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**--The future of gastrointestinal disease management?**

*Abstract: ---* There are numerous debilitating diseases of the gastrointestinal (GI) tract and these need to be accurately diagnosed before treatment. Robotic capsule endoscopes (RCEs) with embedded ultrasound probes may offer the solution by allowing painless access to any region of the GI tract and in situ, rapid diagnosis. We developed a prototype of this technology and tested in on the benchtop and in a biological environment. Results showed that we could successfully manipulate the RCE using magnetic control and acquire ultrasound images of a substrate. Using ultrasound and RCE position feedback, we were able to autonomously move the RCE and acquire images at the push of a button. We could reconstruct images of the substrate and accurately take measurements – an important feature for future diagnoses. The study concluded with proof that this is a clinically feasible technology and, with advancements in ultrasound probe design and RCE miniaturization, could be the future of GI disease diagnosis and management.

Diseases of the gastrointestinal (GI) tract place a huge burden on society and include colorectal cancer, which alone accounts for almost a million deaths each year. Standard flexible endoscopy is the gold standard procedure to diagnose these diseases. It involves the skillful navigation of a long “scope” through the GI tract by a highly trained doctor. This allows direct inspection of the tissue and basic tasks such as tissue biopsies to confirm diagnoses. Although it is performed millions of times every year, it has major drawbacks, including severe patient discomfort, risk of serious complications, high procedure complexity and an inability to access all regions of the GI tract.

We wanted to solve this by exploring the concept of combining robotic capsule endoscopy (RCE) and microultrasound. RCEs – small, capsule-shaped robots – can potentially access the entire GI tract while allowing the operator to maintain control over their position. Microultrasound is high frequency ultrasound with a resolution in the tens of microns - perfect for the GI tract which has a thickness in the order of a few millimeters. This could allow doctors to visualize the individual layers of the bowel tissue, take measurements and perhaps determine whether the tissue is healthy or diseased. However, at this small scale, microultrasound probes are very challenging to use as they must be pressed into and aligned continuously with the tissue. The GI tract is soft, unstructured, dynamic and very hard to access.

To manipulate the probe – and the RCE generally - we leveraged our previous expertise on magnetic manipulation as a method of actuation. Forces and torques are applied via interacting magnetic fields (one in the RCE and one attached to a robotic arm outside the patient). We can pull the RCE through the GI tract, steer it around the bends and finely adjust the orientation to align the probe with the tissue for ultrasound imaging. With position and ultrasound feedback we can also autonomously adjusts the RCE pose until ultrasound images of a substrate are seen. So our study focused on asking: Is it clinically feasible to combine RCE and microultrasound technologies? What level of robotic assistance is necessary to achieve this?

The first task was to design and fabricate the RCE. This needed: a camera and light-source to aid navigation through the GI tract; the magnet core for actuation; a circuit with position sensors; the microultrasound probe and its electronics. The prototype was 3D printed and then assembled carefully by hand.

Next, tests in a laboratory environment were performed to characterize the system and show the core functionality: Can we accurately manipulate the RCE? Can we acquire clear ultrasound images? Can we do both of these autonomously? For these tests we developed a substrate that mimics the acoustic properties of soft tissue and we placed interesting features inside it to detect with ultrasound. We then performed tests in a biological environment to show clinical feasibility and what level of robotic assistance is required. A biological environment is crucial for testing, as synthetic materials don’t come close to mimicking the complex properties of a living organism.

We successfully combined magnetic RCE and microultrasound technologies and showed that magnetic manipulation is an effective method of actuation because it is safe and encourages continuous contact with the environment. However, even in a controlled environment, it is very difficult to manually position the RCE for ultrasound imaging because the probes must be aligned precisely.

Microultrasound feedback was combined in the robotic control to perform autonomous ultrasound imaging; precisely tilting the RCE and applying force until a clear image was seen. This allowed the capture of ultrasound images with ease and allowed more complex movements, including, autonomously scanning across a surface. The resulting ultrasound data was collected and combined to form an image of the substrate that was used to detect and measure features with high accuracy (~1-2mm).

Clinical feasibility was shown in biological model. While manual control of traditional abdominal ultrasound probes is practical, in this environment robotic assistance is essential and images of the bowel wall were only captured successfully with the robotic assistance.

We have shown what the future of GI intervention could look like by designing, fabricating and testing the first RCE with magnetic control and microultrasound sensing. With advancements in probe design and device miniaturization, this technology could transform the way we diagnose and treat GI disease.