Fast, Low-cost, and in situ Detection of Microplastics by Medical Ultrasound Imaging and their Robust Classification by AI

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I. Literature Review

A. MP detection methods and considerations

Paper [1] reports MP accumulation spots, synthesize mechanisms, degradation and formation characterizations. Spots with lower flow rates create favorable conditions for the formation of a thin biofilm on the surface of plastics, facilitating the adherence and retention of plastic debris. Tidal zones and beaches are also potential habitats for plastic accumulation. The environmental weathering of plastic debris is known to be a gradual process. Even though it occurs slowly, the debris still undergoes breakdown, resulting in changes to its polymer properties. These changes can be attributed to **biological** and/or **abiotic processes**.

Abiotic degradation means change in physical and chemical properties of plastics due to factors like light, temperature, air, water, and mechanical forces. Plastics are hardly absorbed by organisms (poor bio-availability). Hence, Abiotic degredation precedes the biodegredation. **Photoddegredation**, cause by solar irradiation, is the most importan degradation process. Plastics without chromophores are resistant to photoddegredation (e.g. Polyethylene (PE)).

Thermal degredation stems from elevated temperatures in Plastics. When sufficient heat is absorbed by the polymer to overcome the energy barrier, long polymer chain is broken and radicals are released. These radicals react with oxygen, causing thermo-oxydative reactions. **Mechanical degredation** is the breakdown of plastics as a result of external forces. These forces can come from collision and abrasion of plastics with sands and rocks caused by winds and waves. **Biotic degradation** is caused by living organisms including bacteria, fungi, and insects. Organisms can degrade plastics by biting, chewing, digestive fragmentation, and biochemical processes. Microorganisms colonize the plastics and create a biofilm, which affects the light transmittance of plastic and causes biodegredation. In aphotic zones (no sunlight), biodegredation is the main cause of degredation while in floating plastics, photodegredation is the main reason.

Paper [2] reviews identification of micro-plastics (MP) in aquatic environments. The process includes extraction, isolation, identification, and classification. The main challenge in this process is that MPs have various shapes, colors, and types. For this reason, two or more methods are combined to analyze MPs. One of the methods should analyze the physical characteristics of MPs and a chemical characterization is followed for confirmation. An example is a microscopy examination followed by a spectroscopy analysis.

Scanning electron microscopy (SEM) is a method to detect plastic particles with clear and high magnification and the high resolution images can facilitate the identification of carbon-dominant plastics from inorganic particles. **Fourier transform infrared (FTIR)** can extract information about chemical bonds of particle and detection of carbon-based polymers is possible with this method. In addition, it can discriminate between MPs, organic, and inorganic particle.

Raman spectroscopy irradiates the particles with laser and analyzes different frequencies from the reflected scattered lights. The scattered lights create a spectrum which is unique for each polymer. Raman is accurate to a few micro-meters but sensitive to additives and pigments. There are also methods based on thermal analysis which measure physical and chemical properties depending on thermal stability of materials. Even with these accurate methods, it becomes extremely difficult to detect MPs as their size becomes less than micro-meters.

Field deployability is feasible if data preparation is minimal. Analysis methods should be evaluated based on the intrinsic physical properties that they engage to distinguish MPs from their surroundings. Standards exist for MP sample collection and preparation. However, the MP analysis techniques vary considerably in terms of content and quality. Evaluation methods can be categorized as chemical, mechanical, and electrical. Paper [3] has investigated MP detection methods focusing on their field deployability and data products (what they offer after analysis). Field deployability is evaluated considering cost, durability, portability, low-power operation, fast-time response, and high-quality data generation. The most important quality of a sensor is recognizing MPs as polymers from their surrounding non-MP particles. There is a design trade-off between field deployability and data products. For instance, FTIR is poor in field-deployability but strong in data generation as it outputs polymer type, size, and count. The reason is the need for expensive, sensitive, and bulky optomechanic facilities. Raman and Hyper-spectral imaging also suffer from the same problem when it comes to field-deployability, although they provide sufficient information. The Ultrasound is one of the methods proved to be better than the others as the required equipments are low-cost and portable.

B. Ultrasound instruments

Wavelength of the ultrasonic device must be chosen wisely. Lower wavelengths (higher frequencies) offer better spatial resolution while higher wavelengths provide a better penetration depth. Ultrasonic images are two dimensional and there are methods to get three dimensional sample volume. It is possible to mechanically rotate or translate the sensor or use a matrix array of transducers. Particles can be counted using conventional image processing techniques, but recognizing them from the natural particles should be considered. Although acoustic impedance of MPs is different from their surroundings, there are methods that use mechanical excitation, like using a strong acoustic pulse or laser pulse, to manipulate the particles.
Ultrasound scanning is a widely used medical imaging technique that utilizes high-frequency sound waves to create real-time images of the body's internal structures. It offers various scanning modes that allow healthcare professionals to visualize different aspects of the anatomy and diagnose various conditions. Here are some commonly used ultrasound scanning modes according to reference [4].

1) A-mode (Amplitude mode): This is the simplest ultrasound scanning mode and presents the amplitude of the reflected sound waves on a plot. It is primarily used for measuring distances and assessing the depth of structures, such as determining the length of the eye or the thickness of the cornea.

*2) **B-mode (Brightness mode)**:* B-mode ultrasound is the most commonly used scanning mode. It produces a two-dimensional cross-sectional image of the scanned area, displaying the echoes as varying shades of gray. The brightness of each pixel corresponds to the amplitude of the reflected sound waves, allowing the visualization of organ boundaries, structures, and abnormalities. B-mode ultrasound is useful for evaluating organs like the liver, kidneys, heart, and fetus during pregnancy.

*3) **M-mode (Motion mode)**:* M-mode ultrasound displays a one-dimensional motion graph over time. It is commonly used in cardiology to assess the movement of structures such as heart valves, heart walls, and blood flow. M-mode can provide valuable information about the timing and duration of specific events in the cardiac cycle.

4) Doppler mode: Doppler ultrasound measures the velocity and direction of blood flow within vessels. It uses the Doppler effect, where the frequency of sound waves changes when reflected by moving objects (such as blood cells). Doppler mode can be displayed in two formats:
a. Color Doppler: This mode assigns different colors to indicate the direction and velocity of blood flow. It allows for the visualization of blood flow patterns in real time, making it useful in assessing vascular conditions, such as deep vein thrombosis or blood vessel obstructions.
b. Spectral Doppler: This mode presents a graphical representation of blood flow velocities over time. It displays the velocity spectrum as a waveform graph, providing detailed information about the speed, direction, and patterns of blood flow. Spectral Doppler is commonly used in cardiology and vascular medicine.

5) 3D/4D mode: Three-dimensional (3D) ultrasound scanning creates volumetric images by acquiring multiple 2D slices of a scanned area. These slices are then reconstructed to produce a 3D representation of the anatomy. Four-dimensional (4D) ultrasound adds the element of time to the 3D images, allowing real-time visualization of moving structures, such as a fetus during pregnancy. 3D/4D ultrasound is useful for detailed visualization of fetal anatomy and abnormalities.
3d ultrasound volume reconstruction consists of interpolations and approximations with tracking relative spatial locations to create a 3d volume grid. Paper [5] introduces pixel-nearest neighbor (PNN), voxel-nearest neighbor (VNN), distance weighted (DW), radial basis function (RBF), and image-based algorithm as examples of volume reconstruction techniques for medical purposes. The paper introduces different ways to scan in 3d like using a 2d array of transducer system, rotation and translation of sensor arrays with an actuator, and tracking the position of a freehand-based system. Although great in accuracy, first two methods are too expensive, hard to develop, and acquire limited volume of data. On the other hand, the freehand systems offer more flexibility, lower price but more irregular shapes and sparse points.
Ultrasonic scanning tools offer different modes of operation. Each ultrasound scanning mode has its specific applications and benefits, and healthcare professionals choose the appropriate mode based on the clinical context and the information they seek to obtain.
Apart from medical devices, ultrasonic devices are very common in ocean exploration. Ultrasonic sensors used for ocean exploration include single-beam sonar, multi-beam sonar, sub-bottom profiler, and side-scan sonar [6]. Knowing the topography of the ocean can help us understand marine geology, identify resources, monitor geohazards, and route cables and pipelines. Single beam sonars can only illuminate a small area, like a small flashlight. For large geological investigation, multi-beam and side-scan sonars are proved more effective. Like medical applications, the frequency settings play a crucial role in breadth-depth trade-off. For instance, 20 kHz beams can go through the full depth without attenuation. The paper discusses the effect of frequency on footprint and resolution of the acquired images and mentions high resolution data acquisition and post-processing of the reflected signals as key steps toward successful mapping of the environment. Multibeam

method uses several sonar beams simultaneously and side-scan method uses two transducers equipped on a towfish. Side-scan sonar can detect substrate composition using strength of echos and wider coverage. Nevertheless, multi-beam sonar maps the seafloor irregularities with an excellent quality.

C. AUV navigation

Ocean exploration relies heavily on the use of different types of submersibles, which play a crucial role in various scientific and commercial activities. These submersibles can be broadly classified into several categories, including human-occupied vehicles (HOV), remotely operated vehicles (ROV), autonomous underwater vehicles (AUV), hybrid ROV and AUV, and underwater gliders. Each type of submersible serves a unique purpose and offers distinct capabilities that contribute to the comprehensive study and understanding of the oceans. Having a map from seafloor would have made underwater exploration more convenient. However, lack of this map has limited human investigation of the oceans. Global navigation system (GPS) cannot be used underwater but dead reckoning (DR), acoustic and geophysical navigation methods are now commonly used by AUVs.

Inertial/Dead Reckoning is a navigation method that estimates a carrier's state using accelerometers, gyroscopes, and other sensors. It utilizes an Inertial Navigation System (INS) with an Inertial Measurement Unit (IMU) for acceleration and direction measurements enhanced by Kalman filters. IMUs, using MEMS technologies, are small and accurate for submersible applications. Acoustic navigation is also widely used for underwater positioning. It utilizes beacons deployed underwater, such as long-baseline (LBL), short baseline (SBL), and ultra-short baseline (USBL) systems. LBL offers high accuracy, while SBL uses transponders on the mother ship. Both measure distance and direction differently. Geophysical navigation uses sensors to recognize environmental features underwater. It includes compasses, depth gauges, cameras, and sonar. AI-powered algorithms aid in feature recognition. Geophysical navigation is commonly used for hovering AUVs and relies on sonar for imaging and ranging.

Long-term use of INS leads to error accumulation, while acoustic navigation suffers from low accuracy and high latency. Acoustic navigation heavily relies on the mothership and beacon deployment. Geophysical navigation remains challenging due to the limited visual quality in seawater. However, a promising trend is the fusion of multiple navigation sensors, which enables universal and accurate navigation by leveraging the strengths of different approaches.

References

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