NEXT GENERATION PROSTHETICS

TeSI 2024 - Team 4

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1. Introduction

TeSI has challenged us in ways we couldn't imagine. Coming from very different backgrounds, we had only one thing in common: attention to detail. Unfortunately for us - we thought - for half of the duration of the project, the professors asked us to do the opposite: explore as many opportunities in as little detail as possible. This allowed us to embark on a journey of discovery, unexpected friendships, many bad ideas, and technology exploration.

Our ideas ranged between cow milking and space exploration, beer brewing and water leaks, making it very hard to settle on a specific field. However, our visit to CERN was a turning point for us. It really changed the way we worked, and helped us to immerse ourselves fully in the project, do what we know best - explore in detail - and finally allowed us to make a choice. By the second day at CERN, the project was clear, no one had doubts that we had found the best application to leverage the AHEAD technology: sensor-embedded knee prosthetics. The concept was straightforward,leveraging existing technology with immense market potential and societal impact.

This report serves as a narrative of our journey, documenting both failures and successes, delving into our solution and its potential ramifications.

2. AHEAD technology

2.1. Interview with Chrysoula Manoli

In the interview, we explored the technology she is developing regarding 3D printed piping with integrated sensors. The primary material used for the 3D printed pipes is stainless steel, chosen for its ease of production and minimal material waste.

The manufacturing process employs metallic powder and a laser, ensuring precision and efficiency in creating the pipes. It consists of two main parts, the bottom and the top section, with a sensor embedded in resin placed in between them. The pipe designed by Manoli's team can incorporate either commercially available off-the-shelf sensors or 3D printed sensors created using aerosol printing with silver ink. In both cases, the printing process of the pipe is temporarily stopped in order to place the sensor with the resin before resuming to complete the piece. This requires high precision to ensure the integrity of the pipe.

The motivation behind Chrysoula Manoli's development of 3D printed piping with integrated sensors is to address the significant restrictions and challenges faced by CERN, particularly in their refrigeration systems. These systems require precise temperature data about the fluids they handle, necessitating the installation of various sensors that differ in size, shape, and capabilities. Traditional sensors encounter several issues, such as space and weight restrictions, which are also critical in applications like rocket cooling systems — another research area being considered by Manoli's team. These restrictions often force the placement of sensors outside the system, resulting in surface-only data collection that can lead to potential data loss. Additionally, the installation of traditional sensors can cause leaks. AHEAD technology aims to address these issues by embedding sensors directly into the 3D printed pipes, ensuring more accurate and reliable data collection. However, this approach has a significant drawback: if a sensor fails, the entire pipe must be replaced, which can be both costly and time-consuming. Therefore, rigorous testing is essential to ensure the system's long-term reliability and to minimize the need for frequent replacements.

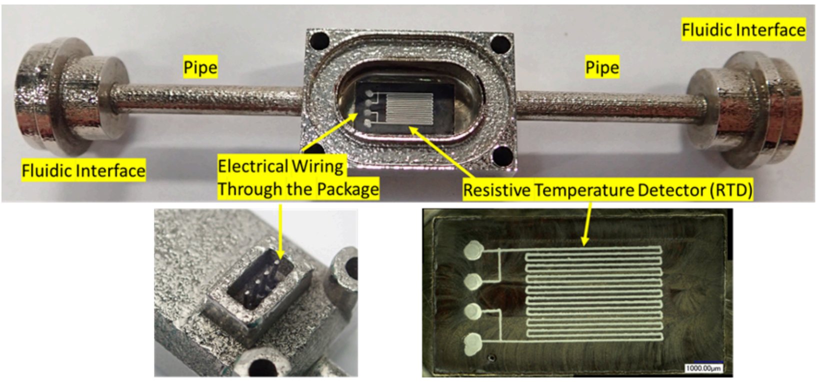

Figure 1. Smart pipe element developed in ATTRACT Phase I

Manoli emphasized that the developed pipe and its components are capable of bearing the pressure of liquid CO2 at 100 bars, highlighting the robustness of the design. However, she noted that the system's limitations might vary depending on the type of liquid and the specific shape of the pipes. Currently, sensors require power via cables, but Manoli envisions a future where wireless power and information transmission are integrated. She mentioned the potential for utilizing kinetic power from fluid movement and other energy harvesting devices to support continuous flow and monitoring. Although she is not specialized in energy harvesting, she is open to testing various methods to determine their efficacy.

Figure 2. Energy harvesting system using liquid movement

Regarding the cost of production, Manoli admitted that she is uncertain about the exact figures but suggested that materials and printing costs may fluctuate over time and shouldn't be a stopper. She reassured that the current high budgets of users employing such devices might offset these costs.

The ultimate objective of Manoli's research is to explore applications involving other materials such as titanium, copper, aluminum, and even non-metallic flexible plastics and resins. She also aims to expand the types of sensors integrated into the pipes, including those measuring flow rate and pressure, with a strong focus on enhancing the monitoring capabilities of these systems.

2.2. Takeaways and insights

After the interview, we realized that AHEAD's technology isn't just about the pipes with embedded sensors, it's about the potential to embed sensors themselves. Furthermore, we realized that the scope of sensors we can embed extends beyond temperature or liquid property measurements alone.

The three primary constraints to overcome are space, weight, and positioning. With this in mind, we began exploring industries that might encounter difficulties with sensors due to these limitations. In the end, we narrowed down our focus to three main questions to explore:

1. In what context or situation are we currently unable to measure or observe something, and where would it be advantageous to do so?
2. What types of sensors or actuators are currently in use, and what issues do they encounter?
3. What embedded systems do already exist?

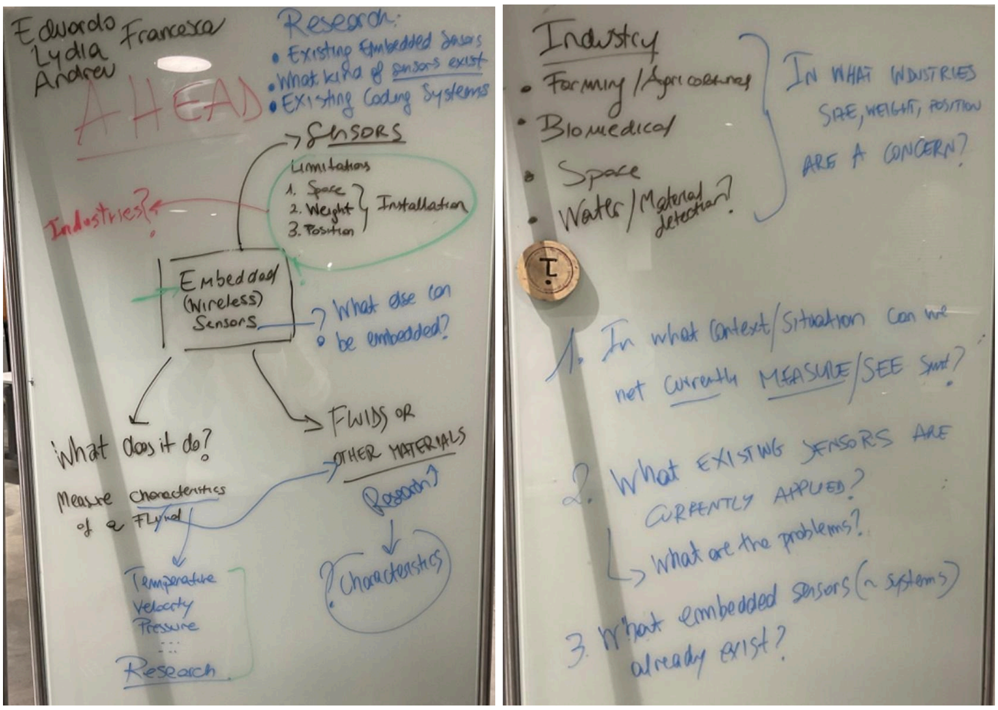

Figure 3. Brainstorming session in Fusion Point after the interview

3. Initial ideas

3.1. Design

During a coaching session with an experienced industrial designer, valuable observations were made regarding the application of 3D metal printing technology with embedded sensors across various industries. The designer highlighted several potential uses for this technology. In engine design, temperature sensors embedded within parts can monitor optimal operating conditions, ensuring the longevity and performance of the engines. In aerospace, components for airplanes or space shuttles can be equipped with sensors to track material flexion, temperature, and critical stress points, potentially preventing failures in parts designed to break under certain tensions. This technology could also be applied to vehicle tires to gather data on performance and wear.

The designer noted that while the medical field presents challenges due to the lack of real-time data requirements for metallic implants, applications such as pacemakers, blood flow measurement, and glucose monitoring could benefit from this technology. These insights emphasize the broad potential of 3D metal printing with embedded sensors, particularly in industries requiring precise monitoring and data collection to enhance safety, performance, and reliability.

3.2. Automotive EV

In our discussions with a co-founder of an electric vehicle (EV) company, several potential applications for 3D metal printing with embedded sensors were explored. While the expert acknowledged numerous possible use cases, he expressed skepticism about the added value of this technology for the EV industry, given that existing measuring tools and software already perform effectively and are integrated into the manufacturing process.

One area where the technology might be useful is the cooling system of EVs, potentially replacing traditional sensors with integrated ones to streamline design and functionality. Additionally, embedding temperature sensors in the stator could enhance performance monitoring. Position sensors in bearings could provide precise data on the rotor's position to optimize the stator's electrical action. However, the expert noted that bearings with integrated sensors already exist, suggesting limited but possible opportunities for improvement in this area. Despite these insights, the overall sentiment was that the current state of sensor technology in EVs is already quite advanced, leaving limited room for the proposed innovations.

3.3. Pollution

Pollution detection is critical for monitoring and managing environmental health, particularly in urban and industrial settings. By integrating sensors directly into the structure of devices, it becomes possible to enhance the functionality of pollution monitoring tools. These embedded sensors can be used to detect pollutants in car exhaust systems, providing real-time data on emissions and helping to enforce environmental regulations. Similarly, they can be employed in industrial pipes to monitor for hazardous substances, ensuring compliance with safety standards and preventing environmental contamination. The ability to customize and quickly produce these devices with AHEAD technology means that sensors can be tailored to specific pollutants and environments, offering precise and efficient detection capabilities.

3.4. Water leaking

The idea is to detect water leaks, which is crucial right now in Catalonia due to the drought. We plan to embed sensors in water pipes to detect vibrations caused by leaks. Leaks in copper, steel, and cast-iron pipes typically produce sounds in the range of 500 to 1,500 Hz, while leaks in PVC pipes generate sounds in the range of 70 to 850 Hz.

We spoke with Adrià Salvans from AVENTEC[1] who provided insights into the current state of the art in this field. He mentioned a meter that already incorporates a sensor to detect leaks: the flowIQ® 2200 by Kamstrup[2].

3.5. Marine exploration devices

Marine exploration devices, such as underwater drones and submersibles, are essential tools for studying and navigating the depths of the ocean. By integrating sensors directly into the structure of marine exploration tools, it becomes possible to enhance their functionality and reliability. These embedded sensors can monitor environmental conditions, detect underwater obstacles, and provide real-time data on pressure, temperature, and salinity. This allows for more precise and efficient exploration and data collection. Additionally, the ability to customize and quickly produce these devices with AHEAD technology means researchers can deploy specialized tools tailored to specific missions more rapidly.

[1] https://aventec.cat/
[2] https://www.kamstrup.com/en-en/water-solutions/meters-devices/meters/flowiq-2200/documents

3.6. Space

In this industry, we've identified two primary areas where AHEAD technology could be beneficial: spacecraft and life support.

Embedded sensors offer a versatile solution across areas like propulsion systems and structural monitoring, payload tracking or fault detection. By integrating sensors directly into these systems, real-time data can be captured, providing invaluable insights into their performance and health without sacrificing space or adding new weight to the structure. This is particularly advantageous in the context of miniaturized satellite systems like CubeSat, as their compact size and adaptability is crucial to make them ideal for space applications where traditional methods may be impractical.

Sensors can also be used to ensure the safety and well-being of astronauts in confined environments by monitoring vital parameters such as oxygen levels, carbon dioxide levels, humidity, and temperature. Moreover, sensors embedded in spacecraft, habitats, or spacesuits can detect and report structural deformations, stress, or damage, ensuring the integrity of critical components throughout missions. Furthermore, we can look for applications of the technology within closed-loop agricultural systems, where sensors are used to monitor plant growth parameters and enable precise control over environmental conditions, optimizing crop growth and ensuring food production sustainability for long-duration missions.

After reaching out to several companies within the aerospace industry, including Pangea Aerospace (known for their work in 3D printed aerospace pieces), Sener and GMV, as well as researchers in ICE-CSIC, the Melissa research group, and PhD student Lluis Contreras Benito specializing in CubeSats, we unfortunately did not receive any responses. As a result, we decided not to keep exploring applications in this industry.

3.7. Blind stick

Blind sticks, also known as white canes, are mobility tools used by visually impaired individuals to navigate their surroundings safely. By integrating sensors directly into the structure of the stick, it becomes possible to enhance the functionality and reliability of these essential mobility aids. These sensors can detect obstacles, changes in terrain, and provide real-time feedback to the user through vibrations or audio signals, thus offering a more intuitive and responsive experience. Additionally, the smart stick can be connected to GPS for navigation assistance, ensuring that users can travel more safely and independently.

The importance of this innovation lies in its potential to significantly improve the quality of life for visually impaired individuals by providing them with greater autonomy and confidence while navigating their environments.

3.8. Monitor cow health and milk quality

Mastitis is a prevalent and costly disease in dairy cattle, significantly affecting animal health and milk production. Clinically affected cows exhibit noticeable udder inflammation, with milk containing clots, lumps, and occasionally blood, whereas subclinical mastitis is diagnosed through somatic cell count tests or the California Mastitis Test. The integration of embedded sensors in milking machines offers a promising solution for early detection. These sensors include coagulation sensors, multispectral vision for lump detection, thermography, ultrasound, and electrochemical or optical sensors for blood detection. Early identification and treatment are crucial for reducing costs, minimizing losses in milk yield and quality, and improving cure rates.

An expert in the field, who conducted a research project on mastitis detection, noted that this technology could bring her redesign project to fruition. She highlighted that the new sensors' space efficiency and cost-effectiveness address significant constraints in existing designs. However, she pointed out a lingering question about whether the complexity lies more in the sensors or the valves required for the system. Despite this challenge, integrating advanced sensors into milking machines has the potential to revolutionize mastitis management, enhancing both economic and animal welfare outcomes in the dairy industry.

3.9. Beer brewing

The beer brewing process, from water preparation to cooking and fermentation, requires precise monitoring to ensure the quality and consistency of the final product. In exploring the application of 3D metal printing with embedded sensors in the beer brewing industry, we consulted with a factory manager who provided valuable insights. The expert expressed enthusiasm about the technology, noting numerous potential uses within the brewing process.

One specific application discussed was the integration of sensors in the tips of hoses used during brewing. These sensors could measure flow speed, volume, and temperature — critical factors that significantly influence the taste and quality of beer. By embedding flow meters within the hoses, brewers can manage the exact volume of beer being transferred, ensuring consistency and precision. Additionally, monitoring temperature and flow speed without the need to open or intervene in the brewing process is crucial, as even minor variations can drastically affect the final product.

The use of metallic connectors at the hose tips further enhances the functionality and durability of these sensor-equipped components. This innovative approach allows for more accurate control and monitoring of the brewing process, ultimately leading to better quality and consistency in beer production. The implementation of such advanced technology in the beer brewing industry demonstrates its versatility and potential to improve traditional manufacturing processes across various fields.

In the following figure, we illustrate the initial steps of developing a prototype as an initial exploration to assess the project's potential. However, as detailed later in this report, we ultimately decided to pursue a different idea.

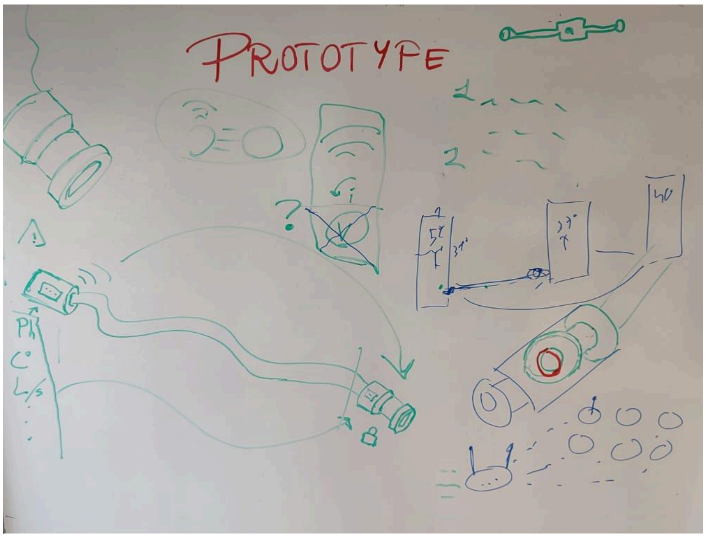

Figure 4. Idea for a prototype for applying embedded sensors in breweries

3.10. Gynecology: Speculum redesign

The Papanicolaou test, commonly known as the Pap smear, is a critical procedure for detecting cervical cancer and precancerous cells. This test involves collecting cells from the cervix and analyzing them in a laboratory. As of January 2022, no sensor-based methods exist that can fully substitute for the traditional Pap smear.

In our preliminary research, we explored the potential for redesigning the speculum, an instrument used during gynecological exams, to incorporate advanced technology. Although the expert we contacted did not respond, we considered how embedding sensors into the speculum could enhance the examination process. Possible innovations might include sensors to monitor tissue health, detect abnormalities, or even collect data on cervical cells in real time, potentially improving the efficiency and comfort of the Pap smear procedure. This approach could pave the way for more advanced, less invasive diagnostic tools in gynecology.

3.11. Prosthetics

Our project ultimately focused on the prosthetic industry, specifically knee replacements, due to the promising potential of 3D metal printing with embedded sensors. Before finalizing this focus, we consulted three medical professionals: a generalist, a physiatrist, and a hip prosthetics expert. Initial research highlighted several potential applications for embedded sensors in orthopedic implants. Load and stress sensors could measure the forces experienced by the implant, providing valuable data on its efficacy and durability. This information could help assess the structural support quality provided by the implant. Additionally, sensors detecting microfractures, wear, temperature changes, and inflammation could alert medical professionals to potential complications such as infections. Remote connectivity would allow for continuous monitoring of the implant's performance, while position and movement sensors could enhance the functionality of joint replacements, ensuring they better mimic the patient's natural movements.

Conversations with the doctors yielded diverse and constructive ideas. They emphasized the importance of defining the specific sensors to be used, considering factors such as plasticity, size, and quantity. They noted that follow-up and continuous monitoring are crucial. The most significant insight was the critical need to monitor wear and the overall state of the prosthetic piece. Wear is a primary concern for prosthetics, and real-time biometric data could be revolutionary in tracking this aspect. The hip prosthetics expert highlighted the limitations of in vitro data and the challenge of gathering accurate in vivo data, due to the difficulty in analyzing prosthetics until they are no longer needed by the patient. This underscores the importance of developing implants that can provide continuous, real-time data throughout their use. By enabling real-time monitoring of wear, load, stress, movement, temperature, and other critical factors, this technology can significantly enhance the performance and longevity of prosthetics, improve patient outcomes, and provide invaluable data for the continuous improvement of prosthetic design and functionality.

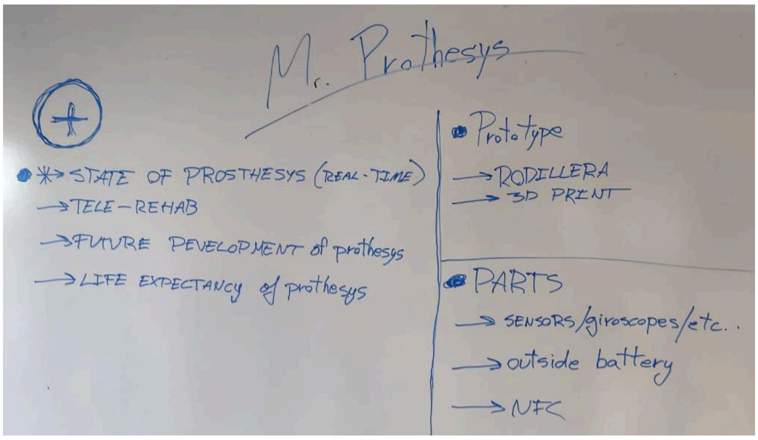

Figure 5. Brainstorming session in IED before travelling to CERN

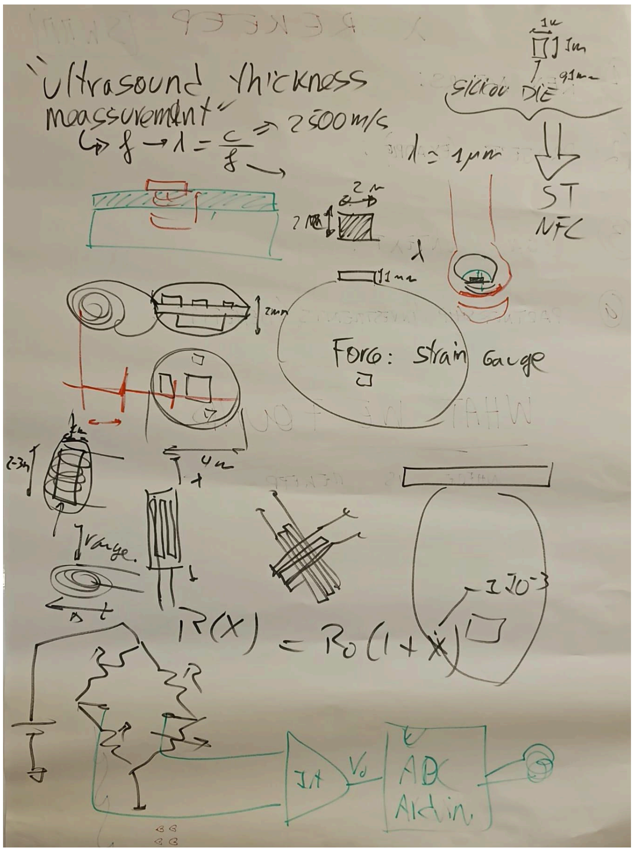

Figure 6. Brainstorming session in IdeaSquare

4. Prosthetics

4.1. Today's problems and state of the art

Today, doctors lack a precise method to monitor the condition of a patient's prosthetics, leading to the industry standard of replacing them after approximately 15 years. Typically, a patient returns to the doctor after this period for an MRI to assess the prosthetic and often decides to replace it. The need for prosthetic replacement arises because the knee's motion wears down the central plastic component over time. To minimize the number of surgeries a patient must endure throughout their lifetime, doctors often delay the initial surgery.

Annually, nearly one million hip and knee replacement surgeries are performed in the United States, reflecting the widespread need for these procedures due to conditions like osteoarthritis and rheumatoid arthritis. This substantial number underscores the importance of developing more durable prosthetics and advanced monitoring techniques to improve patient outcomes and reduce the frequency of invasive surgeries.

According to the American Academy of Orthopedic Surgeons, the demand for knee replacement surgeries is expected to grow significantly, potentially reaching 3.5 million procedures annually by 2030[3]. This growth emphasizes the urgent need for innovations in prosthetic design and monitoring to extend the lifespan of knee implants and enhance the quality of life for millions of patients worldwide[4][5].

4.2. Our solution

We have come up with a way to address the issues mentioned earlier by using AHEAD technology. To do so, we first have to understand how a knee prosthesis works. As you can see in Figure 7, a prosthesis has 3 main parts: The femoral component that is attached to the femur, the tibial component that is attached to the tibia and the patellar component, a plastic piece that goes in between the two metal parts acting as a separator. This last element is the one that wears out during time due to use and friction with movement.

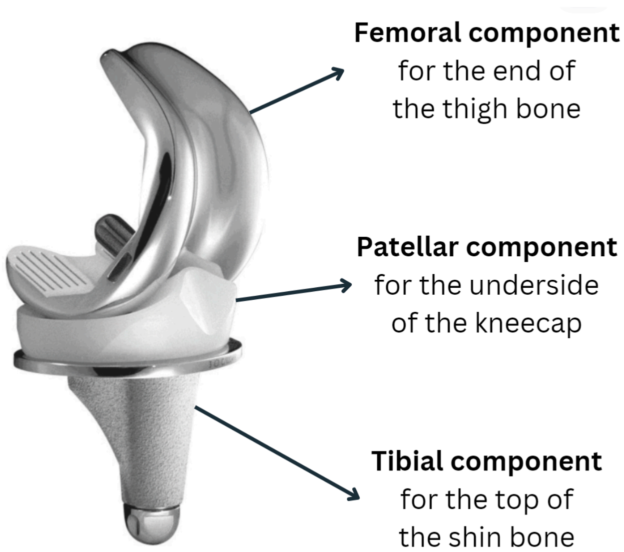

Figure 7. Knee prosthesis and its parts

To monitor the state of the plastic piece, we decided to embed sensors in the tibial component. It's crucial to place the sensor in one of the metallic parts to ensure its proper function, making this component ideal. Furthermore, as it encases the patellar component, it ensures that both parts are always together. Additionally, the tibial component offers enough space to accommodate both a sensor and a microchip inside.

3 https://www.aaos.org/aaos-home/newsroom/press-releases/2022-ajrr-annual-report-announcement/
4 https://www.thecenteroregon.com/medical-blog/knee-replacement-surgery-by-the-numbers/
5 https://www.aaos.org/aaos-home/newsroom/press-releases/american-joint-replacement-registry-releases-2021-annual-report/

Before designing the piece, we need to determine what components need to be included. We will focus on three main parts: the sensor, the power supply, and the communication with the outside.

- The sensor:
  To detect the width of the plastic material, we will use an ultrasound sensor. Here's how it works: When the ultrasound wave encounters a boundary between two materials, part of the wave is reflected. The amount of energy reflected depends on the difference in acoustic impedance between the materials. In this case, we are interested in the ultrasound wave that reflects back from the plastic-metal interface to the transducer[6].

- The power supply:
  Since it is very complex and dangerous to place a battery inside the body, we decided it was unnecessary. Instead, we will power the device from the outside using electromagnetic induction. Inside the device, we will have a ferromagnetic coil that converts the magnetic field from an external source into electricity. This technology is commonly used in mobile phones for wireless charging. However, the power generated by a mobile phone might not be sufficient, so we may need a more powerful device. Additionally, we don't need a constant power supply for the prosthesis, as we only need to read data periodically.

- The communication:
  To communicate with the outside of the knee, we need a transmitter. An NFC chip that can send information through metal and has a range of about 10 cm would be ideal. We found that the company ST[7] offers this technology. We would need to test which specific model is suitable for our prosthesis. Additionally, these NFC chips can power a small circuit, meaning the power supply and communication can use the same technology, eliminating the need for a coil.

Putting all these elements together, we now have a clear idea of what we need. Figure 8 shows a render of the final product. At the bottom is the main circuit, which includes the communication and power supply chip. On top, there are two sensors connected to the main chip. We use two sensors because the femoral component has two support points, and we need to measure both sides since the wear might differ due to the user's movements.

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[6] https://www.researchgate.net/publication/340182304_Monitoring_Mixing_Processes_Using_Ultrasonic_Sensors_and_Machine_Learning
[7] https://www.st.com/en/nfc/st25-nfc-readers.html

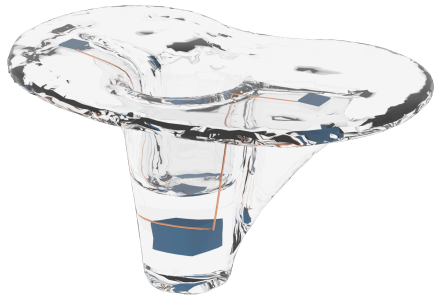

Figure 8. Render of the tibial component with the circuit

4.2. New user experience and benefits

The proposed user journey for prosthetic monitoring begins with post-surgery rehabilitation, an essential phase to ensure the patient's optimal recovery and adaptation to the prosthetic device. Following this, the patient schedules a routine appointment for a check-up to assess the state of the prosthesis, a standard procedure in post-surgery care.

However, in a departure from conventional methods, the evaluation of the prosthetic is conducted using AHEAD technology. Instead of relying on X-ray imaging, MRI or invasive procedures, the doctor utilizes this innovative technology for a non-invasive reading to assess the condition of the prosthetic accurately, and do a diagnosis using his knowledge.

If the evaluation indicates that the prosthetic is functioning correctly, the patient can proceed without further testing. This streamlined process reduces the need for additional medical interventions and allows the patient to leave the appointment promptly.

The benefits of this approach are significant for both patients and medical resources. Patients experience reduced risk, with minimized need for revision surgeries and invasive tests, leading to enhanced quality of life and potential for remote check-ups. Medical resources benefit from time optimization and equipment efficiency, as AHEAD technology streamlines the evaluation process and minimizes reliance on costly diagnostic equipment.

In summary, the proposed user journey leveraging AHEAD technology revolutionizes prosthetic monitoring by providing real-time data, minimizing unnecessary interventions, and empowering patients to take an active role in their healthcare journey. This approach not only enhances patient outcomes but also optimizes medical resources and paves the way for future advancements in prosthetic technology and patient care.

4.3. Future work

In the future, the integration of artificial intelligence (AI) and machine learning (ML) stands as a symbol of transformative potential. These cutting-edge technologies offer the unprecedented ability to predict wear patterns and potential failures in prosthetic devices with even greater accuracy. By leveraging AI and ML algorithms, doctors can implement preemptive maintenance measures, ensuring optimal performance and durability of prosthetic limbs. Moreover, this predictive capability facilitates the development of personalized prosthetic solutions tailored to individual needs and preferences, initiating a new era of orthopedic care marked by improved patient outcomes and better quality of life.

Furthermore, the future of prosthetic technology anticipates a significant shift towards remote monitoring and patient engagement, allowing patients to perform remote checks on their prosthetic, leading to timely detection of any issues or abnormalities. This proactive approach empowers patients to take control of their healthcare journey, generating a sense of independence and confidence.

Moreover, the integration of additional sensors, such as stress sensors or others mentioned in the initial ideas section, further boosts the functionality and utility of these next generation prosthetic devices. These kinds of sensors can monitor the forces applied by users during various activities, providing valuable insights into rehabilitation progress and optimizing prosthetic fit and function. Sensors embedded within prosthetic devices can continuously monitor device integrity and use, and alert users and doctors to any potential issues, facilitating interventions and ensuring the longevity of the prosthetic and wellbeing of the patient.

5. Prototype

5.1. 3D printing

For the project, we developed a prototype that demonstrated the potential of the AHEAD technology, which utilizes 3D metal printing with embedded sensors for prosthetic applications. Our prototype was created using a standard PLA 3D printer, simulating the manufacturing process of AHEAD.

The prototype was a scaled-up recreation of a human knee with a prosthetic, including various parts designed to showcase the integration of our innovative technology. The key component of our prototype was a redesigned section of the knee prosthesis. This part was also printed separately, with different cuts to reveal the internal structures and demonstrate where sensors could be embedded. We used pins to assemble the parts, allowing for easy disassembly and examination of the prototype's internal features. To enhance understanding of the components, we rendered the 3D model from multiple points of view using transparent materials, providing clear visibility of the intricate details. This approach ensured that the functionality and benefits of the AHEAD technology were effectively communicated through our prototype.

For a more advanced prototype we envision using 3D titanium printing, also known as direct metal laser sintering (DMLS) or selective laser melting (SLM), which offers numerous advantages for prosthetic applications. Titanium is an ideal material due to its biocompatibility, high strength-to-weight ratio, and corrosion resistance, making it suitable for long-term implantation within the human body. The process involves melting titanium powder layer by layer using a high-powered laser, precisely forming complex geometries with exceptional accuracy. This additive manufacturing technique allows for the creation of custom-designed prosthetic components tailored to each patient's specific anatomy and needs. Unlike traditional manufacturing methods, 3D titanium printing eliminates the need for extensive machining and tooling, resulting in reduced waste, shorter lead times, and lower costs. Additionally, the ability to embed sensors directly into the titanium structure enhances the functionality of prosthetics, enabling real-time monitoring of various parameters such as load, stress, and temperature. Overall, 3D titanium printing revolutionizes the production of prosthetic devices, offering unprecedented customization, durability, and performance.

5.2. NFC chip

To replicate NFC communication with the outside of the knee, we considered using a small NFC tag as a prototype. We discovered that Texas Instruments offers a high-frequency NFC tag measuring 4x4 mm, compatible with ISO15693[8] (a standard protocol readable by most phones). By placing one of these tags inside the open 3D printed piece, it can be read from the outside.

6. Conclusions

The journey through this course contained numerous challenges and learning opportunities. As a team, we were able to overcome all the obstacles collaborating and resulting in cohesive decisions to problem-solving. This unity and mutual understanding were crucial to develop a project of these characteristics. Even though we came from diverse backgrounds, we could bring different perspectives and skills that enriched our final result. This diversity was evident in our brainstorming sessions, where we evaluated the different applications of AHEAD.

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[8] https://www.ti.com/product/es-mx/RF37S114

Developing the prototype also was a technical challenge; we had to work with 3D printers and NFC technology to create a model that could demonstrate the feasibility of our concept. This hands-on experience made us further understand the manufacturing processes and the technical challenges that could cause.

Our developed solution can have huge potential in the innovation field. If we integrate artificial intelligence to the monitoring of the prosthesis, we could enable predictive analysis and personalized care for the patient. Additionally, all the data collected can help improve the devices (design, materials, functionality…)

In conclusion, our project has helped us delve into lots of different areas and gain new skills, knowledge and insights. We are grateful to be able to collaborate with people from different disciplines and with advanced technologies to address real-world problems. Our work on sensor-embedded knee prosthetics represents a significant step forward in medical innovation, and we are excited about the future possibilities in this field. Working together has been a pleasure, and we are proud of the innovative solution we have developed, which we believe has the potential to make a meaningful impact in the medical field.