Experimental Characterisation of an Optical Tracking Sensor for Capsule Localisation in the Small Intestine

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Abstract—This study reports the first systematic characterization of a miniature laser-based optical tracking sensor for smart capsule odometry in the small intestine in controlled and biologically relevant conditions. Data was collected by attaching the sensor to a CNC milling machine, allowing sensor measurements to be validated against ground-truth displacement data. A series of experiments were performed to probe the effects of biological tissue, interface material, material thickness, and environmental illumination on sensor performance. The findings suggest that the sensor exhibits consistent, repeatable results in identical conditions. Additionally, the effect of intestinal digesta content on the localisation performance of the sensor is investigated for the first time. Results show a 40% underestimation of distance travelled when traversing over high levels of digesta, indicating the importance of patients' fasting before any in-vitro application. Despite this underestimation, the near-linear performance of the sensor indicates its feasibility for capsule odometry applications given suitable calibration

Index Terms—Optical tracking sensor, capsule odometry, small intestine, digesta content, sensor characterisation.

I. INTRODUCTION

Wireless capsule endoscopy (WCE) is an innovative technology that allows for non-invasive imaging and sampling of the gastrointestinal (GI) tract [1]–[3]. Capsule-based systems enable complete traversal of the GI tract, including regions of the small intestine that are difficult to access using conventional approaches [4], and improve early detection of disease symptoms such as bleeding, inflammation and tumours [1], [5]. Although high resolution imaging has been achieved, it remains difficult to precisely locate the 3D spatial position of detected abnormalities [9]. However, clinical decision-making depends on accurate localisation for targeted therapy and surgical planning [5]. This is also the case when microbiota are to be sampled from specific parts of the GI tract [6]–[8]. In either case it is required that capsules are able to determine their position inside the small intestine when an abnormality is detected or a sampling location is reached. One novel approach is to use optical tracking sensors to achieve capsule odometry inside the small intestine [10].

Optical motion sensors work by taking sequential images of the surface and estimating displacement by correlating spatial features between consecutive frames [11]. This technology is used in computer mouse technology, which allows high resolution tracking of relative motion without the need for external infrastructure. Therefore, optical sensing may offer a compact, low-power option for measuring the displacement of capsules as they transit through the small bowel [11]. In one of the first examples of optical sensor use for this, Vedaei *et al.* [12] combined commercially-available optical mouse sensors with an inertial measurement unit (IMU) to perform visual-inertial odometry inside a human GI track. Two sensors were combined to improve localisation performance which depends on precise calibration and may degrade over time. In a subsequent study, they [13] integrated magnetic sensing with side wall cameras detecting all minute capsule displacements, achieving a mean localisation error of 3.5 mm. While more precise compared to their previous technique, this approach required external magnetic sensor arrays, thus increasing system complexity and making point-of-care use difficult. Outside of GI localisation, optical mouse sensors have also been explored as high-resolution motion sensing devices, for example, in navigation of microscopic robotic manipulators for identification and surgery, leveraging fine displacement measurement with low power consumption [14]. Paijens *et al.* [15] utilized these sensors in mobile robot odometry and emphasised their precision was highly dependent on surface features, vertical distance, and calibration, while Tresanchez *et al.* [16] demonstrated their capability in biomedical motion tracking, even though optical and illumination adjustments were needed. Likewise, Zabaleta *et al.* [17] employed multiple optical sensors for navigation of a robotic arm by sensor fusion; however, they observed large errors, highlighting constraints in complex environments. Despite these advancements, the characterisation of miniaturised optical tracking sensors for capsule localisation in the small intestine remains largely unexplored. Also, investigation of the effect of tissue digesta content on localisation performance of a capsule has not been previously reported to the best of the authors' knowledge. Therefore, in this paper, the performance of a miniaturised optical tracking sensor is experimentally investigated under conditions representative of the small intestine, including the effects of illumination, interface material, interface thickness, and intestinal content as well as sensor integration into a capsule prototype.

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II. MATERIALS AND METHODS

Sensor performance was evaluated through controlled physical experiments, with the method relying on real-time positioning data measured by the sensor while a sample was translated relative to the sensor by a motion setup (Fig. 1(a)). An embedded system was employed to process the recorded data, allowing for comparison with predefined reference values. In brief, a miniature optical tracking

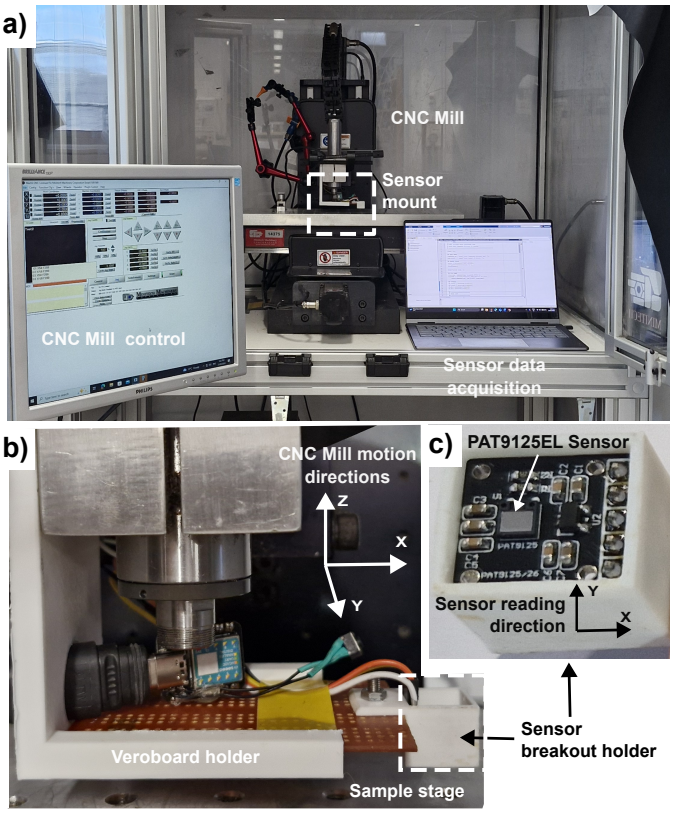

Fig. 1. Motion setup used for data acquisition. (a) Photograph of the CNC mill used to actuate the aluminium stage underneath the sensor mount, position control and data acquisition highlighted. (b) Sensor breakout board and enclosure mounted onto the mill spindle, with motion directions and sample stage indicated. (c) Close-up of the sensor breakout board showing the exposed optical sensor and reading direction.

sensor measuring 3.5 × 3.2 × 1.0 mm (PAT9125EL-TKIT, Pixart) communicated with a microcontroller unit (MCU) on an Arduino board (Seeed Studio XIAO) utilizing the inter-integrated circuit (I^2C) protocol. The sensor was set to function at its highest resolution, corresponding to 1275 counts per inch (CPI) or ~0.02 mm per count, allowing for maximum sensitivity. The optical sensor operates by capturing incremental motion data across two longitudinal axes (x and y). At each sampling instant, the sensor provides displacement increments in terms of digital counts. Summing these incremental counts determines the total displacement. Fig 1(b&c) shows the sensor mounted on a breakout board-measuring 1.5 x 1.3 cm, which is connected to the MCU and attached to a Vero board via a custom designed holder.

This setup enabled the attachment of the sensing system to a x,y,z movement stage. To guarantee precise and repeatable movements, a computer numerical control (CNC) milling machine (Mini-Mill/3, Minitech) was used for this purpose. This system provides an overall travel of 300 mm along the x axis and 200 mm along the z axis, with a minimum commanded movement resolution of ±100 nm and a positioning accuracy of ±2.5 μm. G-code was employed to program motions of the milling machine stage to perform predefined linear movements with a feedrate of 100 mm/min. Throughout the tests, the sensor was kept still while the milling machine stage moved underneath it. The approach allowed for predefined translations along the x axis and thus provided ground-truth reference when assessing the sensor performance.

Experiments were first performed on the aluminum surface of the milling machine stage to verify the baseline sensor performance using the readings from the movement of the stage. Next, sensor performance was assessed in an ex-vivo, biologically relevant environment using a piece of beef small intestine tissue that was cut longitudinally, flattened and placed on the milling stage to create a testable surface. A constant vertical (z axis) separation of 0.5 mm was kept between the sensor and the moving sample surface throughout all experiments. When a polycarbonate cover was used, this corresponded to the distance from the sensor to the top of the cover. Real-time data acquisition was carried out using a custom-built MATLAB code (R2024b, Mathworks) that received data from the microcontroller via a serial connection. To assess ex-vivo performance, a capsule body was 3D printed (Phrozen Sonic Mighty Revo 16K) using a biocompatible photopolymer resin (BioMed Clear, Formlabs). A sensor breakout board was embedded in the capsule body, maintaining stable alignment and working distance between the optical sensor and the surrounding tissue. A 0.38 mm thick polycarbonate sheet was used as the transparent interface between the capsule surface and sensor. The capsule was then manually drawn through the intestinal sections to simulate in situ settings for commanded displacements of 20, 50, 100, 200, 300, 400 and 500 mm.

III. RESULTS AND DISCUSSIONS

A. Baseline sensor characterization

Before use, newly purchased sensors were characterized to assess intrinsic performance and potential device-to-device variation. The milling machine stage was commanded along the x axis to distances of 10, 20, 40, 60, 80 and 100 mm, and the measured distances recorded by different sensors were compared. Fig 2 shows the consistency and repeatability of five different sensors on an aluminum surface, confirming that the sensors were accurate and reliable under controlled conditions.

B. Effect of tissue insertion

Following initial sensor validation, beef small intestine tissue was cut longitudinally and laid flat onto the milling machine stage to investigate the sensor response to biological material. Fig 2 shows that the optical sensor exhibited a consistent and approximately linear response to displacement of the tissue over the tested range (x axis, 10–100 mm), but with systematic underestimation of 25%. As the y axis data illustrates, cross-axis drift remained negligible for both aluminum and tissue, indicating directional stability. The linearity of these results demonstrates that the major factor for using the sensor in practice is a scale factor that corrects the measured data.

C. Effect of a cover sheet and its thickness

Given that the sensor would be located behind a protective cover in a capsule, the influence of potential cover materials on sensor measurements was investigated. For this, polycarbonate was chosen to cover the intestinal tissue due to its bio-compatibility, durability and semi-flexibility [18]. To allow a direct comparison with the initial experiments, the polycarbonate sheets were placed onto tissue which

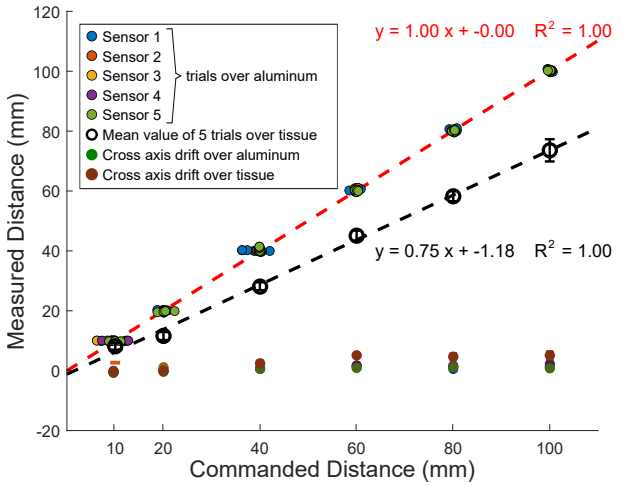

Fig. 2. Performance and device-to-device variation for optical sensors. The graph plots measured versus commanded distance for five sensors on an aluminum surface and the mean value of five trials with one sensor on intestinal tissue. Linear fits for the measurements and cross-axis drift (deviation along y axis for zero commanded y distance) are also shown.

was again moved relative to the sensor using the mill (Fig. 3(a)). Sheets of 0.38, 1 and 3 mm thickness, which correspond to the range of shell thicknesses used in commercial capsules [19], were tested for a commanded distance of 50 mm. Fig 3(b) illustrates that the addition of a cover reduced the measured distance compared to no cover being present by 7%. When the thickness of the sheet increased from 0.38 to 3mm (Fig. 3(c)), the measured distance increased by only 7%. Consequently, a thickness of 0.38 mm was used for subsequent experiments given the need to minimize capsule size.

D. Effect of tissue surface condition

The effect of digesta content on sensor performance was assessed using washed and unwashed intestinal tissue (Fig 3(a)). Unwashed samples were sorted into low and high digesta groups. Fig. 3(d) shows sensor readouts over washed tissue were comparable to those of low-digesta tissue, whereas measurements over high digesta tissue exhibited pronounced underestimation. For example, when moved 50 mm over each sample, the sensor measured a distance of 11 mm over the high digesta sample compared to almost 31 mm over the low digesta and washed samples. Hence the high digesta samples introduced an additional 40% error between commanded and measured distance. However, as the underestimate remained constant, this error can be removed by calibration.

E. Ambient light influence

Since optical sensors can be affected by ambient lighting conditions, in a separate experiment, the milling machine was enclosed by a blackout curtain. This avoided possible interference from external light, thus better simulating conditions encountered in the small intestine. It was observed that the performance of the sensors remained unchanged under darkness for all studied distances.

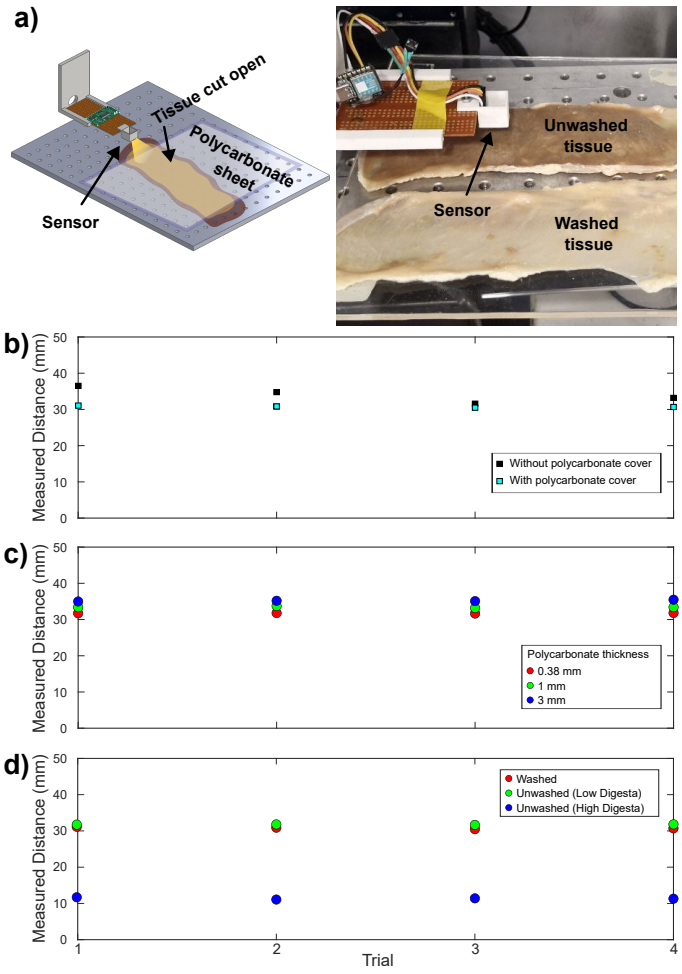

Fig. 3. Effects of sensor cover and tissue condition for a commanded distance of 50 mm. (a) Schematic and photographs of the experimental setup used to study the effects of sensor cover and tissue conditions. (b) Comparison of measured distances for uncovered tissue and tissue under 0.38 mm polycarbonate. (c) Measured distances of four trials on tissue covered with polycarbonate sheets of thicknesses 0.38, 1 and 3 mm. (d) Comparison of measured distance for washed tissue and tissues with high and low levels of digesta.

F. Ex-vivo assessment of sensor performance

To test the sensor performance for capsule odometry applications under physiologically relevant conditions, a capsule embedding the sensor was manually moved through beef tissue with and without digesta present (Fig. 4(a)). The resulting sensor measurements were collected and compared with the results for aluminum, as shown in Fig. 4(b). Despite the harsher conditions, a near-linear correlation between commanded and sensed displacements was observed, albeit again with a consistent underestimation. As can be seen from the linear data fitting, the slope obtained from the experiment using intestinal tissue without digesta was about twice as high (~0.15 versus ~0.07). This indicates that fasting should be recommended prior to capsule application to improve sensor measurements and thus localisation. To overcome the encountered underestimation, a scaling process was carried out using the average ratio of the motion commands and the respective mean values obtained from measurements for each step size. After applying the obtained value as a correction factor

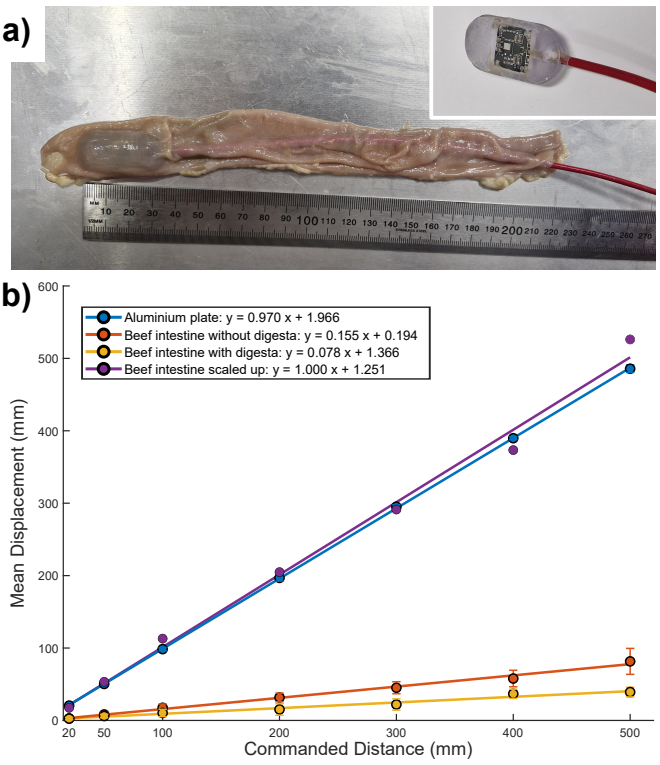

Fig. 4. Ex-vivo sensor performance. (a) Photograph of the fabricated sensor capsule being pulled through a piece of beef tissue. Inset shows the capsule with optical sensor behind a clear polycarbonate cover. (b) Scaled and unscaled distance recorded by sensor versus externally measured distance for the capsule travelling through beef tissue with and without digesta. Displacement readouts of the capsule pulled over an aluminum surface are shown as ground truth. Measurements shown are the mean of ten trials.

to the sensor output of a capsule moving through tissue, the output exhibited an almost ideal slope with minimal intercept (Fig. 4(b)). This consistent linear performance further supports the suitability of the optical sensor for use in capsule odometry within the small intestine upon calibration.

IV. CONCLUSION

The feasibility of the miniaturised optical tracking sensor for the capsule odometry in the small bowel is evaluated. Following an initial validation experiment ensuring reliability of the purchased sensors, the introduction of the tissue exhibited a consistent and approximately linear sensor performance with systematic underestimation of 25% when measuring the traveled distance. The polycarbonate interface which mimics the capsule shell causes an approximate 7% deviation for the sensor readouts. Furthermore, evaluation of tissue content shows that tissue with high digesta reduces the sensor accuracy by 40%, compared to low digesta, emphasising the significance of fasting before the capsule application. Additionally, ex-vivo investigation of the optical sensor embedded in a capsule shows a reduced displacement measurement, which a correction factor can compensate for. Hence, unlike current localisation technology, optical sensors may allow capsule localisation without requiring external equipment or combining multiple sensing techniques. These findings will inform future work, developing a self-contained capsule capable of trajectory reconstruction while transiting the intestines; hence, enabling in-vivo validation of the capsule localisation system.

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