Towards Self-Powered Smart Contact Lenses: Integration of Autonomous Power Sources, Microfabricated Antennas, and Multidisciplinary Design Constraints

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ABSTRACT

We present a multidisciplinary approach to self-powered smart contact lenses integrating autonomous energy sources, microfabricated antennas, and advanced materials. Power is harvested via tear-based biofuel cells, blink-activated nanogenerators, and kinetic motion, enabling continuous operation without external power. A 9.5 mm double-loop antenna operates in the low microwave band, supporting robust wireless communication. Design integrates ASICs, sensors, and hybrid energy systems into a biocompatible, transparent lens. Key challenges addressed include thin-film coatings, SAR compliance, signal integrity, and uncertainty quantification. This work lays the foundation for smart lenses enabling real-time biosensing, health monitoring, and augmented vision in fully autonomous wearable devices.

Keywords: lens, eye, energy, optics.

1. INTRODUCTION

The rapid development of smart contact lenses (SCLs) [1-4] is opening new frontiers in non-invasive health monitoring, augmented vision, and biomedical applications. This work provides a multidisciplinary analysis of the challenges and solutions related to the integration of autonomous energy sources, advanced antenna systems, and complex design constraints necessary for fully functional smart contact lenses [5-6]. In a part 2, the functional principles of smart contact lenses are examined, emphasizing their ability to perform continuous health monitoring (e.g., glucose levels, intraocular pressure), deliver augmented vision functionalities (e.g., real-time text translation, night vision), and offer visual aids for the visually impaired. Central to these applications is the integration of sensors, ASICs, and communication modules into a miniaturized, biocompatible platform. Material selection, such as polydimethylsiloxane (PDMS), plays a critical role in ensuring optical clarity, flexibility, and long-term biocompatibility. Recent advancements in microfabrication, including 3D printing and multi-material direct laser writing, enable precise structuring of micro-lenses and adaptive optical elements within the confined volume of the lens. Part 3 addresses one of the fundamental challenges for these devices: autonomous powering. Several innovative approaches are explored, leveraging the body's intrinsic resources and surrounding environment. Tear salinity is harnessed via biofuel cells, utilizing the electrolyte-rich tear fluid to drive redox reactions in micro-batteries [7-9]. Biomechanical energy from blinking is converted into electrical power through nanogenerators, enabling efficient and sustainable energy harvesting without discomfort. Additionally, kinetic energy from head and body movements is proposed as a complementary energy source. The integration of multiple energy harvesting mechanisms demands precise design and hybridization strategies to balance power supply, spatial constraints, and user comfort. Conceptual integration roadmaps are presented to guide the miniaturization and assembly of these hybrid systems, ensuring efficient energy management while maintaining lens transparency and breathability. Part 4 delves into the necessary technical expertise and stringent design constraints required for the successful realization of these systems. The fabrication of thin-film optical coatings is vital for enhancing lens performance while maintaining durability and safety. The analysis of material interfaces and biocompatible coatings is critical for safe and long-term ocular contact, ensuring compliance with international safety standards such as SAR (Specific Absorption Rate) guidelines. Wireless communication requires careful frequency analysis, particularly in the 900 MHz to 1.1 GHz range, which balances data transfer efficiency with minimal interference and energy consumption. Furthermore, signal integrity diagnostics, uncertainty quantification, and comprehensive knowledge of the patent landscape are essential components of the development process, ensuring not only functional viability but also commercial protection and regulatory compliance. Together, these multidisciplinary efforts create a robust foundation for the advancement of smart contact lenses. By uniting innovations in biosensing, micro-scale energy harvesting, and high-frequency antenna design, this research paves the way for next-generation, self-powered, networked contact lenses capable of providing real-time health monitoring, augmented reality, and advanced visual assistance in a fully autonomous and biocompatible form.

2. SMART CONTACT LENSES: FUNCTIONAL PRINCIPLES

Smart contact lenses integrate sensors, communication interfaces, and power management circuits into a transparent, soft substrate worn directly on the cornea. Potential use cases include: (i) Non-invasive health monitoring (e.g., glucose or intraocular pressure), (ii) Augmented vision (e.g., night vision, real-time text translation), (iii) Visual aids for the visually impaired. Thiele et al presents the first demonstration of 3D-printed hybrid refractive/diffractive achromatic and apochromatic micro lenses using multi-material direct laser writing, significantly reducing chromatic aberrations in the visible range by combining diffractive surfaces and photoresists with different dispersions [10]. The same group 3D-printed a compact, multi-lens foveated camera system directly onto a CMOS chip, mimicking eagle vision by combining lenses with varying focal lengths to enhance central image resolution [11]. Interesting functionalities can be achieved by working with materials such as Polydimethylsiloxane (PDMS) for 3D-printed lenses. PDMS an elastomer with excellent optical, electrical and mechanical properties, which makes it well suited for several engineering applications. More recently, advanced 3D printing methods, including two-photon polymerization, have given researchers new ways to create tiny, precise structures and complex lens shapes.

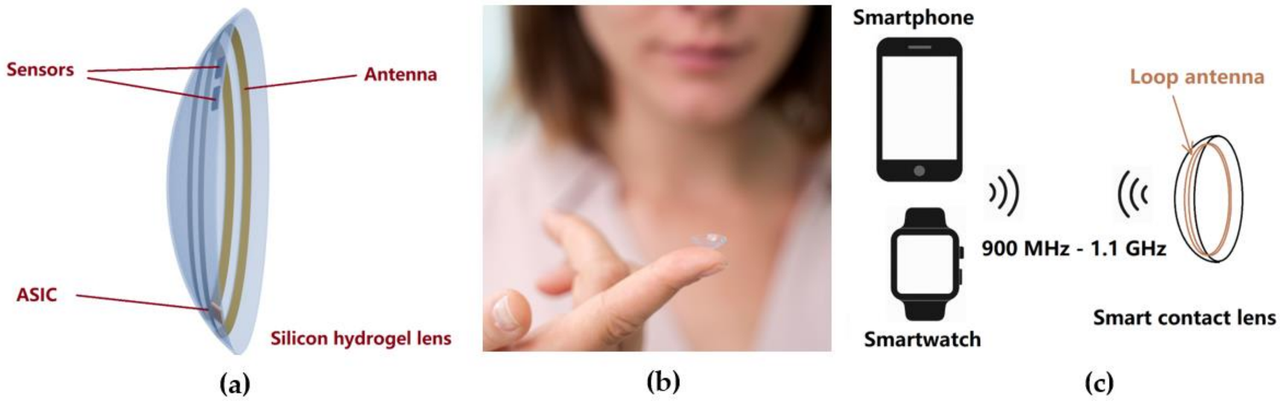

Figure 1. (a) This Figure illustrates the general principle of making a contact lens, which includes an antenna, an application-specific integrated circuit (ASIC), and sensors to communicate with a smartwatch, a mobile phone, or a computer. Technologically, the addition of components in a lens allows, if necessary, to position a progressive contact lens by correctly orienting it. These technologies are feasible. (b) This Photography [12] illustrates the scale and delicacy of a standard contact lens, highlighting the complexity of embedding electronic systems within such a confined space. (c) Illustration of the communication between a smart contact lens and a smartwatch and/or a smartphone. Indicated frequency bandwidth corresponds to what is discussed in [6,13].

Building on these developments, our research aims to develop new adaptive optical parts for contact lenses using the latest microfabrication tools. The design must balance miniaturization, transparency, oxygen permeability, and mechanical comfort. The integration of components integrated into the lens is shown schematically in Figure 1. Advanced materials such as flexible biocompatible polymers and nanoscale thin films are crucial to achieving these goals. Recent reviews have discussed material advances and sensor integration for ophthalmic applications. Smart contact lenses are emerging wearable devices that enable non-invasive disease monitoring and therapy by detecting various ocular biomarkers and delivering drugs, although their development is still in early stages [14]. Smart contact lenses are being actively developed for non-invasive health monitoring by leveraging the eye's ability to reveal both physical and chemical biomarkers, with recent advances focusing on biosensing, data transmission, drug delivery, and energy storage technologies [15]. Tear exchange between the ocular surface and contact lenses is limited, especially with soft lenses, leading to debris build-up and potential complications, and despite innovations in lens design and measurement methods like fluoro-photometry, understanding of tear hydrodynamics and exchange remains insufficient [16].

3. AUTONOMOUS POWERING VIA EYE-INTRINSIC OR OTHER SOURCES

This development of smart contact lenses has accelerated, driven by advancements in bio-compatible electronics and the growing need for autonomous wearable devices. A key challenge remains: how to provide sustainable, safe, and efficient power to these miniature systems. This section explores emerging strategies for energy harvesting directly from the human body or its immediate environment. Section 3.1 investigates the use of tear salinity as a natural electrolyte for powering biofuel cells. Section 3.2 focuses on biomechanical energy generated from blinking, leveraging nanogenerators to convert motion into electricity. Lastly, Section 3.3 considers other potential sources, including kinetic energy from head and body movements, offering new avenues for self-sustaining smart lenses, and Section 3.4. discuss aspects of integration.

3.1. Energy from tear salinity : Tears contain a mixture of electrolytes—mainly sodium and potassium ions—that can be harnessed for low-power biofuel cells. Recent developments have demonstrated tear-based micro-batteries that operate continuously by leveraging this natural saline environment as discussed in the introduction. In particular, glucose-coated ultra-thin batteries can undergo redox reactions catalyzed by tear fluid, extending the lens's operational time. It has to be underlined that in Singapore, the group of Seok Woo Lee from Nanyang Technological University (NTU), demonstrated a prototype contact lens with such a battery, capable of lasting 13 hours using only tear fluid as an energy source [8,9,17], where it is shown how recent advancements in smart contact lenses (SCLs) have led to innovative features like overlaying information and monitoring blood glucose levels, but these require a reliable power source. Lithium-ion batteries are currently used, but due to safety concerns, polymerized hydrogels like Copper Hexacyanoferrate (CuHCFe) and Prussian Blue (PB) – or Preußischblau in German (used in medicine as an antidote for certain kinds of heavy metal poisoning and for electrochemical energy storage) [18], are being explored as safer alternatives, with promising results showing a storage capacity of 0.132 mAh (the amount of current that a battery can supply for one hour before it is fully discharged), when tested with tear solutions. The lens remains fully biocompatible and safe for prolonged use.

3.2. Energy from blinking : An alternative energy harvesting method relies on biomechanical motion. Eyelid blinking, occurring tens of thousands of times daily, can actuate piezoelectric or triboelectric nanogenerators. Innovative hybrid systems combining a flexible silicon photovoltaic cell with a blink-activated Mg–O_2 collector have been proposed [19], enabling dual-mode energy capture (optical and mechanical): this paper discusses a hybrid energy generation system for powering smart ocular devices, combining a flexible silicon solar cell and an eye-blinking activated Mg–O2 metal–air harvester. The system continuously generates electrical power, providing stable DC output without needing external accessories, with power management circuits boosting voltages for consistent energy supply to ocular devices. Such energy harvesting solutions pave the way for fully autonomous, wire-free lenses that recharge "in the blink of an eye."

3.3. Other potential sources : It's possible to imagine other energy sources that could help smart lenses function. Natural head movements or the movements of an individual walking or running are possible potential energy sources that could be used to drive smart lenses. We know that the human body involves an expenditure of energy which can also be approached in frequency terms [20]. What is generally perceived as an energy cost could turn out to be a source of energy for microdevices. Utilization of elastic energy in human movement is definitely a possible source for micro batteries [21].

3.4. Integration : Integrating multiple energy harvesting methods into 10 mm smart contact lenses demands such a conceptual roadmap. This includes optimizing a miniaturized energy source through hybrid systems — Power source — while maintaining biocompatibility. A 9.5 mm double-loop antenna must be precisely deposited on the periphery of the lens. A low power ASIC manages power distribution and sensor data. The integration of two or more sensors requires careful spatial design to ensure seamless functionality, user comfort, and reliable wireless communication within the compact lens architecture. In addition, antennas and active or passive components must be protected by a thin layer ensuring the passage of oxygen and biocompatibility. For 3D-printed lenses, manufacturing processes become more complex. We remind that the weight asymmetry due for example to ASIC is a guarantee of self-alignment for lenses correcting astigmatism or presbyopia. Figure 2 illustrates how the integration of a miniaturized energy source obviously requires specific design work adapted to a contact lens.

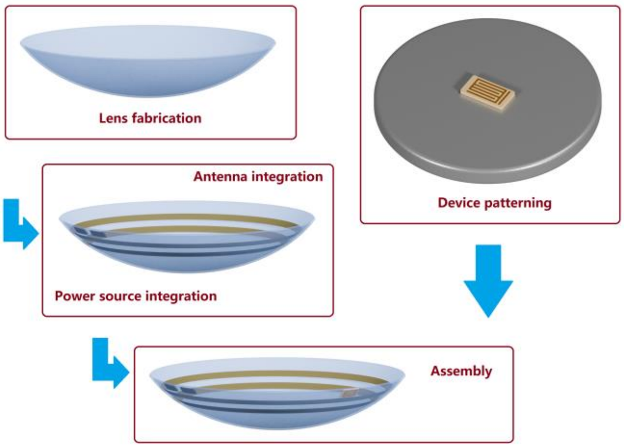

Figure 2. This Figure illustrates the conceptual roadmap for integrating multiple energy harvesting methods into 10 mm diameter smart lenses.

4. TECHNICAL EXPERTISE AND DESIGN CONSTRAINTS

The development of smart lenses—devices capable of integrating various technologies for visual enhancement or information display—is a highly complex challenge. The feasibility of creating these lenses hinges on expertise in multiple technical domains. Here is a deeper look into the Following five points:

- *Fabrication of thin-film optical coatings related to our experience in lens manufacturing*: The fabrication of thin-film optical coatings [22,23] is crucial for controlling the behavior of light passing through or reflecting off the lens surface. These coatings can serve various purposes, such as enhancing the optical quality of the lens, providing anti-reflective properties, or enabling the lens to interact with light in specific ways (e.g., filtering, polarization control). Achieving precise and high-quality fabrication of these coatings is essential to ensure that smart lenses not only meet optical requirements but also maintain durability, especially in demanding environments like every day wear or medical applications.
- *Analysis of material interfaces for biocompatible coatings and signal transfer – Specific Absorption Rate (SAR):* The interaction between materials used in the smart lens must be carefully considered, particularly in areas where the lens will come into direct contact with human tissues or fluids, such as the eye. Biocompatible coatings are necessary to prevent irritation, inflammation, or other adverse effects. These coatings should not only be chemically compatible with the tissues of the eye but also enable efficient signal transfer (such as through wireless communication or light signals) without degrading over time. Understanding and analyzing material interfaces [24] is critical because any imperfections in these interfaces could lead to issues like reduced optical performance, unreliable data transfer, or irritation. Research in biocompatible coatings and materials, therefore, plays a significant role in ensuring that smart lenses are safe, functional, and long-lasting. For individuals using SLCs, it's crucial to ensure that the magnetic loop antenna's emitted power remains within safe limits to prevent potential harm to the human body. Regarding Specific Absorption Rate (SAR) standards, SAR measures the rate at which the body absorbs energy from radio frequency electromagnetic fields, expressed in watts per kilogram (W/kg). Various international standards define exposure limits to ensure safety. For example, the European Union sets a SAR limit of 2.0 W/kg averaged over 10 grams of tissue [25,26]. It is legally and medically reasonable to follow the precautionary principle: for SAR, there is no standard that specifically concerns a device or a component that would be in contact with the eye, which is why it is prudent to refer to the two standards IEC/IEEE 62209-1528:2020 [25] and IEC 62209-3:2019 [26] that concern SAR of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices, in particular IEC 62209-3:2019. In the United States, the Federal Communications Commission mandates a SAR limit of 1.6 W/kg averaged over 1 gram of tissue for mobile devices. In China, the maximum permitted SAR value for mobile phones is 2.0 W/kg, measured over 10 grams of tissue, with the same standard used in Europe, based on the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. In India, the SAR limit for mobile devices is 1.6 W/kg.
- *Frequency analysis and signal integrity diagnostics in systems*: Smart lenses integrate systems that use light (optical signals) to perform tasks like image recognition, display projection, or health monitoring.

The performance of these systems depends heavily on maintaining the integrity of the signals being transmitted and received. Any disruption in the signal (due to noise, interference, or attenuation) can significantly impair the functionality of the lens. Frequency analysis is vital to understanding how signals behave [27,28] in the components of the lens, especially in the context of wireless communication (e.g., 2400 – 2483.5 MHz Bluetooth, 2.4 GHz Wi-Fi for 450 Mbps or 600 Mbps, 5 GHz Wi-Fi for up to Gbps, 900 MHz 3G, 1800 4G, and 3.5 GHz 5G microwaves for upper bandwidth) and power transfer. Signal integrity diagnostics are necessary for detecting and troubleshooting issues in signal transmission, ensuring reliable operation of the smart lens over time. Ensuring that these components operate seamlessly is crucial for the lens to function as intended. In France, for example, the distribution of frequency bands is codified and distributed by the National Frequency Agency. The National Frequency Band Allocation Table is set by a decree of the Prime Minister [29]. The frequency band likely to be used for communications between SLCs and a smartphone or smartwatch is in the band around 1 GHz, as we see in reference [13]. It is therefore important to control the risks associated with potential intermodulation effects. This problem has been the subject of studies, both regarding passive intermodulation distortion in antennas [30], and for the interaction with amplifier elements in electronics [31–33]. Just above 1 GHz, another widely used application is Global Navigation Satellite System (GNSS) [34–37], with bottom of the lower Band-L (1.151–1.214 GHz) for GPS L5 and Galileo E5 are located, with E5a and L5 coexisting in the same frequencies. The remaining L2 (GPS), G2 (GLONASS) and E6 (Galileo) signals are in the 1.216–1.350 GHz bandwidth. These bands are allocated to Radio-location Services for ground radars by the Aeronautical Radio Navigation Service and Radio Navigation Satellite System on a primary basis, thence the signals in these bands are more vulnerable to interference transmission and reception signals up to 1.1 GHz.

- *Uncertainty quantification in measurement systems*: Measurement uncertainty is an inherent challenge in any engineering system, especially one that integrates many advanced technologies. For smart lenses, this uncertainty could affect a variety of measurements, such as light intensity, optical alignment, sensor readings, and even user interaction. Quantifying this uncertainty helps engineers design systems that account for potential errors and variability in performance. By applying uncertainty quantification techniques, such as statistical analysis and error modeling, developers can ensure that their smart lenses provide reliable, consistent performance even in the face of manufacturing tolerances, environmental variations, or wear and tear over time. This is essential for ensuring the accuracy of measurements and the overall effectiveness of the device. We rely on our experience in calculating uncertainties on complex microwave optics systems [28, 38–41].
- *Patent landscape awareness to secure intellectual property and funding*: Intellectual property (IP) is a key asset when developing innovative technologies such as smart lenses [42,43]. A deep awareness of the patent landscape allows developers to protect their innovations from competitors and ensure that their work doesn't infringe on existing patents. Additionally, a strong IP portfolio can be essential for securing funding from investors or institutions, as it adds credibility to the project and demonstrates a clear competitive advantage. The patent landscape for smart lenses likely includes patents for the lens design itself, the technologies integrated into the lenses (e.g., microelectronics, sensors, wireless communication), and methods for manufacturing these lenses. Staying ahead of trends in patent filings and securing broad protection for novel innovations can be a strategic advantage.

These domains must converge to develop viable, safe, and functional prototypes of energy-autonomous smart lenses. The development of energy-autonomous smart lenses requires the convergence of all these areas of expertise. Successful integration of thin-film coatings, biocompatible materials, optoelectronic systems, and robust signal diagnostics must occur within a framework of intellectual property management and careful measurement of uncertainties. For example, a lens that uses optical coatings to enhance visual quality must also have embedded sensors or electronics that are seamlessly powered and communicate with external devices without interference or signal degradation. The integration of these technologies is not only about functionality but also about user safety and usability. The ultimate goal is to create a viable prototype that is not only functional but safe to use, efficient in power consumption (hence autonomous), and manufacturable at scale. Creating smart lenses is a multidisciplinary endeavour where expertise in optics, materials science, electronics, patent law, and system engineering must be harmonized to ensure the development of safe, high-performing, and commercially viable products.

4. CONCLUSION

The development of self-powered smart contact lenses represents a convergence of cutting-edge science and engineering, bridging optics, microelectronics, energy harvesting, and biomedical design. By integrating autonomous energy sources such as tear-based biofuel cells, blink-driven nanogenerators, and kinetic harvesters with advanced microfabricated antennas, these lenses move beyond conventional vision correction into multifunctional platforms capable of continuous sensing and communication. The research presented highlights not only the technical feasibility of such systems but also the complexity of balancing miniaturization, transparency, comfort, and biocompatibility. Equally critical are the safety and regulatory dimensions, including compliance with SAR standards and long-term biocompatibility of thin-film coatings. Frequency allocation, signal integrity diagnostics, and uncertainty quantification further underscore the multidisciplinary expertise required to ensure functional reliability. At the same time, awareness of the patent landscape and intellectual property protection will be vital in translating prototypes into scalable, commercially viable products. The promise of smart contact lenses extends well beyond augmented vision, encompassing real-time health monitoring, drug delivery, and adaptive visual aids for patients with chronic conditions or impaired sight. With continued progress in microfabrication, hybrid energy systems, and biosensor integration, smart lenses are poised to become powerful tools at the intersection of healthcare, wearable technology, and human–machine interaction. Ultimately, this work lays the groundwork for a new generation of autonomous, biocompatible, and networked ocular devices that could transform personalized medicine and redefine how humans interact with digital and biological environments.

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