Development of mathematical tools for capsule endoscopy and biopsy

Many patients undergo endoscopic procedures to diagnose gastrointestinal (GI) disorders such as cancer and inflammatory bowel disease, and this number continues to grow. According to Cancer Research UK, the number of procedures being undertaken annually in the UK has increased by 44% between 2015 and 2020, until as many as 750,000 are performed. To acquire the required expertise to practice endoscopy safely, clinicians undergo lengthy training periods and work within highly developed professional regulatory frameworks. Multi-disciplinary teams are required to manage patients through their painful procedures, and complex decontamination processes are required for the expensive, reusable instruments. The burden of endoscopy is thus increasingly challenging for patients, the NHS and the economy.

Despite major advances in image acquisition and processing over recent decades, the basic design and ergonomics of endoscopes have barely changed in more than 40 years. In the last two decades, new capsule-based testing has become available as an alternative. Whilst this has been readily incorporated into practice for examining the small intestine (an area once considered inaccessible to clinicians), their limitations have prevented significant uptake in the examination of the colon, where the majority of examinations are targeted. These limitations include the reliance on peristalsis to propel the capsules through the GI tract, leading to variable locomotion speeds, with the result that significant portions of the target intestine may be missed and viewing periods may be prolonged and burdensome to clinicians.

This PhD project aims to deliver a step change in GI endoscopy by developing mathematical tools (i.e., mathematical model, analytical and control methods) for a self-propelled capsule robot for diagnosis and biopsy. From the applied mathematics point of view, the capsule robot [1,2] is a non-linear system involving both friction and impact, which has a rich variety of non-linear phenomena. Thus, the challenges that could be explored in this project include:

1. To build a realistic model of capsule locomotion through a full understanding of the friction and resistance mechanisms in the GI tract. This will provide deeper insights into the capsule's locomotion and energy consumption in clinical scenarios.
2. To study the dynamic characteristics of the capsule robot numerically and experimentally and understand its (a) bifurcation mechanism, (b) stability, and (c) robustness. For example, the capsule robot can easily lose stability and bifurcate from a forward periodic motion into an unwanted backward chaotic motion, due to either its sensitivity to control parameters or the robustness to the intestinal resistance.
3. To develop control strategies for the capsule robot for switching between different operating modes (e.g., fast or energy-saving modes; diagnosis or biopsy modes). Here, the ultimate goal is to develop a systematic control method for the self-propelled robot, including prediction of capsule's dynamics and the enhancement of capsule's stability.
4. To verify the mathematical tools of the robot experimentally in collaboration with the experimenters (PDRA and PhD students) at the supervisor's laboratory.

References:

[1] Liu Y, Páez Chávez J, Zhang J, Tian J, Guo B, Prasad S. (2020) The vibro-impact capsule system in millimetre scale: numerical optimisation and experimental verification, *Meccanica*, volume 55, no. 10, pages 1885-1902.

[2] Yan Y, Liu Y, Manfredi L, Prasad S. (2019) Modelling of a Vibro-Impact Self-Propelled Capsule in the Small Intestine, *Nonlinear Dynamics*, volume 96, pages 123-144,