

Soft continuum magnetic robot actuation using electromagnetic coils.

MECH5845M Professional Project

***Soft continuum magnetic robot actuation
using electromagnetic coils.***

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SCHOOL OF MECHANICAL ENGINEERING



UNIVERSITY OF LEEDS

MECH5845M Professional Project

TITLE OF PROJECT

Soft continuum magnetic robot actuation using electromagnetic coils.

PRESENTED BY

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Company Name and Address:

This project report presents my own work and does not contain any unacknowledged work from any other sources.

Signed

date 11/08/2022

A handwritten signature in black ink, appearing to read 'V. Francescon', written over a light blue diagonal line.

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Nomenclature

<i>CR</i>	Continuum Robot(s)
<i>DoF</i>	Degrees of Freedom
<i>GUI</i>	Graphical User Interface
<i>NdFeB</i>	Neodymium-iron-boron
<i>MCR</i>	Magnetic Continuum Robot
<i>PDMS</i>	Polydimethylsiloxane
<i>PSU</i>	Power Supply Unit

Abstract

While currently existing endoscopes may be classified as soft continuum robots, their control mechanisms vary from completely manual to robotically assisted. The actuation methods utilised are almost exclusively intrinsic to the catheter used and hence are limited in miniaturisation potential and rigidity. Thus, intrusive operations can often result in trauma onto the patient. Efforts into realising a soft catheter able to minimise traumatic incidents have led to actuation being moved outside of the catheter through magnetism. Furthermore, introducing full automation to the system can aid in decreasing incidents. Hence, it is desirable to create a platform capable of full control over a magnetic soft robot's shape.

Adopting magnetic automation onto soft robots does also, however, introduce a number of challenges: catheters require bespoke fabrication procedures to enable magnetisation, reliable systems to generate required magnetic fields are necessary and accurate modelling of said magnetic actuation onto the robot while in motion is essential and generally more complex than more traditional tendon-drive approaches.

A system of 3 pairs of co-axial electromagnets can be utilised to apply uniform fields in 3 directions in their common workspace. Therefore, the work presented here covers the development of software for such a platform in pursuit of full shape control.

The efforts have been separated into three objectives: developing software to directly control the hardware platform, visually inspect the workspace via camera input to extract relevant features, and finally apply closed-loop control to achieve full shape control. The software was fully developed in the C++ programming language, specifically aimed at Unix-type systems in an attempt to maximise performance and compatibility. The limitations of each section of the work carried out are finally analysed both individually and in the larger scope of the project.

Thus, software was developed to remotely control the operation of the electromagnet array provided and deduce the pose of a catheter being inserted in the workspace. Finally control strategy for this arrangement has been theorised and designed but not implemented. This strategy has been kept completely sensor-agnostic to allow for utilisation of further sensing techniques in the future and as such does not rely on any functionality specific to visual-based sensors. It is believed that implementation of such a control strategy would amount to a novel contribution to the field of closed-loop control of magnetically actuated soft robots.

1. Introduction

1.1. Introduction

Endoscopic procedures involve inserting an endoscope (generally a long, thin tube) through a patient's body to inspect or collect samples from otherwise unreachable areas without the use of open surgery, thus limiting the intrusiveness of the procedure. This type of manipulator (often referred to as Continuum Robot [1]) exhibits an infinite number of Degrees of Freedom (DoF) and differs from a standard robotic manipulator in that it is not made of a set of rigid links connected by a series of joints, but instead is composed of a virtually infinitely long string of points capable of bending.

Traditional endoscopes use semi-flexible materials and are mechanically driven by a system of cables, while also accommodating for a fibre-optic based visual sensor and/or gripper to be fit inside of the endoscope. To properly utilise such a device, extensive training is required [2] which may still not be enough to guarantee a complication-free operation.

Developments in endoscopic technology have allowed for softer materials and higher fidelity sensors [3], but still ultimately apply intrinsic mechanical actuation and hence are limited in their flexibility and miniaturisation potential.

Attempts at facilitating (and partially automate) the user's task have resulted in robotic endoscopic systems [4] that enhance the control and visibility of the operating workspace, while still maintaining mechanical actuation.

Ultimately, excessive contact with internal pathways during operation (be it due to improper manoeuvring or mechanical constraints), can potentially cause trauma to the patient [5] [6]. Thus, a clear need to reduce trauma to the patient during operation arises.

This may be achieved by either minimising the contact time during operation or by ensuring that contact-caused damage is kept at a minimum by employing smaller catheters made of softer, and/or more flexible, materials.

While reducing the hardness of the catheter by employing softer materials is possible, the greatest hurdle to both miniaturisation potential and flexibility is the inherent stiffness and size restraints that the mechanical actuation system imposes. Therefore, it is necessary to first address the actuation system employed.

By adopting an extrinsic actuation system, it is possible to remove all of the miniaturization and stiffness constraints previously considered. More specifically, by embedding permanent magnets [7] or magnetic particles [8] within the catheter, is possible to manipulate it by applying a magnetic field.

While this actuation stratagem resolves issues tied to the physicality of the endoscope, it also introduces further complexities as to how to replicate the range of motion previously achieved mechanically. Additionally, the previously existing issue of accurately modelling a CR's behaviour in motion is carried over in this soft, magnetic iteration.

1.2. Project Aims

The aim of the project is to achieve shape control over a Soft Magnetic Continuum Robot using a set of three co-axial electromagnets and visual-based closed-loop control.

1.3. Objectives

Prior to any practical work commencing, an expansive list of six objectives had been developed to break down the components required to achieve the project aims. With the benefit of hindsight, those objectives can be streamlined into a set of three macro-objectives, encompassing all the project requirements:

- To develop software to control the three co-axial electromagnets through a set of three corresponding Power Supply Units (PSU) and abstract this control software to a Graphical User Interface (GUI).
- To develop computer vision software to isolate a Continuum Robot in its workspace from a video-feed and identify its key features (tip and fundamental shape).
- To utilise the two previous components in conjunction to achieve closed loop controlling to allow the CR to achieve a predetermined shape and maintain it despite any disturbances applied.

1.4. Report Layout

The following sections of this report first cover the work and contributions carried out in existing literature: Chapter 2 covers the concepts and approaches carries out in previous research in the field while Chapter 3 summarises some of the fundamental theory relating to magnetism and soft robot modelling. Chapters 4, 5 and 6 cover subsections of work carried out, each corresponding to one of the three objectives laid out above. Finally, Chapter 7 provides a summary of the results achieved and outlines further work to be carried out.

2. Literature Review

With the introduction of endoscopes nearly two centuries ago [9], numerous efforts have been made to improve the base procedure (be that by introducing robotics or through iterating on existing designs). Thus, a plethora of literature exists on the matter of endoscopic catheters, their modelling as Continuum Robots (CRs), their fabrication and control strategies.

This section of the report aims at briefly reviewing the state of the art in Continuum Robots and analyse the main benefits and drawbacks in the current bleeding edge.

2.1. Actuating Designs

While soft magnetic robots were ultimately the focus of development within the project, multiple actuating mechanism designs are possible [10]. The following section covers some popular configurations.

2.1.1. Tendon-based Mechanisms

As described in Chapter 1, these types of CR feature an inner element that may contract or retract, causing a deflection along the length of the manipulator. Examples of this approach can be found commercially in the Monarch platform developed by Auris Health Inc. [4], as well as a

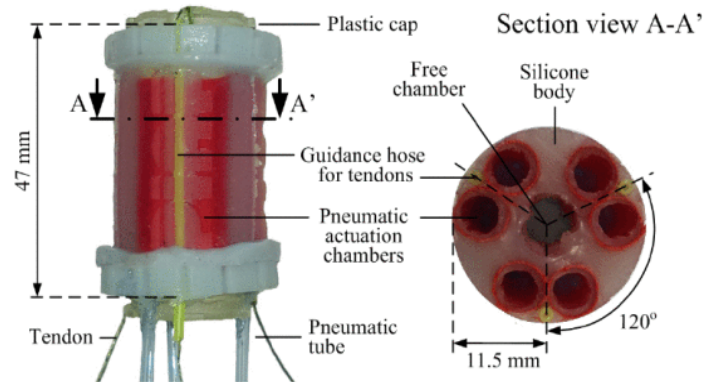


Figure 2.1: An example of a tendon-based Continuum Robot. Adapted from [11]

Pneumatically actuated solution developed by Shiva et al. [11], pictured in Figure 2.1. This Pneumatic solution particularly allows for control over the stiffness of the robot during operation.

The employment of tendon-based mechanisms allows for the actuation to happen at the proximal end of the manipulator by applying tension, effectively outside of any operating area. Although this configuration does allow for precise shape manipulation, it is required for the tendon to run through the end of the robot, limiting miniaturisation potential.

2.1.2. Concentric Tubes

In the case in which a specific (and relatively heavy) instrument is to be transported inside the human body, it may be preferable to maximise the hollow area within the robot. To achieve this, a set of tubes concentric to the payload to be delivered can be constructed. [12]

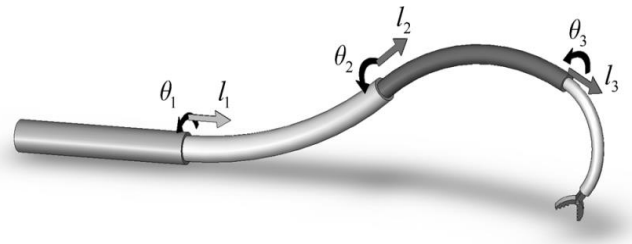


Figure 2.2: Concentric tube featuring four distinct sections. Adapted from [12]

Here, each tube features a specific stiffness and relaxed curvature, with the greatest stiffness usually found on the outmost tube and vice versa for curvature. Gradually extending a more flexible component out of a stiffer outer tube will result in it returning to its relaxed curvature. This process can then be repeated for as many tubes as are put in place, until the instrument is reached. Figure 2.2 shows one such concentric tube design, featuring four outer tubes and a gripper end effector.

An example of such a robot can be seen from Vasilyeva et al. [13], who embedded a tissue removing tool and successfully extracted tissue in a *in vivo* scenario with the system piloted by a trained cardiovascular surgeon.

Much like tendon-based mechanisms, actuation can be applied at the proximal end (in this case torque), allowing each tube to rotate and change orientation. Due to the need to imprint the resting curvature for each component of the system ahead of time, the set of possible configurations the system is available to achieve is limited and hence catheters would have to be built for purpose.

2.1.3. Magnetic Actuation

While the other Continuum Robot designs described previously feature an intrinsic actuation (applied at the proximal end and transferred through the length through various means), magnetically actuated Continuum Robots experience deflection or displacement directly at the distal end directly via an

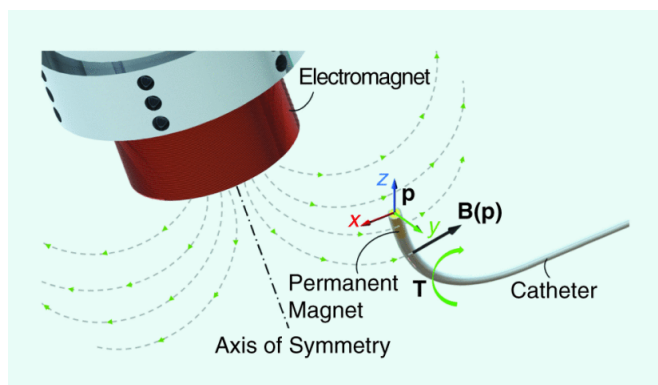


Figure 2.3: A magnetically actuated continuum robot bending when exposed to an electromagnet. Adapted from [40].

electromagnet. A visualisation of this actuating mechanism can be seen in Figure 2.3 where a catheter with a tip-mounted permanent magnet experiences deflection when exposed to an electromagnet. For the desired behaviour to occur, it is necessary for the catheter to be somehow magnetised, different strategies to achieve this will be described in Section 2.2.

Examples of this design can be observed in the work of Kim et al. [14] and Llyod et al. [15], who combine it with soft materials to reach inner lumens in fabricated phantoms. It is also worth noting here that the Kim presents a Continuum Robot actuated and controlled about the distal end only, while Llyod proposes an approach featuring discretely magnetised segments along the length of the robot.

2.1.4. Comparisons

Having identified some of the main designs, it is now possible to define some strengths, weakness, and possible use cases.

In the first place, a clear distinction can be made between the intrinsically actuated designs (tendons and concentric tubes) and the extrinsically actuated one (magnetic actuation). While the rigidity of intrinsically actuated designs does pose a challenge with regards to miniaturisation and flexibility, it also allows for systems more capable of holding their position and pose through disturbances due to inertia.

Further, the intrinsic actuation methods apply tension or torques to the system, which are straightforwardly reflected onto the length of the catheter, therefore proving possibly less troublesome to employ and model.

As previously mentioned, concentric designs manage to offer a combination of high dexterity and structural rigidity, at the cost of limiting said dexterity to a specific use case, resulting in extremely specialised designs.

Where magnetic actuation resolves a plethora of issues regarding the size and rigidity of the resulting robot, such benefits come at the price of specialised manufacturing, requiring both the magnetisation of the catheter and the application of magnetic fields. While a fully-fledged system capable of applying three-dimensional magnetic fields (and/or gradients) would allow for full exploitation of a soft continuum robot's hyper-redundancy, acquiring and utilising such a system can be identified as a set of challenges on its own.

2.2. Fabrication

Though the work presented in the following sections of this report is chiefly concerned with modelling and control, the fabrication process that the catheter has undergone is nevertheless non-neglectable as it allows to customise features of the robot such as

its magnetisation, stiffness, friction etc. This section offers a brief overview of some key aspects of the fabrication process.

2.2.1. Magnetisation Paradigms

Firstly, it is necessary to distinguish the methods utilised to achieve a magnetised continuum robot. As previously stated, this may be achieved via embedding permanent magnets or magnetic particles within a construter robot.

Lin et al. [7] construct a continuum robot by embedding permanent magnets of in a rubber tube of variable stiffness (pictured in **Error! Reference source not found.**).

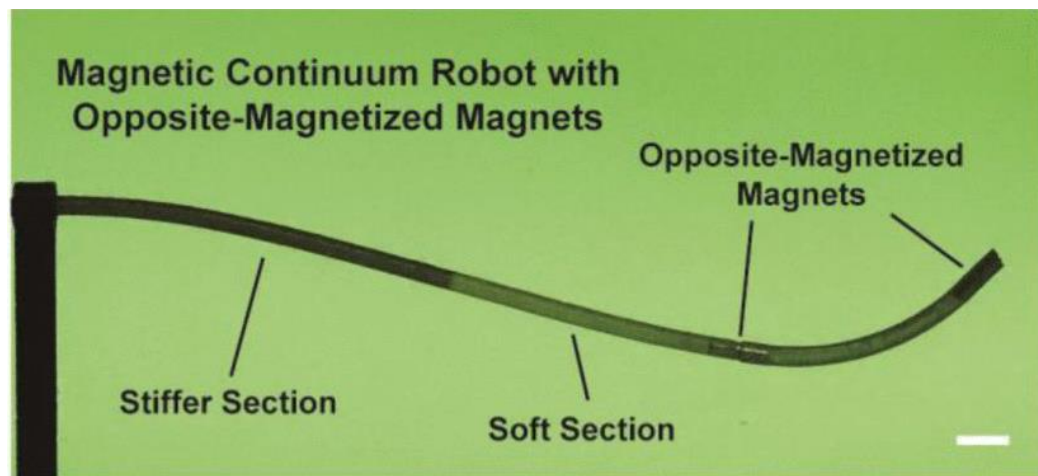


Figure 2.4: Soft Continuum Robot with Embedded Permanent Magnets. Adapted from [7]

This arrangement allows for ease of fabrication (as different magnets can simply be slid into place) and fully guarantees not only that the desired segment is magnetised, but that the remainder of the robot is not. Thus, this approach functions extremely well when paired with control strategies chiefly concerned with manoeuvring the tip of the Magnetic Continuum Robot (MCR). Further, Lin et al. utilise magnets of opposite magnetisations, achieving multi-mode deformation and hence higher dexterity. A similar approach had been earlier utilised by Jeon et al [16] with identical magnetisation on all segments to achieve three-dimensional steering in a vascular phantom.

Alternatively, it is possible to embed magnetic particles along the length of the robot. While in principle this approach achieves the same end goal (magnetisation at a given point), it also allows for magnetisation of whole catheter. Kim et al. [14] employ this approach to obtain a uniformly magnetised MCR which is then controlled solely about the tip. A visualisation of such an approach can be seen in **Error! Reference**

source not found., which presents an MCR magnetised uniformly in the -x direction while unactuated and then subject to a field in the -y direction.

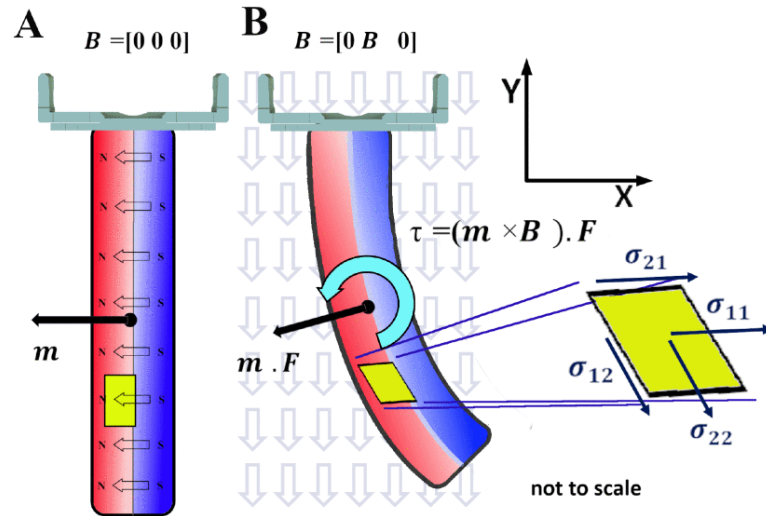


Figure 2.5: Soft Continuum Robot with embedded Magnetic particles. Unactuated on Left, Actuated on Right. Adapted from [8]

In addition to allowing a uniform magnetisation onto the MCR, this method can also be utilised to achieve distinct magnetisations along discrete segments of the robot. Combined with the relative ease with which magnetic particles can be magnetised to a desired profile (as opposed to permanent magnets), this feature enables complex magnetisation profiles to be constructed onto an MCR which in turn enable more complex shape-forming control. Llyod shows an example of this approach et al. [17], who exploit the high degree of control over magnetisation to iteratively find an optimal combination of applied field and segment magnetisation to achieve shape-forming and avoid obstacles.

2.2.2. Assembly

Regardless of the magnetisation method chosen, a method to assemble a continuum robot with must be devised. As previously stated, some of the simpler solutions feature a hollow tube containing permanent magnet(s) [7]. Procedures involving magnetic particles, however, tend to prefer injection moulding or 3D printing; while the non-magnetic base may vary between types of bio-safe silicon polymers (such as PDMS [14] or Ecoflex-0030 [8]), the magnetic sections are handled by NdFeB powder [18].

Further, to enable complex shape-forming control, Llyod et al apply their injection around a 1mm nylon braid, resulting in a structurally stronger MCR [15]. Also due to the distinct requirements in term of magnetisation, the two methods differ in their approach to arrive at it: as Kim et al. require a uniform magnetisation parallel to the length of the robot, this can be applied to the particles prior to moulding with no

issue; Llyod et al. instead develop unique magnetisation trays per required magnetisation.

Another issue to combat with regards to navigating MCRs is friction. To minimise any sort of internal damage that may be caused during traversal, it is desirable to have as little friction with the external environment as possible. As such, Kim et al. apply a hydrogel *skin* (of thickness 10 to 25 μm) [19] to their CR to reduce the friction coefficient by a factor of 10. Alternatively, Llyod et al. propose a less involved approach by submerging the workspace in liquid and utilising buoyancy to reduce the contact forces and hence circumvent friction.

2.3. Magnetic Actuation Systems

Further considerations must be made with respect to the method used to apply a magnetic field or gradient to the workspace must be made: from a single Permanent Magnet being manually moved [14] to Robotic Arms holding Permanent Magnets as end effectors [20] (a)

Figure 2.6a). And, most relevantly to this project, a system of electromagnets.

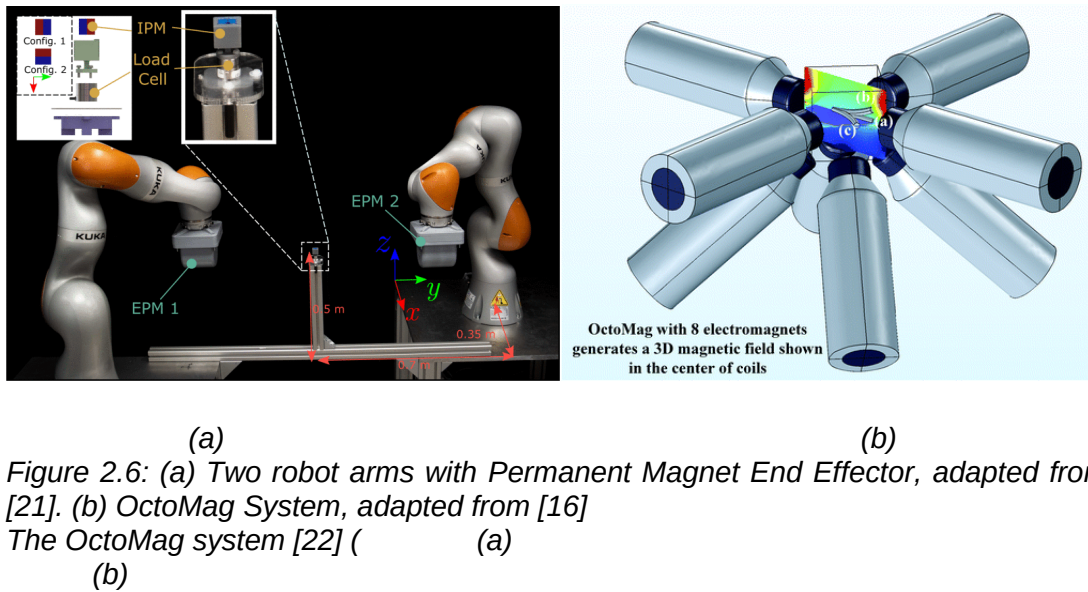


Figure 2.6: (a) Two robot arms with Permanent Magnet End Effector, adapted from [21]. (b) OctoMag System, adapted from [16]
The OctoMag system [22] (a)
(b)

Figure 2.6b) features 4 pairs of electromagnets, projecting a non-uniform magnetic field onto the workspace. While this arrangement proves more complex to control, it does allow for a more compact setup. Conversely, more traditional setups feature pair(s) of (circular) co-axial electromagnets. In such a configuration, allowing the same current to flow through both electromagnets in the pair generates a constant field (Helmholtz coils) [23], while inputting opposite currents on the pair generates a magnetic gradient (Maxwell coils).

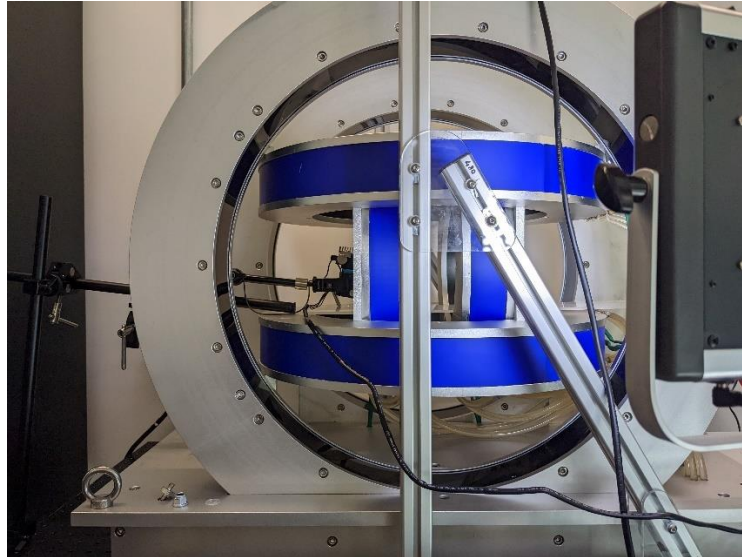


Figure 2.7: Set of 3 co-axial electromagnet pairs used in the project

Arranging 3 pairs of coils orthogonally to each other (as shown in **Error! Reference source not found.**) allows for multiple DoF control within the centre of the smallest of the coils. Though this arrangement allows for both field and gradient control in a relatively simple system, the limited workspace available in which the coils are fully effective does affect how much a Helmholtz/Maxell coil commercial product could be scaled. [23]

2.4. Quasi-Statics vs Dynamics

Finally, it is important to also establish a modelling strategy, so that the pose and position of the manipulator at a given point in time can be predicted, as would be the case in real-world operations.

Thus, a distinction must be made regarding two different approaches to modelling [8]: quasi-statics (assuming the manipulator is effectively at a standstill) or dynamic (assuming the manipulator is in constant motion).

In the first category lie methods with analytical solutions: Rigid Link [24], Energy Density [14] and Virtual Work [20] and finally Cosserat Rod Model [20], presented here in increasing complexity. Of the models listed, Rigid Link assumes the MCR to be a series of straight components connected by rigid links, Energy and Work methods consider the deformations and twisting applied to the member and its reaction to return to equilibrium, while Cosserat Rod Model considers the robot as a whole as a slender rod, providing the most accurate (and expansive) quasi-static approach.

Further, Kim et al. [23] combine Energy Density with fabrication methods similar to those detailed by Lloyd et al. [8] and a tapered structure, in which the MCR is

composed of constrained stiff and soft sections, tuneable depending on the situation to allow different degrees of deflection.

It is also worth noting that these methods are seldom used in isolation and are often combined. Roesthius et al. [24] combine the Rigid Link method with the Energy Density method to arrive at a discrete model of an MCR in action. Wang et al. [20] combined the Virtual Work principles to estimate an initial position and pose of the SCR with a Cosserat Model to be used during motion under load, allowing for accurate estimates of the effects of gravity, loads and even friction onto the system.

Here, Roesthius et al. rely on sensors mounted inside their system, while Wang utilise external sensors only et al. and encounter multiple solutions in their initial position estimation, leading to ambiguity as to which pose the manipulator holds.

Alternatively, dynamic methods may be observed. Due to their more complex nature, analytical solutions are not always possible [25] and hence iterative methods such as Finite Difference or Finite Elements Methods are considered. In a world where the Cosserat Model is considered an expansive one to compute, solving the Partial Differential Equations associated with dynamic models at run-time would be extreme. Thus, Tariverdi et al [25] propose to train a Recurrent Neural Network so that the process can be expedited drastically, providing accuracy on par with Cosserat Model while allowing for faster execution and training.

3. Theoretical Background

While Section 2 offered a brief overview to the concept currently employed in the literature, the following attempts at providing the theoretical background employed in the development of the project.

3.1. Magnetic Actuation

Firstly, it is necessary to establish a solid set of conventions regarding magnetism and mechanical actuations. Abbot et al. [26] offer extensive derivations and explanations to the interactions between magnetic fields and magnetised objects.

Because of the Co-axial coil arrangement used, it can be assumed that no current is flowing in the workspace. As such, Maxwell's equations (Equation (3.1)) apply:

$$\nabla \cdot B = 0 \quad \& \quad \nabla \times B = 0 \quad (3.1)$$

Which is to say, given $B = [B_x \ B_y \ B_z]^T$, the gradient ∇ of the applied field B is trace-free and symmetric. Next, it is possible to approximate a sufficiently small and magnetised object to an infinitely small magnetic dipole of magnetisation $m = [m_x \ m_y \ m_z]^T$. When said dipole is subjected to a misaligned uniform magnetic field B , the dipole experiences a torque $\tau = [\tau_x \ \tau_y \ \tau_z]^T$ in an attempt to align itself with the applied field. Such behaviour is illustrated in Figure 3.1a. With the torque given by Equation (3.2):

$$\tau = m \times B \quad (3.2)$$

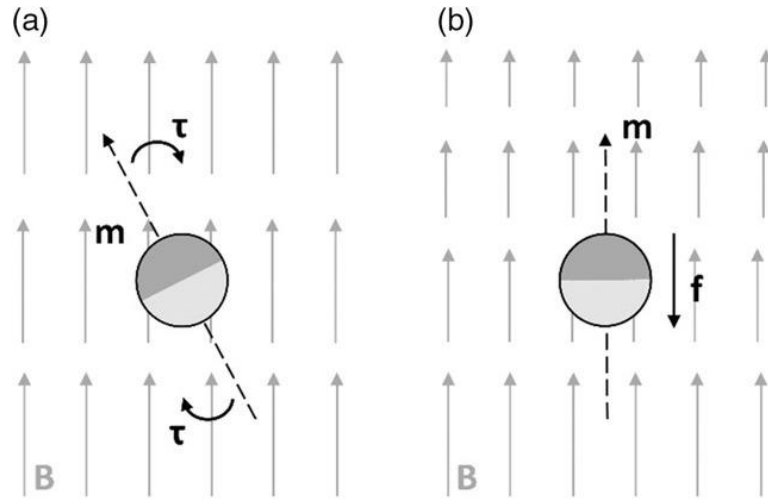


Figure 3.1: (a) Dipole exposed to a magnetic field and rotating due to torque. (b) Dipole exposed to a magnetic gradient and displacing due to force. Both adapted from [27].

From the cross product identity (Equation (3.3)).

$$\tau = m \times B = m_{\times} \cdot B \quad (3.3)$$

Where $m_{\times}$ is the skew-symmetric matrix built from m :

$$m_{\times} = \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix}$$

Which ultimately leads to Equation 3.4 [28]:

$$\tau = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \quad (3.4)$$

When a dipole is exposed to a varying magnetic field (gradient), it experiences a force $F = [f_x \ f_y \ f_z]^T$ in the opposite direction of the magnetic gradient applied (Figure 3.1b). This relationship can then be expressed as Equation 3.5

$$F = (m \cdot \nabla) B \quad (3.5)$$

Given the two conclusions drawn from Equations 3.1 (field is symmetric and has no trace), it is possible to rephrase Equation 3.5 as:

$$F = \begin{bmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & -(\frac{\partial B_y}{\partial x} + \frac{\partial B_x}{\partial y}) \end{bmatrix} \cdot \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \quad (3.6)$$

While further derivations from here are possible [28] (allowing to construct wrenches and mappings from wrench to magnetisation), Equations 3.4 and 3.6 show relationships between the applied field and resultant forces and torque, covering the basics of an actuation system.

3.2. Rigid Link Model

As will later be explored, while Continuum Robots do possess infinite DoF which may be applied about any point of their length, modelling such behaviour is computationally expansive and generally complex [25]. As such, initial attempts at modelling and control (such as in this work), should focus on simpler approaches.

One such approach is the Rigid Link model [15]. Herein, a Continuum Robot may be discretised in a finite number of rigid links connected by an equal number of joints, about which actuation occurs. With these assumptions, the robot effectively becomes akin to a robotic arm. Generally, this kind of arrangement features a combination of joints that either allow linear motion (prismatic joints) or angular motion

(revolute joints), with both types being showcased in Figure 3.2, which features two prismatic joints (d_2 and d_3) and one revolute joint (θ_1). In the case of this project, only bending is modelled (as linear motion is provided externally) and therefore all joints in the discretised MCR are revolute joints, simply assigning the role of end-effector of the robot to the last joint in the chain.

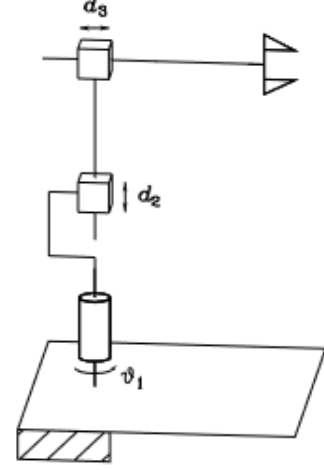


Figure 3.2: A robotic arm based on rigid links. Featuring prismatic joints d_2 and d_3 and revolute joint θ_1 . Adapted from [29]

While approximating most of the robot as a set of rigid beams does technically limit the potential to model curvature, providing a sufficiently small length for each link and a sufficiently high number of joints, curvature can be modelled to an acceptable extent.

3.3. Geometric Jacobians

Having simplified a MCR to a combination of revolute joints and rigid links, it is necessary to be able to determine the contribution of each joint's motion to the position and orientation of the end effector. More precisely, it is possible to construct a matrix to quantify the effect of joint velocities (linear and angular) on the end effector velocities. While it would be possible to derive such a relationship by differentiating the positions and orientations of each joint in the system (thus deriving an *Analytical Jacobian*), in a quasi-static scenario (such as the one assumed in the work carried out for this project), it is preferred to instead derive this relationship from the robot's geometry (hence *Geometric Jacobian*). [29]

Effectively, the end effector velocities can be expressed Equation (3.7:

$$\mathbf{v}_e = \begin{bmatrix} \dot{p}_e \\ \dot{\omega}_e \end{bmatrix} = J(q)\dot{q} = \begin{bmatrix} J_P(q) \\ J_O(q) \end{bmatrix} \dot{q} \quad (3.7)$$

Where $\mathbf{v}_e$ represents the end-effector velocities, $\dot{p}_e$ and $\dot{\omega}_e$ represent the linear and angular components of said velocities, $J(q)$ represents the Geometric Jacobian and $\dot{q}$ represents the joint velocities. As can also be seen in Equation (3.7, the Jacobian $J(q)$ can further be decomposed into its linear and angular components, $J_P(q)$ and $J_O(q)$ respectively. For n joints, the Jacobian J can be generalised to Equation (3.8 [29]:

$$J = \begin{bmatrix} J_{P1} & \cdots & J_{Pn} \\ J_{O1} & \cdots & J_{On} \end{bmatrix} \quad (3.8)$$

With the Linear and Angular components J_P and J_O at joint i given by Equation (3.9 [29]):

$$\begin{bmatrix} J_{Pi} \\ J_{Oi} \end{bmatrix} = \begin{cases} \begin{bmatrix} z_{i-1} \\ 0 \end{bmatrix} & \text{Prismatic Joint} \\ \begin{bmatrix} z_{i-1} \times (p_e - p_{i-1}) \\ z_{i-1} \end{bmatrix} & \text{Revolute Joint} \end{cases} \quad (3.9)$$

With z_i being a unit vector representing the orientation of joint i and p_i representing the position of joint i in space. Thus, it is possible to arrive at the Geometric Jacobian of rigid-link system in a quasi-static environment with relative ease, given the orientation and position of each joint are known.

4. Low-Level Control of the Apparatus

4.1. Introduction and Objectives

To enact closed loop (or any sort of) control onto the system, it is first necessary to be able to achieve basic control of the apparatus. Aligning with the first objective outlined in Section 1.3, this section of the report covers the development process undergone to arrive at software to control the apparatus given. For performance reasons, compatibility with existing systems within the wider research group and familiarity of the author, it was decided to utilise the C++ programming language in a Unix-based environment (Ubuntu 18.04).

Firstly, the component make-up of the apparatus is covered, then the communication protocol used is explored, some of the complications encountered during development and finally the results of the development process are outlined.

4.2. System Overview

A comprehensive view of the system can be seen in Figure 4.1, with annotations on the figure outlining every major component.

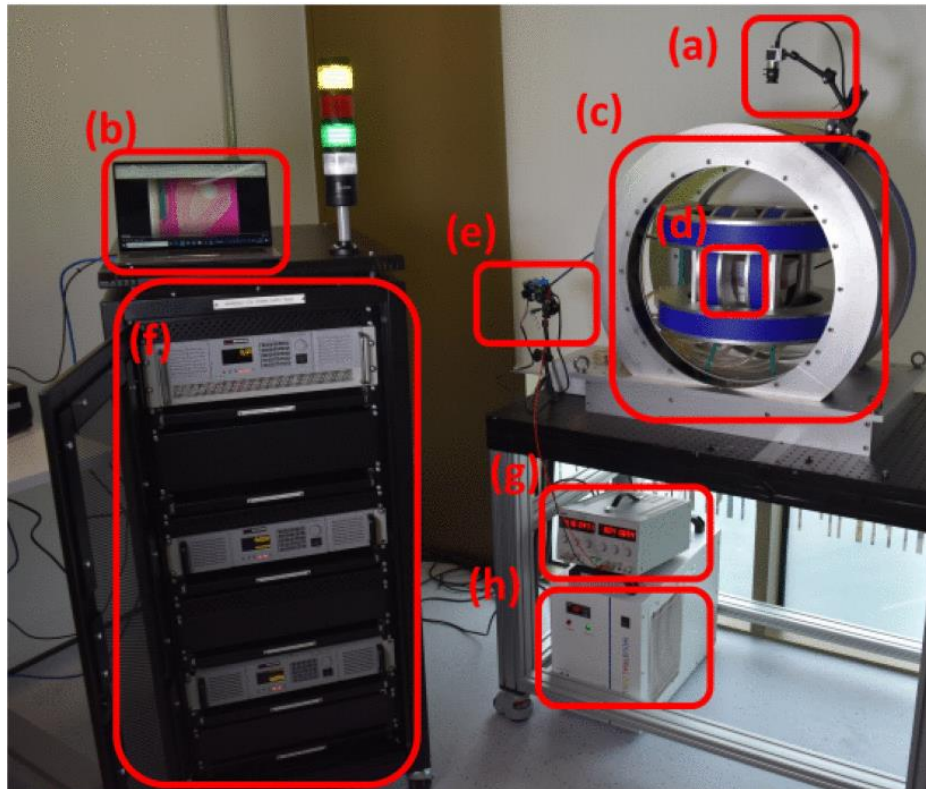


Figure 4.1: Annotated View of the Apparatus. (a) Basler Camera. (b) Computer Used. (c) 3D Coils. (d) 3D Coils Workspace. (e) Linear Introducer. (f) Power Supply Cabinet. (g) Linear Introducer Power Supply. (h) Cooling unit for 3D Coils. Figure and Caption adapted from [15]

As previously alluded to a set of 3 pairs of co-axial electromagnets (3DXHC12.5-300 [30]) are connected to 3 Power Supply Units (PSU, DXKDP [30]). Each supply provides electric current to a respective pair of electromagnets, thus generating a magnetic field about the respective axis. Since both coils in a pair receive the same current, this arrangement is distinctly a 3D Helmholtz Coil. A MCR is introduced into the system's workspace via a stepper motor (Nema 17 [31]) controlled by a uStepper control board [32]. Finally, visual feedback is given back to the control system from a Basler camera [33]. Excluding the cameras utilised, all components are controlled through RS232 serial communication protocol.

4.3. Initial Serial Communication Efforts

The first milestone identified for the project was successful communication with the Power Supply array. Thus, initial efforts were completely devoted to studying the system and its operation. The supply array utilises RS232 serial communication in conjunction with a custom set of instructions, ranging from setting Voltage/Current levels to altering the protection values of the system. This system allows a varying number of bytes to be sent over, always starting with a Synchronisation Character "0xAA" and a Command Word, followed by the related PSU address and any other relevant information. The command would then be terminated with a "Check Bit", the 2 LSB of the sum of all sent bytes, excluding the Synchronisation Character. Table 1 shows a breakdown of a sample instruction and its possible return values.

Table 1: Sample 'Set VI instruction', with return value

Byte	Function	Mock Command Value
1 st	Synchronisation	0xAA
2 nd	PSU Address	0x01
3 rd	Command	0x23
4 th	Length of data sent	0x04
5 th	Voltage LSB	0x10
6 th	Voltage MSB	0x00
7 th	Current LSB	0x30
8 th	Current MSB	0x00
9 th	Check Bit (Sum of Bytes 2~8)	0x68
Returned Value	Acknowledgement	0x06 if Successful 0x15 if Unsuccessful

Following an analysis of this custom communication protocol, a great deal of time was expended attempting to establish a successful serial communication with the system. A number of debugging techniques were attempted (oscilloscope/logic analyser probing, various software), but no data was ever received or returned from any of the supplies.

While attempting different cables and connectors to rule out faulty communication hardware, it was discovered the resistance associated with the length of the cable originally used was just high enough to cause a non-neglectable loss in signal amplitude, making it so no signal sent would ever reach or leave the power supplies.

Thus, utilising a shorter cable to connect to the PSUs allowed for the recorded successful Serial Communication.

4.4. Initial Designs and Development

Having confirmed a first Serial Communication with the system, Figure 4.2 was developed, envisioning an overall architecture for the system.

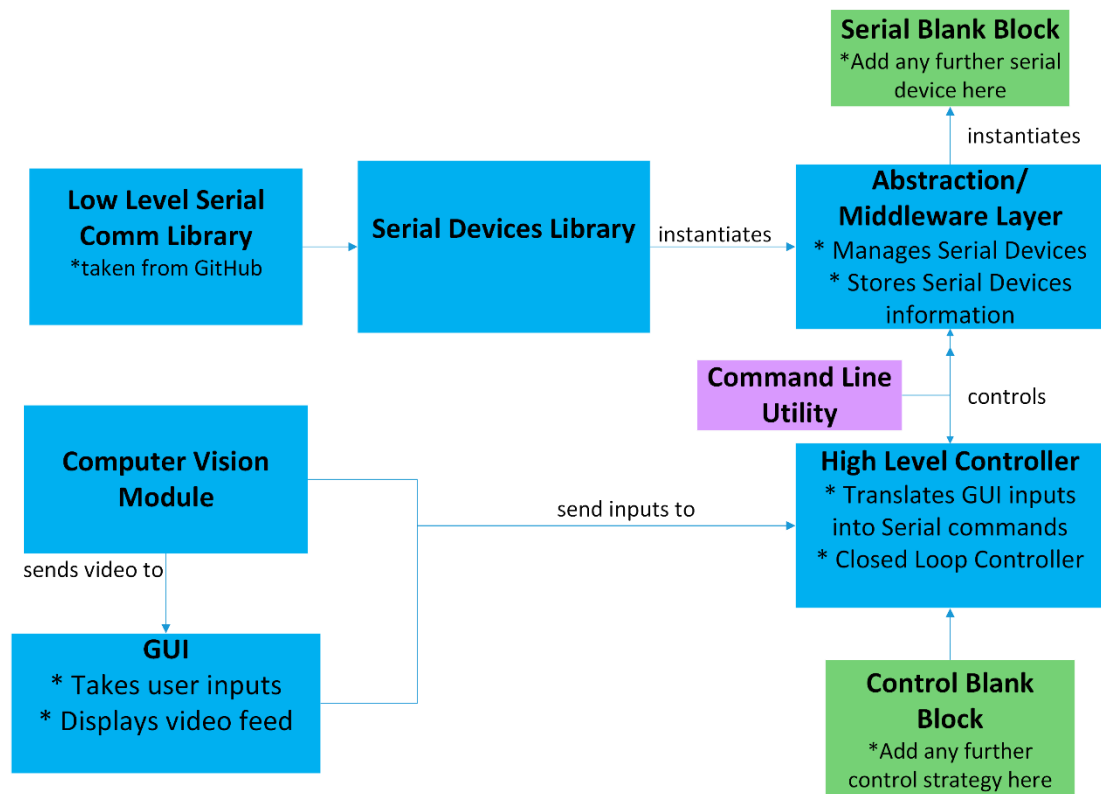


Figure 4.2: Overall Architecture Designed for the System

While Figure 4.2 covers the whole system to be developed, it was decided to attempt a total design immediately to avoid issues of incompatibility between different sections of the project later down the line, with the first main row covering the development relevant to the current section.

In short, it was decided to allocate each serial device (PSU array, Introducer, Tesla meter) a distinct serial interface in C++ (or Library), each self-sufficient and complete. The developed Libraries would then be grouped and abstracted into a Middleware Layer, which calls existing functionality from the existing Libraries and provides the user with simpler interfaces. For instance, setting a Field of 15mT in the Z direction manually would require knowing which Power Supply is connected to the Z coils, what the conversion rate between Amperes and mT is in the Z direction and finally know the command required to set the required current.

With the interface developed, all the above work is abstracted to a simple function call to set the field in one direction to a desired value. This modular approach to abstraction grants multiple benefits such as lower technical overhead required of the user interested simply in setting a magnetic field, implementing further devices (indicated by the Blank Boxes in green) and isolating individual blocks to prevent errors from spreading.

4.5. Developed Software

With successful serial communications reliably possible and a full architecture plan devised, the Serial Devices Libraries were fully developed. Additionally, all the software relevant to this section was fully documented and uploaded as a webpage, allowing future developers for the system to learn about the system without having to read the source code directly. Figure 4.3 shows the front page of the documentation developed.

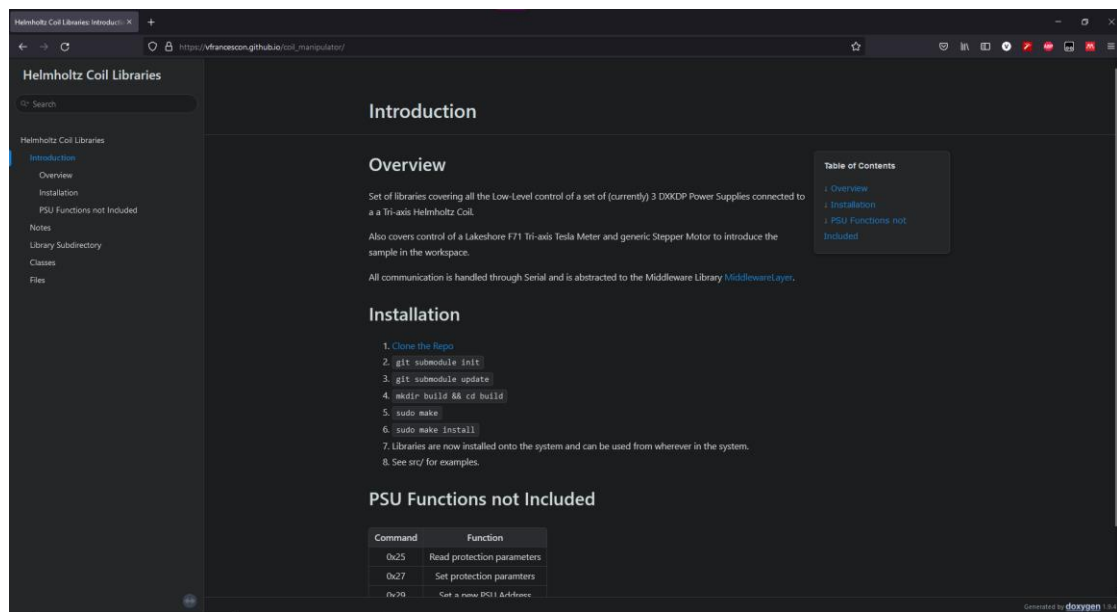


Figure 4.3: The front page of the Documentation Website

Additionally, as hinted by Figure 4.2, a Graphical User Interface (GUI) was initially to be developed. While such a component was prototyped for the system (and will be developed moving forward), it was decided early in production not to allocate any more development time to it in favour of the machine vision and control model, as they constituted more novel contributions.

This module was envisioned to provide further abstraction from the Middleware library developed, allowing the user to directly control the serial devices via sliders and observe the workspace directly from the cameras. The prototype GUI developed (dubbed skeleton), is shown in Figure 4.4. This was developed using the Qt graphics framework [34], solely chosen because of previously familiarity with the toolkit.

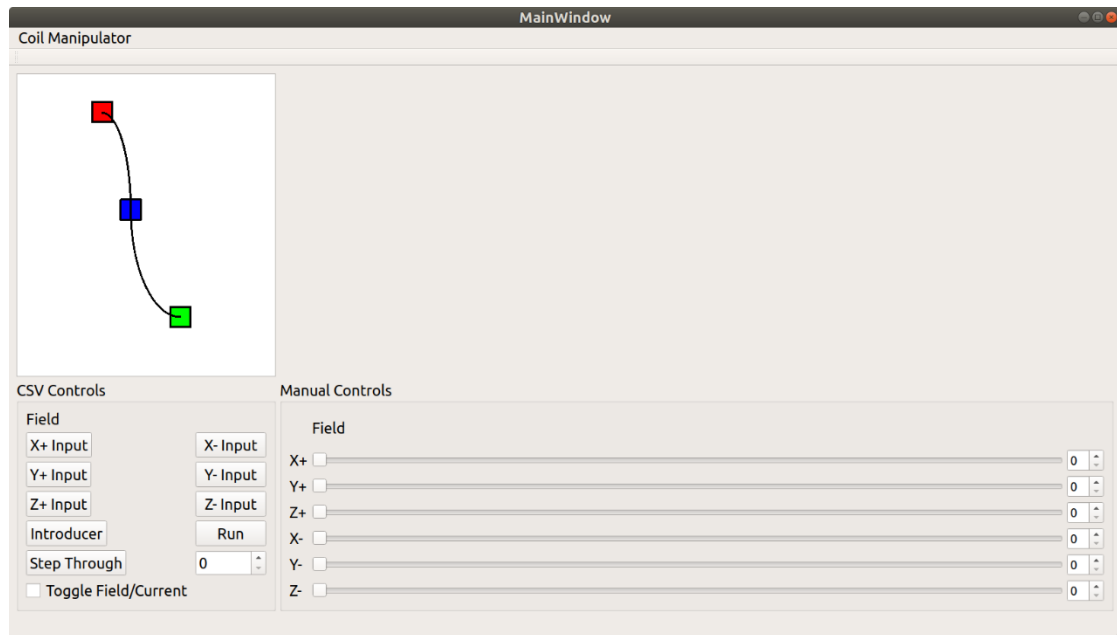


Figure 4.4: The current 'skeleton' of graphical user interface, showing slider inputs for fields in positive and negative direction, plus a mock camera view

5. Machine Vision and Image Processing

5.1. Introduction and Objectives

With a satisfying level of control over the magnetic fields applicable to the workspace and the introduction of a magnetised sample via linear actuators, as per the second objective outlined in Chapter 1.3, it was then necessary to develop the necessary software to track fundamental features of a continuum robot in real-time. This section focuses on the work carried out to develop said software, the product delivered and its limitations.

For the purposes of handling, interpreting, and analysing a continuous stream of images (be it from a camera or pre-recorded video), the OpenCV [35] library is used. Maintaining with the previously developed Low-Level libraries, the software developed here is also built in C++ for a Unix-type system. To ease development, the image processing module discussed here was developed and tested using footage from an existing publication that utilised a nearly identical setup [15] and eventually rolled out on real-time footage captured from the Basler cameras provided.

5.2. Relevant features

Recalling Figure 3.2 (and more generally Chapter 3), we can establish a set of features that must be tracked during operation to enable visual-based control of the system: End Effector, Joints, Rigid Links.

Of the items listed, the first one proves trivial as that is simply the distal end of the robot during insertion. Slight complications arise when attempting to identify the following two items. As both Joints and Links are part of a modelling strategy, they are purely virtual and thus not reflected in the actual system. While visual markers could be placed onto the robot (as is often done during fabrication [8]) to clearly indicate where those virtual joints would be located, this would cause the system to rely on features unique to visual sensing for its analysis techniques, rendering approach of used less sensor-agnostic.

Thus, given an image input, the system must be able to track the distal end of the robot as well as somehow deduce a feasible location for virtual joints to exist, with virtual Links simply being straight lines connecting the joints.

5.3. Image Pre-Processing

As is often required in any image processing program, it is first necessary to apply some sort of pre-processing to eliminate noise and generally undesirable features. More specifically in the case still image used early in development (Figure 5.1a), the Bowden cable used for insertion as well as any visible features of the soft phantom

employed must be eliminated. While the phantom's features can simply be eliminated by applying a thresholding filter, the Bowden is necessarily placed on the same plane as the MCR and thus cannot be directly filtered out. As an initial countermeasure, some experimentation was carried out with background subtraction [36]: this approach would selectively remove sections of an image that were determined to be static by comparing them to previous cached frames in the video.

While this approach worked in principle, any slight disturbance in the video (such as a camera shake or contact between the phantom and robot) would cause undesired information to bypass the filter. Therefore, a simpler, less complaint method was devised.



Figure 5.1: (a) Initial image. (b) Pre-processed image to isolate MCR. Original Image adapted from [15].

Upon starting the video, the first frame is immediately cached and pre-processed. Because the video begins prior to insertion of the robot in the workspace, this initial frame must only contain features that regular pre-processing cannot eliminate but are unwanted. By inverting this processed frame, it is possible to utilise it as a mask and apply it to every subsequent frame, eliminating all unwanted features from the video feed. Figure 5.2 shows the mask developed with this method (a) and the resulting image, fully pre-processed (b).

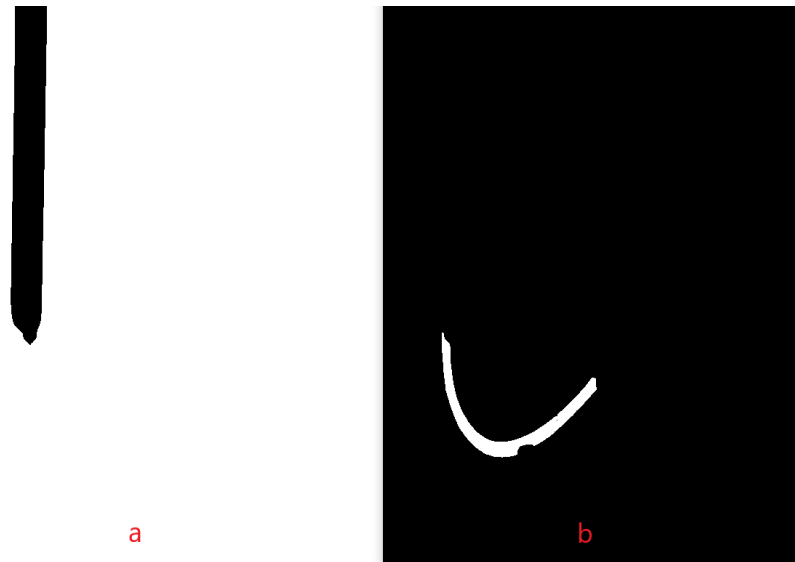


Figure 5.2: (a) Mask from initial Frame. (b) Robot inserted with mask and pre-processing applied. Footage adapted from [15].

5.4. Zhang-Suen Thinning

Having obtained a binary image of the continuum robot during insertion, it is technically possible to immediately track the position of the tip based on simple geometry (tip must be positioned between the two sharpest angles between points). While such an approach would effectively provide a tip location, it does not provide any information useful to deducing joint locations.

For the Rigid Link assumption to hold most accurately, it is desirable for the joints to be placed along the centreline running through the length of the robot. At the same time, it is also true that such a line would contain the tip of the catheter. Therefore, evaluating a centreline for the binary image would serve as an advantageous starting point for both end goals.

Given a binary image, it is possible to analyse its makeup on a pixel-by-pixel basis and evaluate the number of non-zero immediately adjacent pixels (neighbours). Based on that number, the binary image can be “stripped” until only the fundamental shape of it is left. This process, dubbed thinning, effectively evaluates the centreline of an image. Employing an algorithm developed by Zhang and Suen [37] and implemented in the OpenCV libraries, it is possible to quickly and efficiently evaluate the centreline of the robot at every frame without significant performance loss.

5.5. Feature Extraction

Through the centreline obtained from the thinning algorithm detailed above, it is immediately possible to determine the end effector location by looking at its distal end.

Further, it was found the set of points making up the centreline to be linearly related to the length of robot inserted, as depicted in Figure 5.3. Here, the point count for the centreline was recorded during video playback of two insertions, the duration of the video is tracked in terms of its frames. It can be seen that, ignoring some minor overshoots, the point count increases linearly during insertions (frame 0 $\rightarrow$ 150 and 400 $\rightarrow$ 525) and decreases linearly during retractions (frame 190 $\rightarrow$ 310 and 680 $\rightarrow$ 710).

Therefore, given an appropriate conversion factor between length of the centreline and robot length, it is possible to allocate equally spaced points on the centreline as virtual joints for the Rigid Link Model to utilise.

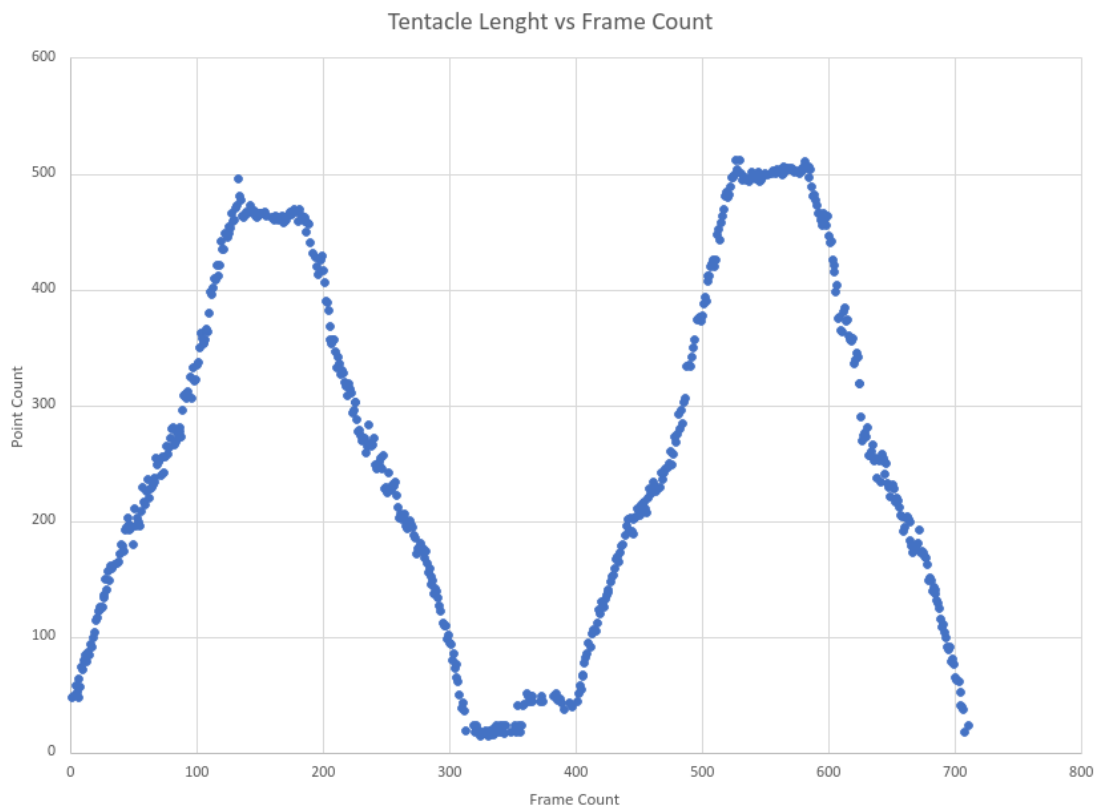


Figure 5.3: Centreline point count vs frame count

With a prototype of the computer vision module developed theoretically, it was decided to test its performance in real time operation. Using footage (captured by a Basler Ace AC2040 Camera [33]) of a MCR being inserted while magnetic fields are actuated from the 3D coils through the power supplies (controlled with the low-level code previously developed), Figure 5.4b was arrived at, with Figure 5.4a showing the same procedure run on pre-recorded video for comparison (in both cases, a snapshot of the video was taken as indication of the whole operation).

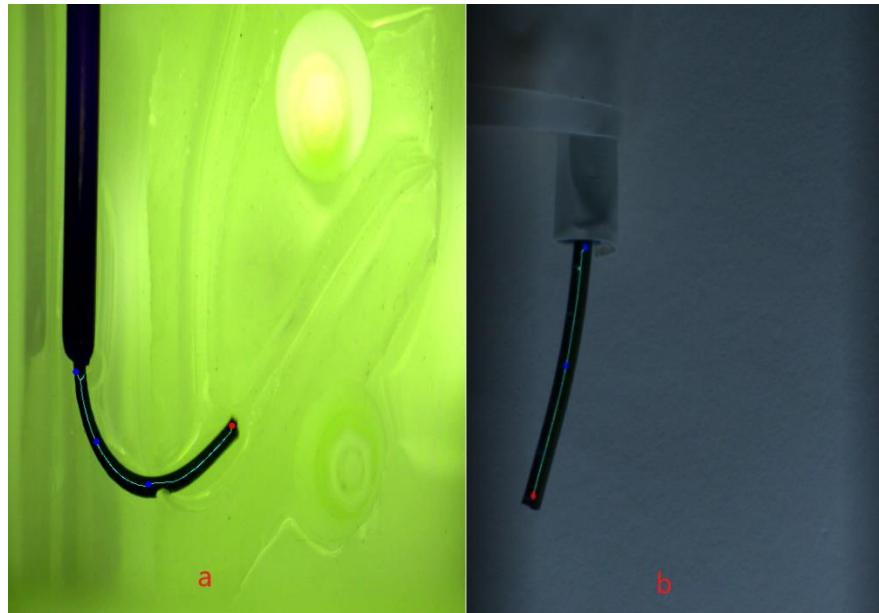


Figure 5.4: Processed frame with drawn centreline (teal), deduced tip (red) and deduced joints (blue). (a) On pre-recorded video [15]. (b) captured in real time.

5.6. Limitations

While thankfully no overhead was ever experienced despite the computations being carried out in real time, testing the computer vision module developed in an experimental setup attempting to replicate that of Figure 4.1 revealed two main limitations:

1. The point of the centreline identified as the 'tip' of the robot is simply the one with the highest (or lowest) x (or y) coordinate on screen.

This translates in a need to modify the source code every time the insertion direction changed. While untested, this issue could be solved by applying curve fitting to the set of points and utilising the results as a metric for sorting.

2. Any deflection or glare in the video feed causes the centreline to diverge.

The divergences in the centreline result in the relationship outlined in Figure 5.3 to fail and hence the position of the joints can no longer be determined simply by taking points from the centreline. A general solution to this problem has yet to be identified, but it may be wise to utilise the centreline as a basis for a more robust metric used to allocate the joints. Alternatively, further work might be required with regards to camera and light placements such that no glare is present.

6. Closed-Loop Shape Forming

6.1. Magneto-mechanic Equilibrium

With the capability to effectively control the magnetic field applied in the workspace and (theoretically) deduce the robot's pose, a control strategy must be put in place. To simplify development, an Open-Loop solution was first studied, after which a Closed-Loop strategy could be incorporated by utilising inputs from the camera.

In both scenarios, the concept of magneto-mechanic equilibrium is applied. Here, it is assumed that the torque imparted onto the system magnetically (as per Equation (3.4) must be equal to the mechanical torque the system experiences as a reaction. Hence, Equation (6.1) [17] equates the mechanical torque (left hand side) to the magnetic torque (right hand side):

$$KQ = J^T m_{\times} B \quad (6.1)$$

Where it may be recalled that $m_{\times}$ is the skew symmetric matrix built from the magnetisation of a dipole and J is the full Jacobian of the system. Additionally, K is a diagonal matrix representing the stiffness of the material and Q is a column vector representing the angular deflection in 3D.

While the Equation (6.1) holds for the deflection of a single magnetised joint, it is obvious that the relationship used must be scaled to work on n joints. Thus, the mechanical side is adapted such that Q becomes a vertical stack of deflection vectors for each joint in the chain and K becomes a diagonal stack of the stiffness matrix of each joint actuated. On the magnetic side of the equation, the Jacobian J is already fully equipped to scale with the number of joints and the applied field B can only be a column vector. Thus, the magnetisation matrix $m_{\times}$ must be modified to scale with n joints.

To that end, Llyod et al. [17] offer a solution based on the work of Salmanipour et al. [28]: assuming that no gradients are in place, a matrix S may be constructed as shown in Equation (6.2):

$$\text{for } 1 < i < n, \quad S = \begin{bmatrix} 0_{3 \times 3} \\ m_{\times}(i) \\ \vdots \\ 0_{3 \times 3} \\ m_{\times}(n) \end{bmatrix} \quad (6.2)$$

That is effectively to say, a vertical stack of all the skew-symmetric matrices built from the magnetisation of each joint, padded with 0s to account for the lack of magnetic gradients applied.

Thus, Equation (6.1) can now be rewritten as Equation (6.3)

$$K^k Q^k = J^{T^k} S^k B^k \quad (6.3)$$

Where k indicates the insertion timesteps (i.e., the number of joints in the workspace).

6.2. Open-Loop Strategy

Generally, the goal of the open-loop controller designed for this scenario is concerned with offering an initial estimate of the field required to hold a given shape, where said shape is defined by a set of joint angle deflection. At this point, the mechanical properties of the robot are known, as is the magnetisation profile of each segment (hence joint).

Essentially, Equation (6.3) can be re-arranged such that the joint angles Q are the input and fields B are the output. Thus, Equation (6.4) can be arrived at:

$$\left(J^{T^k} S^k \right)^+ K^k Q^k = B^k \quad (6.4)$$

Where A^+ represents the pseudo-inverse of a Matrix. This process can then be repeated for increasing k . Being completely removed from system dynamics, this process can be completely carried out ahead of time, ensuring it poses no overhead to the real-time section of the controller.

6.3. Pseudo-Inverses and Infinite Solutions

An issue arisen during the development of the Open-Loop controlled was that of the uniqueness of the solutions derived from Equation (6.4). Considering a general problem in Equation (6.5):

$$Ax = b \rightarrow x = A^{-1}b \quad (6.5)$$

While a regular inverse matrix is such that $A^{-1}A = I$, pseudo-inverse matrices only guarantee that $AA^+A = A$. Therefore, a general solution to a problem involving pseudo-inverses is given by Equation (6.6) [38]:

$$Ax = b \rightarrow x = A^+b + (I - A^+A)w \quad (6.6)$$

Where w is a vector of equal dimensions to x which allows access to all possible values of x for which Equation (6.6) to hold true. While for certain cases $A^+A = I$ and a unique solution does exist, the specific case of Equation (6.4) does not allow that and hence an infinite number of permutations of B might achieve equilibrium as required. While ignoring the infinite number of solutions and considering a pseudo-inverse does return an answer, it was found that said answer is often made of unfeasible values for actuatable fields.

Due to time constraints, the necessary investigation on the method to constrain the solutions to Equation (6.4) to achieve realistic results through Equation (6.6), the Open-Loop controller was not completed.

6.4. Closed-Loop Strategy

By having initially assumed the system to be quasi-static, it is possible to simplify the control system not to require an Integral or Derivative component. As such, it is possible to model the system's behaviour purely with a Proportional component.

Therefore, the rate in joint angles Q with respect to field B . By re-arranging Equation (6.3), the Equation (6.7 can be obtained:

$$Q^k = K^{k-1} J^{T^k} S^k B^k \quad (6.7)$$

Which when differentiated becomes Equation (6.8:

$$\frac{dQ}{dB} = K^{-1} J^T S \quad (6.8)$$

While there exists a more exact approach by applying partial derivatives with respect to each joint angle respectively, this initial attempt would offer at least a qualitative measure of whether applying this approach to closed loop control would be worthwhile.

Finally, the set of desired joint angles Q_d can be compared with the set of observed joint angles Q_o to compute an error function. This can then be utilised to calculate how much to vary the applied field by.

6.5. Conclusions

The system's behaviour was modelled on the basis of equilibrium between applied and reactive forces. This model was then utilised to develop a precomputation, open loop strategy and a closed loop strategy to alter the pose of the robot by altering the applied field. Complications arisen from the non-uniqueness of possible solutions to the initial field estimates have halted development of the remainder of the project.

Best efforts have been placed into making the control module "sensor agnostic", such that adoption of different sensing techniques can be made by simply replacing the Machine Vision module with whatever sensor is used.

7. Conclusion

7.1. Achievements

Work on this project was split amongst three objectives, which were completed to varying extents:

- The serial communication module was fully developed for usage and is being adopted into existing research. It was designed in a modular and open fashion to allow for future additions and revisions.
- In the spirit of open source development, a comprehensive documentation was also developed for the serial communication module, to further allow contributions moving forward.
- A computer vision module was prototyped and shows promise with respect to computational times and accuracy. It is unclear at this stage whether its current iteration is robust enough for future usage or more work will be required on that front.
- A control module was designed on the basis of magneto-mechanic equilibrium. While never implemented, it is hoped that the future implementation of this controller will provide an analytical answer (or the closest relative) to field control in order to minimise the required computations.

7.2. Discussion

Ultimately, the three components making up the project were developed individually and slowly combined and integrated with each other. This approach allowed full focus on each section, which ultimately led to the completed software to be delivered to a satisfyingly high standard. Furthermore, it also allowed to minimise the impact of delays in components arrival and general malfunctions with the hardware (such as the Serial Communication issues outlined in Chapter 4.3 as one objective could be temporarily side-lined for the others while faults were resolved.

Furthermore, maintaining the components separate during development allowed for distinct and bespoke designs to emerge, resulting in each section providing useful software for a specific task, regardless of the others' completion.

An immediate example can be seen in the control model developed being able to operate regardless of the modality used to deduce the catheter pose or how the magnetic field is actuated. Similarly, each component is designed to individually achieve its objectives, as well as being designed for integration with the remainder of the project.

An immediate drawback of this approach is the requirement for an over-arching design of the whole infrastructure, as well as an in-depth the development of three individual designs. Effectively, this resulted in the work carried out being split in three mini-projects.

Furthermore, the individual designs were forcibly required to allow for integration, restricting options for certain design decisions (i.e., the use of multiple programming languages and framework was ruled out). With the integration step still requiring some reconciliation and refactoring of each module to reach an operational state.

Overall, this approach proved successful in developing the software for the first objective but was also found to be extremely time consuming due to the extensive amount of research and planning required for each mini project. It is also true that the original scope for the project chosen was extremely ambitious and wide, which also impacted the amount of time each component required.

Finally, it is worth noting the initial objectives of the project were reined in and congested into fewer, more focused goals. While it is true adjusting the initial aims during development caused delays to the process (ultimately causing the targeted conference deadline originally aimed at unreachable), it is still believed the work carried out offers a solid starting point for future novel contributions.

7.3. Conclusions

In conclusion, the work carried out thus far for this project covered the development of the software required to control a 3D Helmholtz/Maxwell coil platform and the provides a solid foundation from which to build control software for effective shape-forming of continuum robots.

7.4. Further Work

Future work in this project will immediately be focused on completing the control module and possibly increasing the robustness of the computer vision module, hopefully utilising the two combined with the low-level serial interface to arrive at novel contributions with regards to magnetic control of soft continuum robots. Secondly, the current *skeleton* state of the GUI will be re-integrated with the system, to allow easier usage for future users interested in exploring the effects of various magnetic fields applied in the workspace.

Finally, efforts beyond this initial attempt at control should be concerned with expanding the scope to full 3D shape forming and eventually integrate sensing techniques more suited for usage within the human body, such as Fibre-Bragg Grating sensors [24] and Ultrasound imaging [39].

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Appendices

1. Appendix A – GitHub repository

All software developed for the project can be found at:

github.com/Vfrancescon/coil_manipulator

Documentation for the Serial Devices Libraries can be found at:

vfrancescon.github.io/coil_manipulator

All externally sourced software is credited within the readme files or documentation.

2. Appendix B – DXKDP Command Table

Table 2: Set of Command words for Remote PSU operation

Code	Operation
20	Set Power Output State
21	Set Output Voltage
22	Set Output Current
23	Set Output Voltage & Current
24	Set Polarity
25	Read Protection Parameters
26	Read Actual Voltage & Current
27	Set Protection Parameters
28	Read Set Voltage, Current & Status
29	Set new communication address for the PSU
2A	Read status of PSU
2B	Read System info of PSU
30	Toggle Local/Remote