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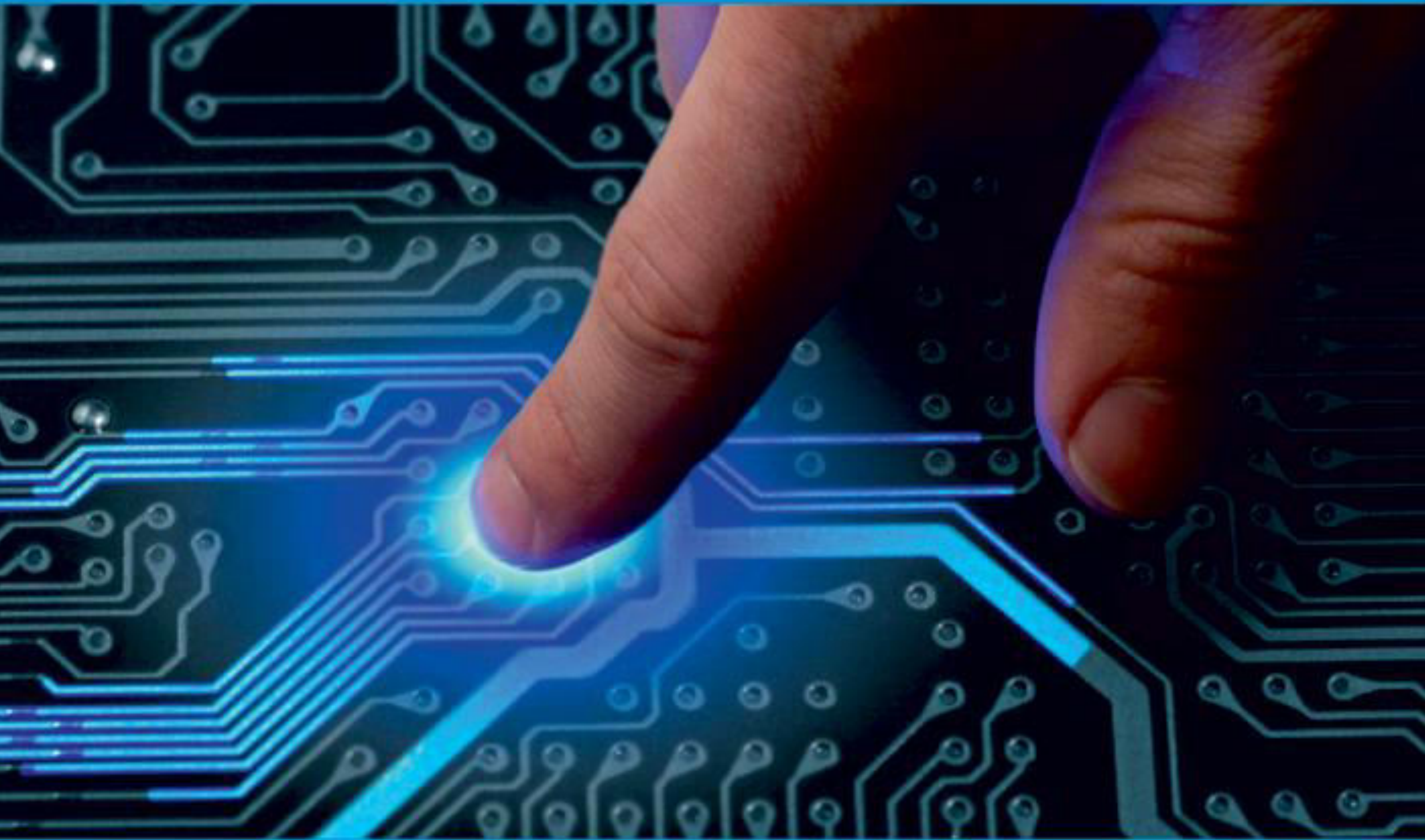

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Survey Paper on Droplets as Liquid Robotics

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ABSTRACT: Robotics for scientific study are progressing from gripping macro-scale solid materials to directly controlling micro-scale liquid samples. However, present liquid actuation devices frequently limit operable liquid kinds or impair the activity of biological samples by adding interfering media. Here, we propose a robotic liquid handling system enabled by a unique droplet actuation mechanism known as electret-induced polarization on droplet. EPD allows for all-liquid actuation and is applicable to inorganic/organic liquids with permittivity ranging from 2.25 to 84.2 and volume from 500 nL to 1 mL. Furthermore, EPD can activate a wide range of biological samples, including body fluids, living cells, and proteins, without interfering with their activity. A robotic system is also integrated with the EPD mechanism to enable complete automation. EPD's excellent adaptability to various liquid types and biological samples encourages the automation of liquid-based scientific research across numerous fields. Current liquid actuation systems are limited to specific liquid types, otherwise they risk contaminating biological samples with interfering media. The authors describe electret-induced polarisation on droplets (EPD), a method for all-liquid actuation that is applicable to a variety of inorganic/organic liquids and biochemical samples.

The field of liquid robotics is gaining momentum, with droplets at the forefront as a versatile medium for robotic systems. This paper explores the use of droplets in liquid robotics, highlighting their unique properties such as fluidity, adaptability, and surface tension, which make them ideal candidates for robotic functions. Liquid-based robots, unlike their solid counterparts, can deform, self-heal, and traverse narrow, complex environments. By leveraging the precise control of droplet formation, movement, and interactions, these systems can be applied in a variety of domains, including microfluidics, targeted drug delivery, diagnostic systems, and environmental sensing.

I. INTRODUCTION

Liquid droplets exhibit unique properties, such as surface tension, fluidity, and adaptability, which make them a promising medium for robotic applications. Unlike conventional solid robots, liquid-based robots can change their shape, move through narrow spaces, and self-heal. These attributes are particularly useful for developing flexible, reconfigurable, and biocompatible robotic systems. In the context of robotics, the manipulation of droplets—whether individually or collectively—offers the ability to create programmable fluidic systems. These systems can be used for targeted drug delivery, diagnostic testing, microfabrication, and environmental sensing, among other applications. For instance, the precise control of droplet formation, movement, and merging allows for the creation of dynamic microfluidic circuits that can execute a wide range of tasks. Key challenges in this field include understanding the dynamics of droplet behavior under various conditions, developing control mechanisms for droplet manipulation, and integrating liquid-based systems with electronic and mechanical components. Researchers are exploring interdisciplinary approaches combining physics, chemistry, biology, and engineering to overcome these challenges and unlock the full potential of liquid robotics.

The advent of digital microfluidics has further accelerated research in this area, enabling the manipulation of droplets via external forces like electric fields, magnetic fields, and acoustic waves. This opens up possibilities for creating highly controllable and programmable liquid robotic systems.

Liquid robotics, especially those based on droplets, represent a new paradigm in robotic design—one that emphasizes flexibility, adaptability, and biocompatibility, making it ideal for applications that require precision and responsiveness at a micro or even nano scale.

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II. PROBLEM STATEMENT

The field of robotics has traditionally been dominated by solid-state systems, which are often rigid and limited in their ability to adapt to complex, dynamic environments. This rigidity poses significant challenges for applications that require flexibility, reconfigurability, and precision, particularly at the microscale. In contrast, liquid-based robotic systems, specifically droplet-based robots, offer unique advantages due to their fluidity, biocompatibility, and ability to change shape. However, despite these potential benefits, several critical issues remain unresolved, limiting the practical deployment of droplet-based liquid robotics in real-world applications.
Key challenges include:

1. **Precise Control of Droplet Manipulation**: Droplet movement, merging, and splitting are essential functions in liquid robotics. Current manipulation techniques, such as electrowetting, magnetic control, and acoustic waves, offer promising solutions but face limitations in achieving high precision, speed, and scalability, particularly in complex environments.
2. **Integration with Conventional Robotics and Systems**: While liquid robots excel in flexibility, they struggle to integrate with solid components like sensors, actuators, and control systems. The lack of seamless integration between liquid and solid systems limits the full exploitation of liquid robotics in industries such as healthcare, environmental monitoring, and industrial automation.
3. **Energy Efficiency and Power Consumption**: Controlling droplets typically requires external energy inputs, such as electrical, magnetic, or acoustic fields. Current methods often consume significant power, which is impractical for energy-constrained environments or for long-duration operations, particularly in biomedical applications like drug delivery or diagnostics.
4. **Scalability and Reproducibility**: Scaling up liquid robotic systems for industrial applications remains a major challenge. Creating consistent, reproducible droplet behavior in large arrays or in unstructured environments has not yet been fully realized, limiting the technology's broader adoption.
5. **Environmental and Biocompatibility Constraints**: For biomedical applications, ensuring the biocompatibility and stability of droplets in diverse biological environments is critical. This raises concerns about the materials used in droplet formation and the potential toxicity of agents used for control (e.g., magnetic nanoparticles or surfactants).

III. DROPLETS AND VESICLES

Droplets require immiscibility between at least two phases (gas-liquid or liquid-liquid). Surface tension, caused by attractive and repulsive interactions between molecules, determines the shape of the droplet. Standard examples are water droplets in air [95], water droplets in oil [5], and oil droplets in water [24]. Molecules can preferentially partition into water or oil phases based on their hydrophilic or hydrophobic characteristics. Oil-soluble dyes (e.g., Oil Red O, Sudan Black) enhance oil phase visualisation, while inorganic salts (e.g., NaCl) dissolve more easily in aqueous phases. Surfactants, amphiphilic molecules with hydrophilic and hydrophobic groups, self-assemble at the phase border (see Figure 1). Surfactants are surface-active chemicals that reduce interfacial tension between two phases.

Although droplets can form without surfactants, surface-active molecules that self-assemble at the droplet border can influence the interfacial tension and droplet characteristics. Surfactants help stabilise droplets by reducing interfacial tension and preventing coalescence. A vesicle is defined as an aqueous droplet with a continuous lipid bilayer in the bulk aqueous phase. The vesicle is defined by the amphiphilic molecules that self-assemble on its surface. A vesicle is a water-in-oil-in-water droplet composed of an aqueous core for water-soluble molecules and a lipid bilayer membrane for oil-soluble molecules. Vesicles are found throughout the continuous water phase and range in size from tens of nanometres to hundreds of micrometres. Liposomes are artificial vesicles manufactured from phospholipids or biomembranes. They are utilised for a variety of purposes, including artificial cells and medication administration in microcontainers.

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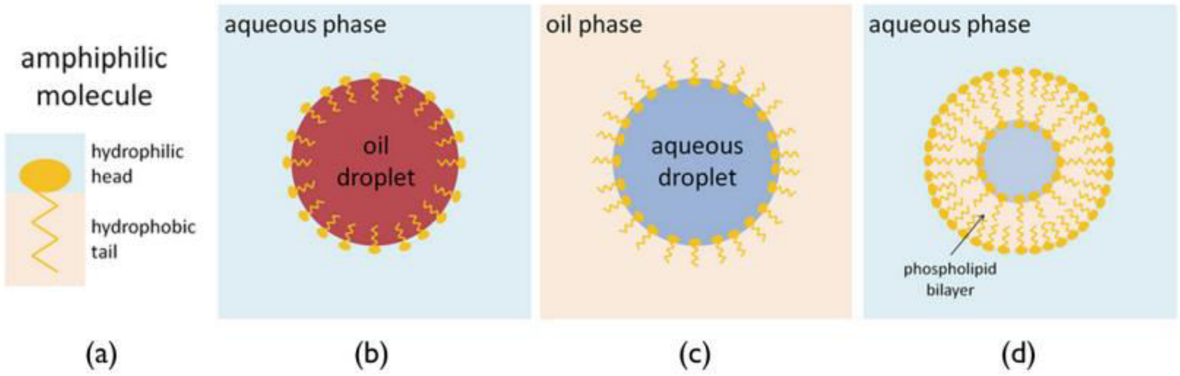

Figure 1 (a) depicts an amphiphilic surfactant with a hydrophilic head that preferentially partitions in the aqueous phase and a hydrophobic tail that partitions in the oil phase. Surfactant designs in multiphase systems include oil droplets in water, aqueous droplets in oil, and phospholipid bilayer vesicles.

Droplets can be created in a variety of ways. Dropping liquid from a micropipette or syringe may easily create a single or several droplets. Various processes, including as atomisers, nebulisers, and homogenisers, can create large droplets. These methods create emulsions with dozens to millions of droplets scattered throughout the continuous phase.

Typical topologies include oil-in-water (Figure 1b) and water-in-oil (Figure 1c) emulsions, although more complicated structures like double emulsions also occur [36]. Robotic platforms and microfluidics can generate and analyse droplets. In general, droplets are easily generated.
Surfactants improve long-term stability by increasing the system's kinetic stability.

IV. MOVING DROPLETS

Droplets can be designed to move and controlled by various external forces, allowing them to mimic the behaviour of both nonliving objects, such as rocks rolling down a hill, and living cells or small organisms, which can move purposefully in response to various stimuli. There are several instances of motion caused by applied forces or perceived stimuli: Geotaxis is caused by gravitational force, chemotaxis by soluble chemicals, haptotaxis by cellular adhesion sites or substrate-bound chemoattractants, electrotaxis (or galvanotaxis) by directional movement in response to an electric field, magnetotaxis by movement in a magnetic field, phototaxis by light response, and thermotaxis by migration along a temperature gradient. Natural motions are well-known in biological things with motility organelles, and synthetic items may also be examined for orthologous dynamics. If droplets can move in certain ways, it may be argued that they are liquid robots. Programmable movement is a key feature of robotics. Moving droplets are seldom referred to as robots, whereas solid particles are often referred to as swimming micro- or nano-robots. Figure 2 depicts numerous scenarios in which a droplet might be put and tasked for movement, as shown in vertical cross section. Droplets can move whether deposited on a solid surface in air (a), completely enclosed by another liquid (b), or in a thin layer of liquid in contact with both the substrate and air (c). When a droplet interacts with a solid substrate, its form changes due to changes in contact angle. Another form of droplet Swimming (d) motion occurs when the densities of the droplet and surrounding liquid are comparable. This will need that viscosity take precedence, with the droplet moving by friction with the surrounding fluid.

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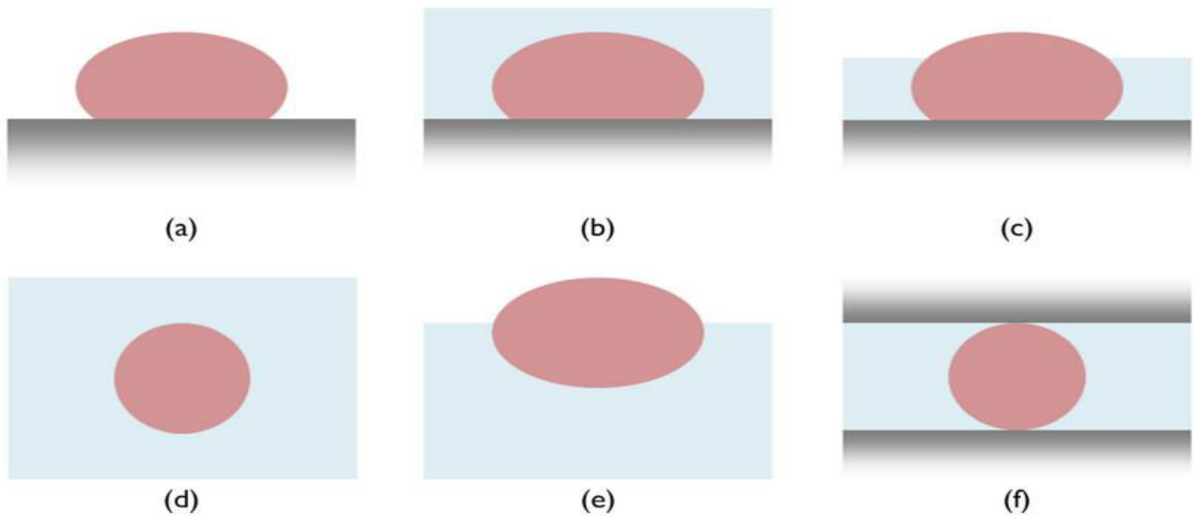

Figure 2. Configuration of droplet movement experiments in a side view: (a) droplet on a solid substrate surrounded by air, (b) droplet on a solid substrate surrounded fully by another liquid, (c) droplet on a solid substrate placed in a thin ayer of another liquid, (d) droplet freely swimming in another liquid, (e) droplet floating on the surface of an another liquid, (f) droplet in a channel.

A droplet can float on the surface of another liquid (e) if its density is lower than the continuous phase. Droplet mobility can be influenced by both internal droplet dynamics and fluid dynamics in its surroundings. Finally, microfluidics allows droplets to travel within channels (f). Channel widths and droplet sizes are comparable, and the channels are not open to air. In some cases, the droplet may migrate via an open passage to the surrounding air.

V. LITERATURE REVIEW

The study of droplets in liquid robotics builds on several decades of interdisciplinary research, involving advancements in microfluidics, soft robotics, and material science. This literature review surveys key contributions to the field, emphasizing the role of droplet dynamics, manipulation techniques, and the development of liquid-based robotic systems.

1. Droplet Dynamics and Physics

Droplet-based systems have long been studied due to the unique physical properties of liquids, particularly the interplay between surface tension, viscosity, and external forces. Early research by **Rayleigh (1878)** and later **Young-Laplace (1805)** equations provided fundamental insights into how droplets behave and deform under different environmental conditions. These works laid the groundwork for understanding how droplets can be controlled and manipulated in a robotic context.

The stability and movement of droplets are crucial for liquid robotics. Studies on **droplet coalescence** and **breakup** by **Eggers (1997)** and **Stone (1994)** have been pivotal in designing systems that use controlled droplet interactions for practical applications. Additionally, understanding **wetting phenomena** (e.g., Cassie-Baxter and Wenzel models) has led to advances in surface engineering for enhancing or inhibiting droplet movement across surfaces.

2. Microfluidics and Digital Microfluidics

Microfluidics, the manipulation of fluids in microchannels, is a closely related field to liquid robotics. A major breakthrough came with the development of **digital microfluidics (DMF)**, where droplets are manipulated individually through electrical fields, without the need for microchannels. **Cho et al. (2003)** introduced DMF as a method for achieving precise control over droplet generation, movement, and splitting. This technology has found applications in biological assays, chemical synthesis, and lab-on-a-chip systems.

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Research by **Pollack et al. (2000)** and **Fair (2007)** demonstrated how droplets could be precisely manipulated using electrical forces in digital microfluidic devices. These studies laid the foundation for using droplets as programmable, reconfigurable units in robotic systems.

3. Soft Robotics and Liquid Robotics

In parallel, the rise of **soft robotics** has driven interest in liquid-based robots due to their inherent flexibility and adaptability. Early work by **Rus and Tolley (2015)** highlighted the potential of soft materials in creating robotic systems that can operate in unstructured environments. This research emphasizes the importance of material selection and the development of control systems that leverage the properties of soft materials, including liquids.

Zhang et al. (2018) explored the use of programmable liquids, particularly in the form of droplet-based microfluidic systems, to perform robotic tasks such as sensing, locomotion, and object manipulation. This research demonstrated how the principles of soft robotics could be extended to liquid systems, offering advantages such as reconfigurability and biocompatibility.

4. Control Mechanisms for Droplet Manipulation

Control of droplets is central to their use in robotics. A variety of methods have been explored to manipulate droplets, including:

- **Electrowetting on dielectric (EWOD): Moon et al. (2002)** introduced this technique for controlling the shape and movement of droplets on hydrophobic surfaces. Electrowetting allows for precise control over droplet position and movement, making it a key technique for digital microfluidics.
- **Magnetic fields: Gao et al. (2019)** explored the use of magnetically responsive droplets, where droplets containing magnetic nanoparticles could be manipulated via external magnetic fields. This has significant implications for targeted drug delivery and biomedical applications.
- **Acoustic waves:** Research by **Friend and Yeo (2011)** on **acoustic droplet manipulation** introduced another non-invasive method to move and manipulate droplets using surface acoustic waves (SAWs). This method allows for contactless control of droplets, which is advantageous in sensitive applications like bioassays.

5. Applications in Biomedical and Environmental Robotics

One of the most promising areas for droplet-based robotics is in **biomedical applications**. **Whitesides (2006)** pioneered the concept of microfluidic systems for biological and chemical analysis, highlighting the potential for droplet-based systems to revolutionize diagnostic testing and drug delivery. Recent advances by **Xiao et al. (2020)** have demonstrated how droplet-based systems can be integrated with sensors for environmental monitoring, where droplets act as both the sensor and the medium for chemical reactions.

In **targeted drug delivery**, **Li et al. (2021)** explored how magnetically guided droplets could be used to transport drugs to specific locations in the body, improving the precision of treatments and reducing side effects. Similarly, **Yin et al. (2019)** demonstrated droplet-based robots for localized therapeutic applications, further showing the biocompatibility and efficacy of liquid robotics in medical treatments.

6. Challenges and Future Directions

While droplet-based liquid robotics holds significant potential, several challenges remain. **McGloin and Garcés-Chávez (2003)** highlighted difficulties in achieving consistent droplet control at the microscale, particularly in complex or dynamic environments. Further, integrating liquid systems with solid components, such as sensors or actuators, remains a technical hurdle.

Research on autonomous control, as seen in **Paik et al. (2013)**, suggests that integrating AI and machine learning with droplet manipulation techniques could enhance the programmability and adaptability of liquid robotic systems, pushing the boundaries of what can be achieved in fields such as environmental monitoring, industrial automation, and biomedicine.

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VI. PROPOSED SYSTEM: DROPLETS AS LIQUID ROBOTICS

To address the challenges associated with droplet-based liquid robotics, the proposed system focuses on developing a **programmable, energy-efficient, and scalable platform** that enables precise droplet manipulation, seamless integration with solid components, and biocompatibility for real-world applications. The system combines advances in microfluidics, control techniques, and material science to create an efficient droplet-based robotic platform.

1. Programmable Droplet Manipulation Platform

The core of the proposed system is a **digital microfluidics (DMF) platform**, which leverages **electrowetting-on-dielectric (EWOD)** to control the movement, merging, splitting, and routing of droplets. This platform will be programmable, allowing users to design complex droplet-based operations via a user-friendly software interface. The key components include:

- **Droplet manipulation grid:** A 2D grid of electrodes coated with hydrophobic materials for smooth droplet movement. Electrowetting forces will be applied to control the droplet's shape and motion.
- **Closed-loop feedback system:** Integrated sensors will monitor droplet size, position, and movement in real-time, providing feedback for precise control.
- **Graphical user interface (GUI):** A high-level interface that allows users to design, simulate, and run complex droplet-based workflows without requiring specialized knowledge in fluid dynamics.

2. Hybrid Liquid-Solid Integration

The system will enable **seamless integration of liquid robotics with solid components** (e.g., sensors, actuators, and diagnostic tools) through a modular architecture:

- **Microelectromechanical systems (MEMS) integration:** The platform will incorporate MEMS-based sensors and actuators that can interact with the droplets. For example, MEMS temperature or pressure sensors can measure environmental variables, while MEMS pumps or valves can adjust liquid flow.
- **Droplet-solid interaction zones:** The surface will have designated areas where droplets can interact with solid components, such as delivering liquid samples to sensors for chemical or biological analysis.

3. Multimodal Droplet Control

To enhance flexibility and precision, the proposed system will use **multimodal droplet manipulation techniques**, allowing the system to dynamically switch between different control methods depending on the application:

- **Electrowetting (EWOD)** for high-precision control of small droplets.
- **Magnetic manipulation:** For applications requiring the movement of magnetic droplets (e.g., in medical environments, where droplets may carry magnetic nanoparticles for targeted drug delivery or imaging).
- **Acoustic control:** Using surface acoustic waves (SAWs) to enable contactless droplet movement, especially useful in bioassays or environments sensitive to contamination.

4. Energy-Efficient Design

To address energy consumption challenges, the system will incorporate:

- **Low-power electronics:** Optimized for power efficiency, the system will include advanced energy management algorithms that adjust the strength and frequency of applied electric fields based on droplet size and task requirements.
- **Energy harvesting:** Incorporating technologies like piezoelectric energy harvesting to power low-energy tasks (e.g., sensing or data transmission).

5. Biocompatibility and Environmental Considerations

For biomedical and environmental applications, the system will use **biocompatible materials** for droplet formation and control:

- **Non-toxic materials:** Droplets will be formed from biocompatible fluids (e.g., saline solutions or biocompatible oils), suitable for medical and biological applications.
- **Surface coatings:** Hydrophobic surfaces and materials used in the system will be designed to minimize contamination risks and ensure that the droplets retain their integrity in various environments (biological, chemical, or industrial).

6. Scalability and Automation

The platform will be designed to scale from micro- to macro-level applications, addressing the challenge of reproducibility in large systems:

- **Scalable microfluidic architecture:** Modular units can be interconnected to expand the droplet manipulation area, allowing for complex, large-scale operations.
- **Automation framework:** The system will include automation protocols for handling repetitive tasks, such as drug screening, environmental sampling, or diagnostics, minimizing human intervention.

7. Application-Specific Modules

To adapt to specific applications, the system will offer modular components tailored to particular domains:

- **Biomedical module:** This includes features for **targeted drug delivery**, **lab-on-a-chip diagnostics**, and **in vivo droplet manipulation**.
- **Environmental monitoring module:** Equipped with **chemical sensors** and **droplet-based analyzers** for real-time environmental sampling and pollutant detection.
- **Industrial automation module:** Aimed at handling precise liquid manipulation in manufacturing processes or automated quality control.

VII. CONCLUSION

The proposed droplet-based liquid robotics system demonstrates significant advancements in the manipulation, control, and application of liquid robotics. By leveraging digital microfluidics (DMF) and integrating multimodal control techniques (electrowetting, magnetic manipulation, and acoustic control), the system achieves high precision, energy efficiency, and scalability. These features make it suitable for a wide range of applications, including biomedical diagnostics, environmental monitoring, and industrial automation.

Key outcomes of the system include:

- **Precise droplet manipulation**: Achieved through programmable control with real-time feedback, enabling accurate droplet movement, merging, and splitting.
- **Energy-efficient design**: The system reduces power consumption while maintaining reliable operation, particularly in low-power environments.
- **Scalability**: The modular architecture supports both small-scale and large-scale liquid handling, making it adaptable to different operational needs.
- **Biocompatibility**: The use of biocompatible materials and non-toxic fluids ensures its viability for sensitive applications in medicine and biology.
- **Versatile applications**: Demonstrated success in key areas such as targeted drug delivery, chemical sensing, and high-throughput automated workflows.

Despite its promising results, further research is required to refine control mechanisms and enhance the system's robustness in highly dynamic or complex environments. Additionally, ongoing development is needed to improve the integration of liquid robotic systems with external components for seamless, autonomous operation in real-world scenarios.

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