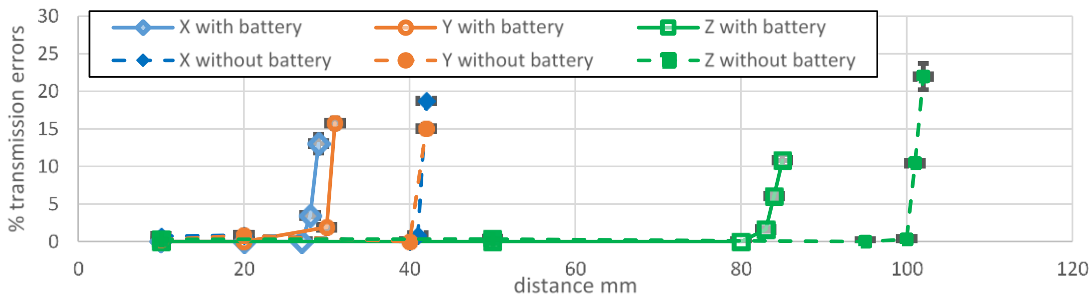


Fig.7 Percentage of transmission errors as a function of Tag-Reader distance for various configurations.

2. We set the tag-reader distance on the z and y axis to zero and we vary the tag-reader distance in the x-axis from 10mm to 42mm.
3. We set the tag-reader distance on the x and z axis to zero and we vary the tag-reader distance in the y-axis from 10mm to 42mm
4. We set the tag-reader distance on the x and y axis to 0mm, and of 80mm on the z axis; we then vary the tag angle in the x-axis between 0° and 180°.

The second set of the experiments aim at evaluating the disturbance of obstacles. To this aim, we setup seven scenarios where the distance between the tag and the reader is fixed. We set the tag-reader distance in the x and y axis to 0mm, and to 80mm on the z axis. For body parts, we used three different objects, namely an open hand, an arm and a shoe with foot inside. The objects are positioned in the gap, as shown in Fig. 5. For metal objects, we used four different objects, namely a hydraulic hose, a universal plier, a pump plier and a 2mm iron plate, as show in Fig 6.

Before carrying out the experiments, we modified the code of the tag and reader further. In details, the reader has been programmed to search for nearby tags, connect to one of them and perform 1000 reads of temperature, pressure, humidity and acceleration from the memory tag. The reader counts the number of reception errors and the time spent in communication and transmits this information to the laptop. A program running on the laptop, which is also connected to the reader, stores all information for each run. As main key performance indicator we adopted the percentage of transmission errors, defined as the number of successful readings divided by the total attempts. Each experiment is repeated 20 times to achieve statistical soundness of the results.

### C. Results

In Fig. 7 and Fig. 8 we summarized the results from the first type of experiments. The first figure shows the relation between the reader-tag distance along the 3 cartesian axes and the number of transmission errors. Within the graph there are 6 different curves, each of which represents a different scenario. As you can see, we marked the experiments performed with and without batteries using the same color. In all the scenarios, we can notice a 2 mm interval in which the percentage of errors increases considerably; leading the system to perform always in the worst way. If we compare the results of the experiments with and without battery, instead, we can notice that there are no significant disadvantages due to the use of energy harvesting, which therefore is proved to be a valid alternative to the battery mode. Unfortunately, with the metrics collected in our experiments we could not find a

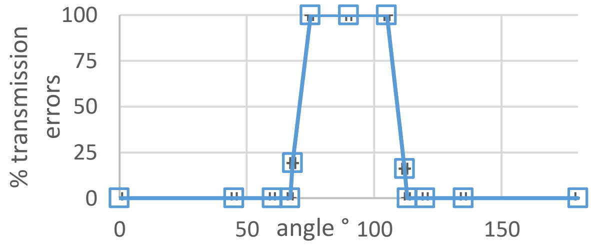


Fig. 8 Percentage of transmission errors as a function of Tag-Reader angle.

reason for this behavior. Its investigation requires further experiments and a deep evaluation of the circuit design of the tag, which, however, is out of scope of this work.

Fig. 8 shows the relation between the transmission error and the Reader-Tag angle. As you can see, the results show a trend similar to the previous case: increasing the angle above 67° increases the percentage error rapidly, eventually the communication becomes impossible when the angle is in the range of 75-105°. Furthermore, we can see that the results obtained are symmetrical with respect to the center (90°) and therefore a rotation of the Tag clockwise or counterclockwise produces the same effects. The same results were obtained with the tag in battery mode; however, we omit their presentation here for the sake of brevity.

TABLE 3
COMPARISON OF THE RESULTS OBTAINED WITH AND WITHOUT DISTURBING OBJECTS

| Object | Frequency | Number of errors |
|---|---|---|
| **No obstacles** | 126,80 Hz | 0 |
| **Hand** | 126,85 Hz | 0 |
| **Arm** | 126,83 Hz | 0 |
| **Foot** | 126,84 Hz | 0 |
| **Tube** | 122,81 Hz | 0 |
| **Plier** | 122,73 Hz | 0 |
| **Pump plier** | 51,46 Hz | 583 |
| **Plate** | impossible to establish connection | |

With respect to the second set of experiments, we summarize the data in Table 3. Since in this case the results obtained with and without battery are similar, for the sake of brevity, we report only the results obtained from the experiments in harvesting energy mode. In order to ensure a fair comparison for the two different operating modes, we considered a tag-reader distance of 80mm. In the first row we report the experimental data without obstacles in order to compare the results obtained. Both the results obtained for the body parts and the metal objects are reported. We analyzed the frequency, transmission time and the number of errors. As you can see, the results of the experiments for the body parts, with the three different obstacles (hand, arm and foot) do not show substantial differences with respect to the baseline obtained without obstacles. We can thus conclude that the communication between Tag and Reader with body parts in between the tag and the reader, at the considered distance, is not altered by the introduction of these objects. On the other hand, when metal objects are considered, we can notice that the level of impact in the performance depends on the size of the object. Specifically, when the tube or the plier are introduced, the communication is not affected. On the other side, when the object has a dimension similar to the one of the antenna (40x40 mm), the transmission error increases significantly and can reach up to 58,3%, such as the case of the plier pump, or it can even disrupt the communication, like in the case of the iron plate that has a dimension greater than the antenna. These results are in line with the results of other experiments presented in literature such as [34], in which the authors shown that the human body does not affect the performance of magnetic induction communication systems when communication frequencies above 30 MHz are considered.

TABLE 4
COMPARISON BETWEEN THE COMPLETION TIME MEASURED IN CORRESPONDENCE TO THE POSSIBLE CASES OF ERROR

| | **Completion time** |
|---|---|
| **No Error** | 8,16 ms |
| **Fragment Error** | 8,02 ms |
| **Collision Error** | 8,08 ms |
| **Timeout Error** | 25,17 ms |

In order to assess the time required to complete a transmission, in Table 4 we report the average completion time, defined as the time between the beginning of the transmission and its completion. In order to provide an insight on the completion time with both successful and unsuccessful transmissions, the average completion time is reported for the different cases of errors that occurred during our experiments, as reported by the driver. These measurements were recorded in an additional set of experiments executed with the configuration of the experiment 2.B. The latter was necessary since the collection of the completion time required additional logs that would have impaired the performance of the system and thus affected the measurement of the maximum frequency. The experiments were executed with only the pump plier, as it was the one with errors. As can be seen, the successful transmission and the fragment error and collision error result in approximately the same completion time, while the timeout error results in a significant increase in the completion time. This was expected as the last error requires a timeout to expire in the sender, thus resulting in a longer completion time.

### D. *Requirements matching*

The results of our experiments allow us to draw the following conclusions with respect to the requirements of biomedical applications:

- **Communication.** NFC can ensure a continuous transfer of data from the sensor to the reader. The maximum data transmission frequency we measured (126Hz in our experiments) can be considered sufficient to accommodate many biomedical use cases, from ECG monitoring, which requires 120 Hz [36], to gait analysis, which requires 50 Hz [37]. In addition to this, our experiments shown that communication reliability is still ensured even when obstacles are placed between the tag and the reader.
- **Usability.** The energy harvesting mode is viable to manufacture sensors that work without battery. Its performance in terms of communication frequency and reliability are not significantly reduced, compared with the battery mode. The removal of the battery can reduce noticeably the size and the weight of the board, thus improving its integration and its wearability.
- **Integration.** The NFC tags we considered in our experiments are equipped with a microcontroller, that has sufficient capabilities to perform basic pre-processing of the collected data. In our experiments, we demostrated that the microcontroller can operate even in the energy harvesting mode, thus allowing the implementation of some basic operations directly on the sensor, even in battery-less condition.

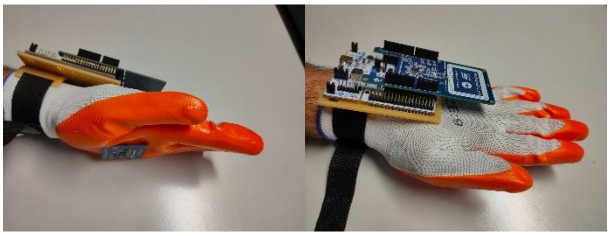

Fig. 9 Prototype of smart glove and smart bracelet

## VII. PROOF-OF-CONCEPT PROTOTYPE

In order to demonstrate the potential of NFC enabled wearables, we created a proof-of-concept prototype, using commercial devices. For the sake of brevity, we focused only on the Smart Factory use-case, as it was presented in Section IV. This use-case was selected over the other Smart Health use-case since it has a stringent requirement. The implementation of a Smart Health prototype is left as future work. Specifically, we focused on monitoring the temperature outside the workers' gloves to prevent possible burns and injuries. We need to monitor the temperature as the glove only partially isolates the hand, i.e. it can protect the hand only within a limited temperature range, outside this range the glove does not isolate, and skin burns can occur. For this reason, the worker wearing the glove does not realize the increase of the temperature until it is too high. For this reason, to prevent skin burns, it is important to warn the worker of the increasing of the glove's external temperature before it is too high. The most critical requirements for this use case are the following: (i) ensuring a temperature reading frequency of at least 10Hz; (ii) guarantee a battery lifetime of at least one working day to guarantee continuous monitoring of the worker. While using our prototype, the reader is connected to a laptop via USB connection. This connection was used to measure the energy consumption of the whole system. The possibility of using data transfer via a wireless technology such as Bluetooth or WiFi could be easily achieved by using an expansion card for the reader. The prototype is shown in Fig. 9 and comprises two main components:

1. a **smart glove**: the work glove is equipped with an NFC battery-less tag on the palm of the hand. The temperature sensor is installed on the glove as hands are the part of the body more often in contact with utilities and high temperature surfaces, thus they are at risk of burns due to the high heat. In our prototype we employed the same STEVAL-SMARTAG1 board used for our experiments. In a real deployment a different technology, like a textile sensor embedded in the fabric of glove using the approach proposed in [14][38] could be adopted in order to ensure wearability;
2. a **smart bracelet**: an NFC reader that powers and reads data from the NFC tag on the glove. In our prototype we employ the same NFC reader adopted in Section VI attached to the arm through support realized via 3d print.

To show that the prototype can read the temperature in real-time, a hazardous working environment is emulated through a heated plate of a 3d printer. A volunteer wearing the system moves the hand in proximity to the plate, while the printer software is instructed to increase the plate's temperature from 37 Celsius degrees to 50 degrees. Fig. 10 reports the temperature reads from the glove during the experiment. For the sake of simplicity of the implementation, the granularity of the measurements reported in the graph has been cut to 1°C degree. The system allowed to collect one value every 100 ms. When the reader receives a temperature above 45 Celsius degrees, a warning is emitted to the user by blinking the LEDs on the smart bracelet: by seeing the visual warning the volunteer raises his hand from the heated plate and consequently the temperature decreases.

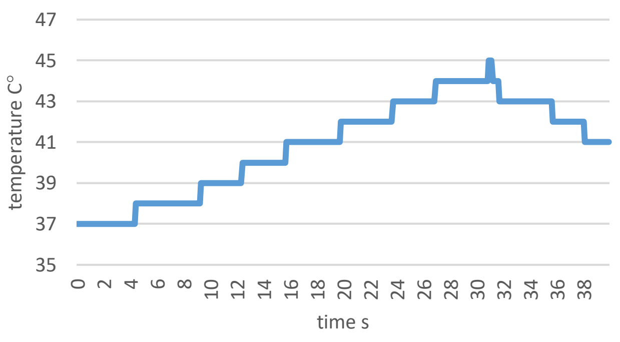


Fig. 10 Graph of the read temperatures of the smart glove

In order to evaluate the possibility of using a battery-powered device as smart bracelet, like a smart watch or a smart band, we also measured the energy consumption of the NFC reader during the experiment to evaluate a raw estimation of the battery lifetime. To this aim we exploited a high precision USB power meter that connects between the reader and the computer, specifically the "AVHzY CT-2"[4].To improve energy consumption, the reader switches between reading mode and sleeping mode. In reading mode, the reader activates the NFC radio, the tag activates the sensor and the reader reads the temperature value. In sleep mode the reader deactivates the antenna and waits 100 ms before switching back to the reading mode. Using the power-meter we measured the energy consumption for 1 minute obtaining an average consumption of about 150mAh. If the smart wearable is powered using a 1200mAh battery, it could cover the entire working day. From these results, we can conclude that the required requirements are met: the prototype can guarantee a 10 Hz monitoring frequency of the temperature, which is sufficient to trigger an alarm in dangerous situations, and a battery lifetime of more 8 hours, which allows to monitor the worker for a whole working day in an uninterrupted manner.

## VIII. Conclusions

In this paper, we carried out an analysis of the feasibility of adopting NFC as communication technology for wearable devices in heterogeneous biomedical applications. The results of our analysis, carried out by means of real experiments, show that NFC is well suited for the development of wearable devices for biomedical applications. Specifically, the results in terms of coverage and reliability show that the technology can be used for continuous monitoring or occasional data offloading, even when obstacles in the communication are considered or the tag and the reader are not perfectly aligned. Moreover, our experiments showed that the energy-harvesting mode does not impair the performance thus allowing a design of devices with minimal surface. With this technology we created a proof-of-concept testbed to demonstrate the potential of NFC enabled wearables. Specifically, we developed a sensorized glove that monitors in real time the temperature of the environment by exchanging information with a system installed on the wrist.

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