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Batteryless Piezoelectric Sensor System for Enhanced Ski Experience

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Abstract— The integration of digital technologies in sports assets is unlocking novel possibilities for managing sports facilities and enhancing learning support. This paper introduces the development of an innovative batteryless sensor system, the Autonomous Ski Deflection Sensor (ASDS), designed to monitor ski wear and assess skier performance. This new system is based on a piezoelectric energy harvester that uses the energy from the ski's deformation and vibrations to power the electronics, avoiding the use of batteries. It integrates minimalist electronics to perform measurements of the ski solicitations in turns (directly correlated to the energy harvested), store the data in memory and send them in real time to a smartphone via Bluetooth Low Energy. The ski level of the user is evaluated thanks to data fusion between the measurements from ASDS and the inertial measurement unit (IMU) of a smartphone. For this purpose, 14 measurement campaigns (200 downhill runs) were carried out to generate the database for the machine learning algorithms for ski level classification. A public experimentation phase has been scheduled during the 2023 FIS Alpine World Ski Championships, proposing 40 pairs of skis equipped with TRL7 ASDS prototypes to participants. This initiative has allowed the evaluation of the system's reliability, and demonstrated its potential benefits for diverse range of end-users within the skiing community. This ASDS system has the potential to enhance the skiing experience for users by providing insights to improve safety, performance, and enjoyment on the slopes. Alternatively, based on the monitoring of the ski usage/health, such system could promote new services and business models based on circular economy principles.

Keywords— Energy Harvesting, Sensor Application, Skiing Skill Classification, Circular Economy

I. INTRODUCTION

The digitization of sports assets offers new opportunities for the management of sports facilities and learning support [1-5]. In this context, Rossignol group and CEA/LETI have been working on the development of a batteryless sensor

system integrated into the ski to monitor ski usage and measure skier performance. This system can offer a new skiing experience for the users through the ski level self-quantification, learning and gamification. Such solution can offer benefits to all the value chain of ski: recreational and professional skiers to evaluate and improve skiing, ski manufacturers and rental companies to have a better vision of their ski usage, ski schools and coaches to enhance their teaching practice [6-9].

Some papers already relate on sensor systems for skiing gesture monitoring to have a better understanding of skiing practice and kinematics [10-11]. For now, such systems are too invasive on the ski to be proposed for any other purpose than scientific research. Some suppliers are already proposing sensor systems to monitor skiing practice: PIQ®, CARV® and Snowcookies® [12-14]. These systems offer the possibility to monitor various characteristics of skiing practice (edge angle; G-force in turns, turn type, jump detection...). However, all these systems suffer from a rather short operating time linked to the use of a battery (from few hours to 5 days of battery life), and none of them is able to measure the ski activity during its entire lifespan. To be fully accepted and widely used by every skier, such sensor system must be transparent to the user: no battery recharge, minimal footprint on the ski, minimal economic and environmental impact.

To meet these challenges, we have developed a low power sensor and batteryless system that integrates a piezoelectric energy harvesting system, denoted ASDS in this paper. This harvesting system uses the energy from the ski's deformation and vibrations to power the electronics, avoiding the use of primary or rechargeable batteries (Fig. 1).

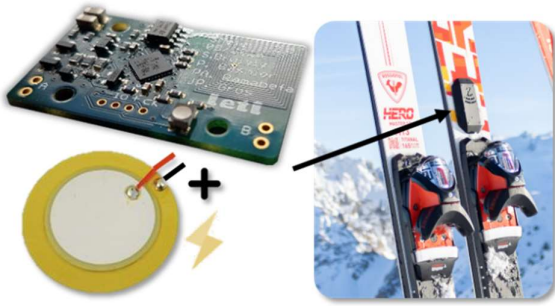


Fig. 1. General presentation of the Autonomous Piezoelectric Sensor (ASDS) system for ski usage and skiing level evaluation

In order to minimize the power consumption of the system integrated on the ski, it includes the only sensor that a smartphone cannot afford: the piezoelectric ski deflection sensor, combined with a dynamic NFC tag and a Bluetooth transceiver for data communication. The smartphone's sensors (IMU and GPS) provide all the other measurements used to evaluate ski practice level (speed, turning frequency, hips angle).

The following paper offers a brief description of the main operating principles of this technology and its implementation for a public experimentation. It is structured as follows. Section II describes the ASDS, which monitor ski solicitations for ski usage/aging evaluation and skier performance classification. Next, section III describes the implementation of ski level classification through data fusion between smartphone sensors and the autonomous ski deflection sensor using machine-learning algorithms. Finally, Section IV outlines the complete system implementation, targeted for a general public experimentation during the FIS Alpine World Ski Championships at Courchevel-Meribel in February 2023.

II. AUTONOMOUS SKI DEFLECTION SENSOR SYSTEM

Skiing is a very complex motion that depends on many parameters and conditions. Consequently, monitoring various physical factors is crucial to assess skiing skill level, including speed, skier positioning, ski bending, applied force, and turn frequency. Among these metrics, ski deflection during turns is particularly valuable for evaluating performance quality and turn effectiveness [15-17]. As this specific metric cannot be directly obtained from a smartphone, a dedicated wireless monitoring system has thus been developed: it is the key element of the solution proposed in this paper.

A. Description of the ASDS

The proposed ASDS system is composed of (i) piezoelectric elements, (ii) a Power Management Circuit (PMC), (iii) a microcontroller unit (MCU) with a Bluetooth transceiver eventually mutualized within a single System On Chip, and (iv) a dynamic NFC tag. The two wireless links of the system, Bluetooth and NFC, serve different purposes. Bluetooth provides real-time data to the smartphone during a ski session, while the dynamic NFC tag records the accumulated solicitation of the ski throughout its lifespan. An overview of the proposed ASDS system is depicted in Fig. 2.

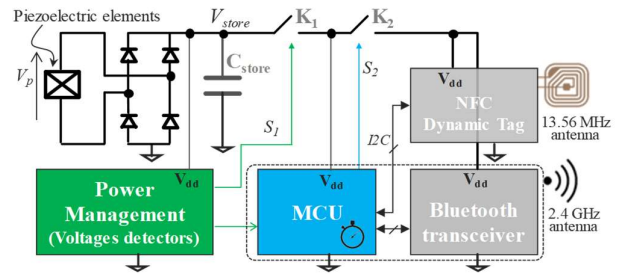


Fig. 2. Overview of the Autonomous Piezoelectric Sensor system

B. Operating principle of the system

During a ski run, the piezoelectric elements, glued on the ski, convert the strain energy into electrical energy. The piezoelectric voltage is rectified and filtered by means of a full diode bridge rectifier. The generated charges are then stored in the main storage element of the system (capacitor C_{store}). Indeed, the proposed system offers the advantage of not relying on electrochemical cells (batteries), which are less tolerant to cold environments, often more expensive, and require more complex management than conventional capacitors. In addition, the energy/voltage level of capacitor C_{store} is a critical aspect of the innovation, as it determines not only the system's ability to operate autonomously but also its capacity to estimate the level of solicitations experienced by the ski, and thus the user's ski level (see section III). Fig. 3 illustrates the internal operation of the system, which is described hereafter.

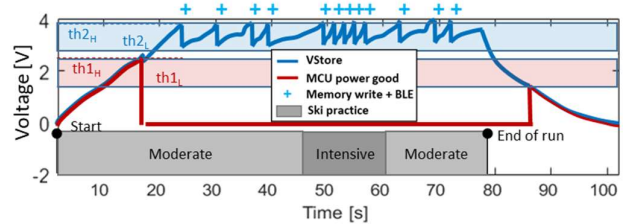


Fig. 3. Illustration of the voltage level in the storage capacitor (C_{store}) to explain the operating principle of the ASDS system

i) Because $V_{store} = 0$ at the beginning of a ski practice, a cold-start mode enables the system to be powered when the energy on C_{store} is sufficient. The first function of the PMC is then to close or open the energy path by controlling the MOSFET K_1 depending on the voltage level of C_{store} . This function is performed by a voltage detection by means of an ultra-low power hysteresis comparator. Indeed, the PMC closes K_1 when $V_{store} > Th_{1H}$ and opens it when $V_{store} < Th_{1L}$, with Th_{1H} and Th_{1L} respectively the high and low thresholds voltage values of the cold-start function.

ii) As long as the control signal S_1 is low, K_1 is ON and the system operates in "Measurements" mode, as shown in Fig. 3. In this mode, the MCU utilizes its internal low-frequency/low power clock to establish a temporal reference. Additionally, the MCU uses a second voltage detector (signal S_2) to trigger an "energy event" by closing K_2 : either a Memory-Write or a Bluetooth-Frame-sent. Each energy event results in writing the data in the memory (or sending by Bluetooth), which quickly lowers the voltage across C_{store} . Each data includes the event number and the time elapsed since the last event. Considering that each event lowers the voltage across C_{store} (V_{store}) by the same voltage drop, the mean electrical power

supplied by the piezoelectric harvesters between each event can then be estimated. As depicted in Fig. 3, which illustrates an alternation between moderate and an intensive ski practice, this metric can be correlated with the level of solicitations experienced by the ski.

iii) At the end of the ski practice, the voltage level on C_{store} drops below Th_{1L} since there is no longer any mechanical solicitations of the piezoelectric element and the system gets back to a no-energy state (C_{store} discharges).

By using firmware and hardware optimization and ultra-low power components (not detailed in this paper), the minimum power consumption of the overall system is around $4 \mu A @ 3 V$ (i.e. $12 \mu W$) and each energy event consumes around $18 \mu J$. The minimum piezoelectric output power to cold-start the system is around $7.5 \mu W$. For instance, the whole ASDS system consumes a power level in the range of $25 \mu W$ to $45 \mu W$ for a Class 2 skiing practice.

III. SKIING LEVEL CLASSIFICATION

For assessing ski usage, the process is relatively straightforward, by integrating the ski solicitations and their respective durations required from the ASDS system. These data are directly accessible from the sensor's memory. Conversely, evaluating ski level necessitates a more intricate approach, involving the acquisition of multiple parameters and the implementation of a sophisticated data science analysis. This process involves fusing data from the ASDS with information from a smartphone's inertial measurement unit (IMU) to generate insights on skier performance. The diagram in Fig. 4 illustrates the operating principle of two key insights derived from the ASDS system: ski wear/aging evaluation and skiing level classification using a fusion between the ski deflection sensor and the smartphone IMU.



Fig. 4. Illustration of the operating principle of two key insights derived from the Autonomous Ski Deflection Sensor (ASDS) system: ski usage/aging evaluation and skiing level classification

The classification used in this application is the one described in the memento of French ski teaching of the ENSA (National School of Skiing and Alpinism) which includes 4 classes from Class 1 (snow ploughing - beginner) to Class 4 (high angle carving - competitor).

The data science technique used to estimate and classify the skier's level from sensor data is performed by a Machine Learning workflow composed of 2 steps. In the first step, a set of statistical features (mean, max, min, std, kurtosis, skewness, quantiles...) are computed from the data of the sensors during the whole run. The sensors involved are the GPS, the IMU and the ASDS system. Among these features, 10 have been selected by Recursive Feature Elimination (RFE) [18] using an Extremely Randomized Trees Classifier [19] with the following parameters: 32 trees in the forest, a maximum of 10 features considered when looking for the best split and a maximum depth of a tree of 10. In the second step, the selected features are provided to a Support Vector Machine (SVM) [20] with the following parameters : a linear kernel, a box constraint $C = 1$, a gamma of type "scale" and a one-vs-one scheme. To select the relevant features and train the model, a database of real signals from 200 runs made by 15 skiers over 14 days was built. The annotation was done by professional ski instructors using video recordings.

The performance of the classification workflow was evaluated by cross-validation with separation by subject: 80% of the subjects in training and 20% of the subjects in testing. The most relevant features are "power of the turns (ASDS system)", "median speed during turn (GPS)", "turn frequency (IMU)" and "angle of the hips (IMU)". The mean balanced accuracy obtained is 95%. The best performances are obtained for classes 2 (97%) and 4 (100%) and the worst for classes 1 and 3 (92%). Fig. 5 shows the results of the classification regarding the ski solicitation power (directly linked to the electric power harvested by the ASDS system) versus the median speed of the skier in turns.

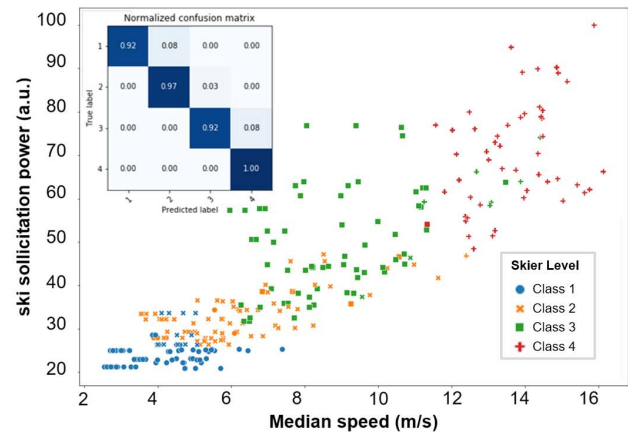


Fig. 5. Classification of the different ski runs regarding ski solicitation versus median speed

IV. IMPLEMENTATION AND TEST

The proposed ASDS system has undergone rigorous testing and optimization in real-world ski environment conditions during its development over the past two years. These trials have successfully validated the system's robustness and reliability for evaluating both ski usage and ski level classification. Indeed, the ASDS system was tested during 200 annotated runs.

Fig. 6 depicts a typical example measurement of the system's behavior : it shows the two instantaneous voltages V_{store} and V_{dd} of the ASDS system logged during a run performed by a class 4 skier using long turn carving at Lans en Vercors - France. Fig. 6 also displays the instantaneous

electrical power consumed by the ASDS system, computed from the data downloaded (NFC memory) after the run. Indeed, the instantaneous electrical power can be estimated from the data, specifically the event number and the time elapsed since the last energy event. This estimation is possible by considering the energy cost of an energy event ($\sim 18 \mu\text{J}$) and the average quiescent power of the ASDS system ($\sim 20 \mu\text{W}$). The instantaneous electrical power then serves as a reliable estimation of the electrical power generated by the piezoelectric harvesters, which directly correlates with the deformation level of the ski. It is interesting to note that the ASDS system regulates its own voltage supply (V_{store}) by duty-cycling K_2 while estimating the deformation level from an unpredictable, intermittent, and irregular energy source, namely the piezoelectric harvesters.

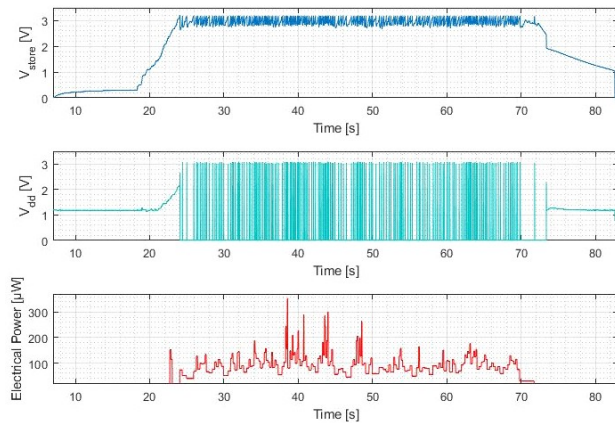


Fig. 6. Measurement of the ASDS's internal voltages for a class 4 skier using long turn carving (V_{store} , V_{dd} , see Fig. 2) and instantaneous electric power estimated from the data

In Fig. 6, an average power of $90 \mu\text{W}$ was estimated over the entire run, with a peak instantaneous power reaching approximately $300 \mu\text{W}$ around 40 s. One can also note that V_{store} starts from 0 V (cold-start) and was intentionally discharged at the end of the run.

For seamless integration of the ASDS system into skis during experimentation, a thermoplastic polyurethane packaging encases and safeguards the components (see Fig. 7). This protective layer shields the system from potential damage caused by ski edge contact while ensuring optimal energy transfer between the ski's deformation/vibrations and the piezoelectric energy harvester. Each ASDS unit is securely attached to the ski using a structural adhesive, effectively preventing delamination and enhancing overall system durability.

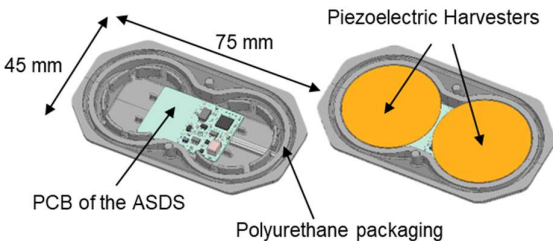


Fig. 7. Packaging of the ASDS system for the CM23 public experimentation

In 2023, 40 pairs of skis were instrumented for a public test during the FIS Alpine World Ski Championships at Courchevel-Meribel. For the deployment of this technology during the World Championships, a collaboration has been established with Lumiplan to create a software suite based on their Mountain Live application for Android and IOS. The application has the following functionalities: pairing between the sensor and smartphone via NFC, collecting Bluetooth data, processing of all sensor data and display of the skier's level after each run (Fig. 8). For the data processing, the classification algorithms issued from Machine Learning workflow has been embedded in this software.



Fig. 8. Example of ski level visualization on the Lumiplan Mountain Live application during the CM23 public experimentation : a) ski pairing by NFC, b) display of the skier's level after each run and c) display of average skier level for the day (advanced corresponding to a level 3 classification)

This public experimentation validated the reliability of the system with a technological maturity level of TRL 7, corresponding to a system prototype demonstration in operational environment. It also demonstrated the interest of the public and professionals in the field : instructor, rental company, coach.

V. CONCLUSION AND PERSPECTIVE

The technology presented in this paper proposes an innovative solution developed to perform real time monitoring of the ski solicitations during operation without any battery. Combined with smartphone's sensors and machine learning based algorithms, this technology can perform ski level classification in few turns offering a new tool for skiing improvement and teaching for both recreational skiers and competitors. Through rigorous testing in real-world ski environment conditions, this autonomous sensor system has demonstrated its robustness and reliability, making it a promising candidate for widespread adoption in the winter sports industry. During a public experimentation at the FIS Alpine World Ski Championships at Courchevel-Meribel in 2023, this technology proved its maturity level (TRL 7) and generated significant interest from both the public and professionals in the field.

Beyond improving skier performance, this battery-less system exhibits also its ability to monitor ski usage and somehow ski wear in a close future. Such ability could yield environmental sustainability benefits compared to an alternative lacking ASDS. Indeed, by encouraging a circular economy in the ski industry, new business models could emerge around reshaping, ski base maintenance optimization, rotating renting and ski swapping, and more, as illustrated in

Fig. 9. The potential economic and technical benefits of this technology are numerous as it can offer value to all stakeholders in the ski industry's value chain. Concerning the potential environmental benefits, a thorough study will be necessary to assess the ASDS's environmental footprint and its various associated services, for example through a life-cycle analysis.

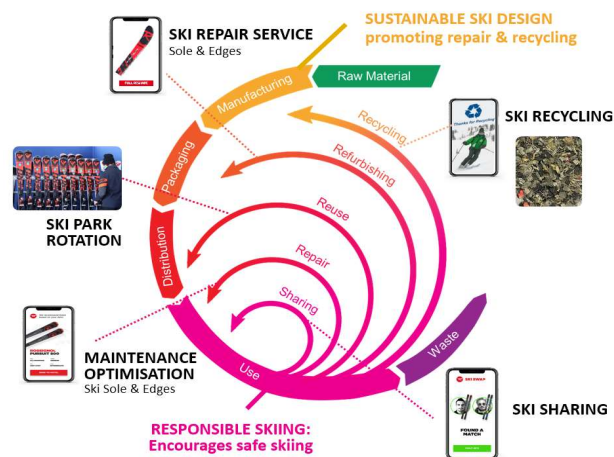


Fig. 9. Illustration of new business models based on circular economy which could propose new services such as reshaping, ski base maintenance optimization, rotating renting and ski swapping.

In summary, the ASDS system represents a significant innovation for improving skier performance, potentially promoting environmental sustainability, and creating new business opportunities in the winter sports industry.

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