Novel Fibre Optic Force Sensors

Combining state-of the art fibre optic strain sensing with AI techniques for bespoke multi-axis force sensor development – cutting edge research for industry implementation

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INTRODUCTION

Background, Motivation & Research Aims

Rising demand for perception and sensing functions in the Internet of Things has prompted a surge in force sensor innovation and development. However, certain areas of the market remain poorly served by existing sensor designs and/or technologies, such as Wheatstone bridge strain gauges, possessing a number of limitations. Fibre optic sensing (FOS) technologies, in particular fibre Bragg gratings (i.e. FBGs), have exciting potential to act as accurate, flexible solutions, with many novel and exciting applications.

Multi-axis force sensors provide three-dimensional measurement of physical quantities such as force, pressure and torque. There are **two integral parts** to every sensor:

(i) the **sensing technique/transducers/element** of the sensor (e.g. ERSG, FOS, capacitive)
(ii) the sensor **elastic host body**

This project aims to address existing limitations by fusing state-of-the art FBG sensing with artificial intelligence techniques to create a robust, cheap, versatile and easily reproducible working sensor with a simple structure that can compete in the identified markets for a range of applications.

THE PROBLEM

- Lack of standardisation and increasing complexity of sensor structures is driving up sensor price
- Extremely precise transducer placement required to achieve accuracy and sensitivity thresholds
- Intricate and impractical instrumentation procedures are increasing sensor manufacture and calibration times
- Lack of adequate sensors in large scale applications involving harsh environmental conditions and/or electromagnetic interference

PROPOSED SOLUTION: A NOVEL MULTI AXIS FORCE SENSOR

FOS sensing:
- Multiplexing capability
- Immunity to electromagnetic and radio frequency interference
- Robust to extreme loads & temperatures
- No risk of damage from water ingress
- Lightweight & flexible

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Column-type structure:
- Simple design & instrumentation
- Straightforward integration into sensor application systems
- Cheap & extensive manufacturing options

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Machine learning:
- Autonomous numerical sensor calibration
- Simultaneous optimisation of sensor performance & manufacturing ease
- "Drop-out" capability i.e. selection of most informative readings

METHOD

FBG Sensing Principles

Fibre Bragg gratings relate changes in Bragg wavelength, i.e. a characteristic wavelength reflected by the grating when incoming laser light reaches it, to changes in strain, as shown in Figure 1 below.

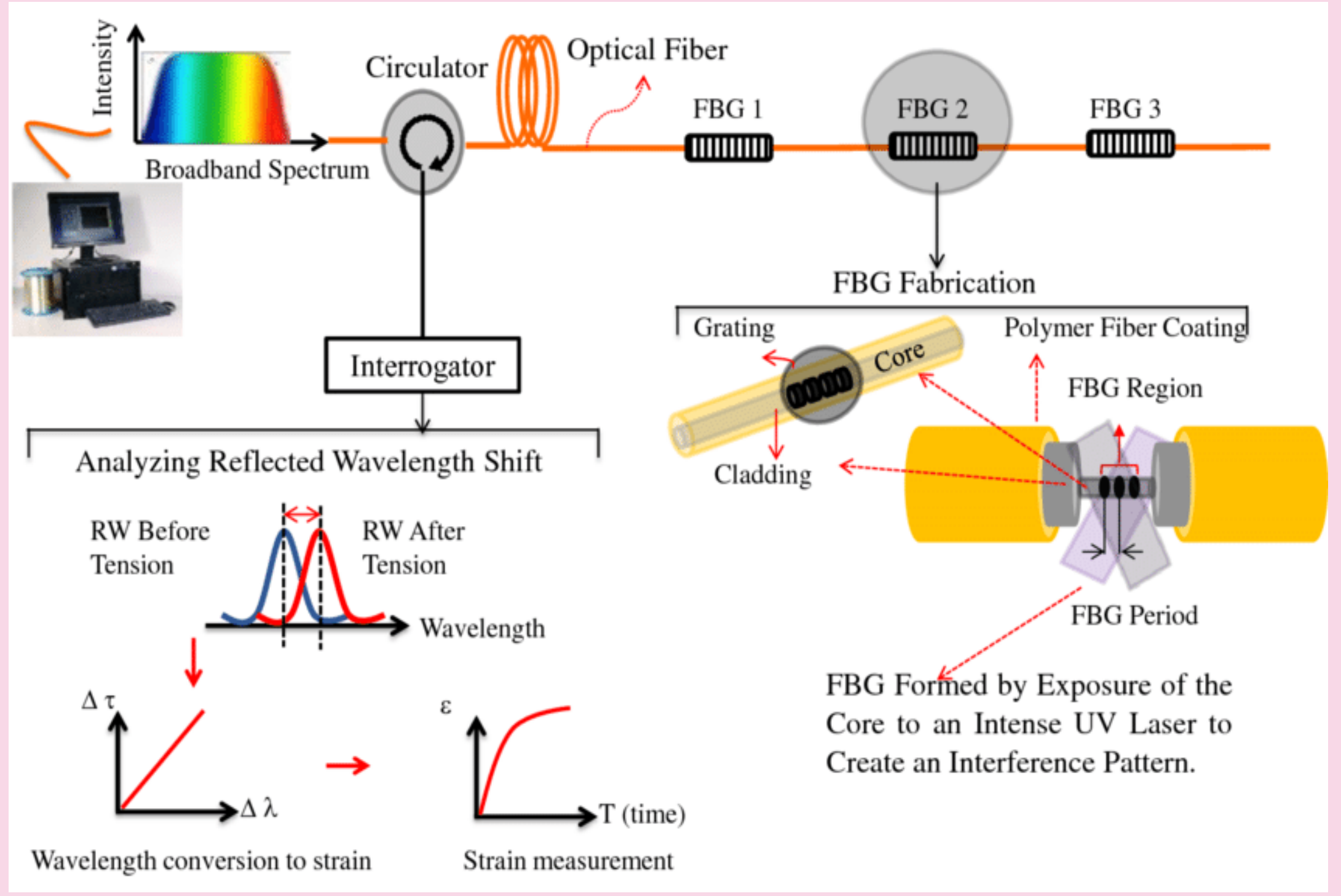


Figure 1: Illustration of the optical behaviour of a uniform FBG, showing indicative incident, reflected and transmitted light spectra [1].

Virtual Sensor Model

To create a **virtual sensor model**, the behaviour of a cylindrical column structure instrumented with FBGs is described analytically based on the framework in Figure 2. The location of each FBG is defined by:

(1) its orientation, θ_i
(2) its position from the bottom of the cylinder along the vertical axis, z_i
(3) its circumferential position on the cylinder, ϕ_i

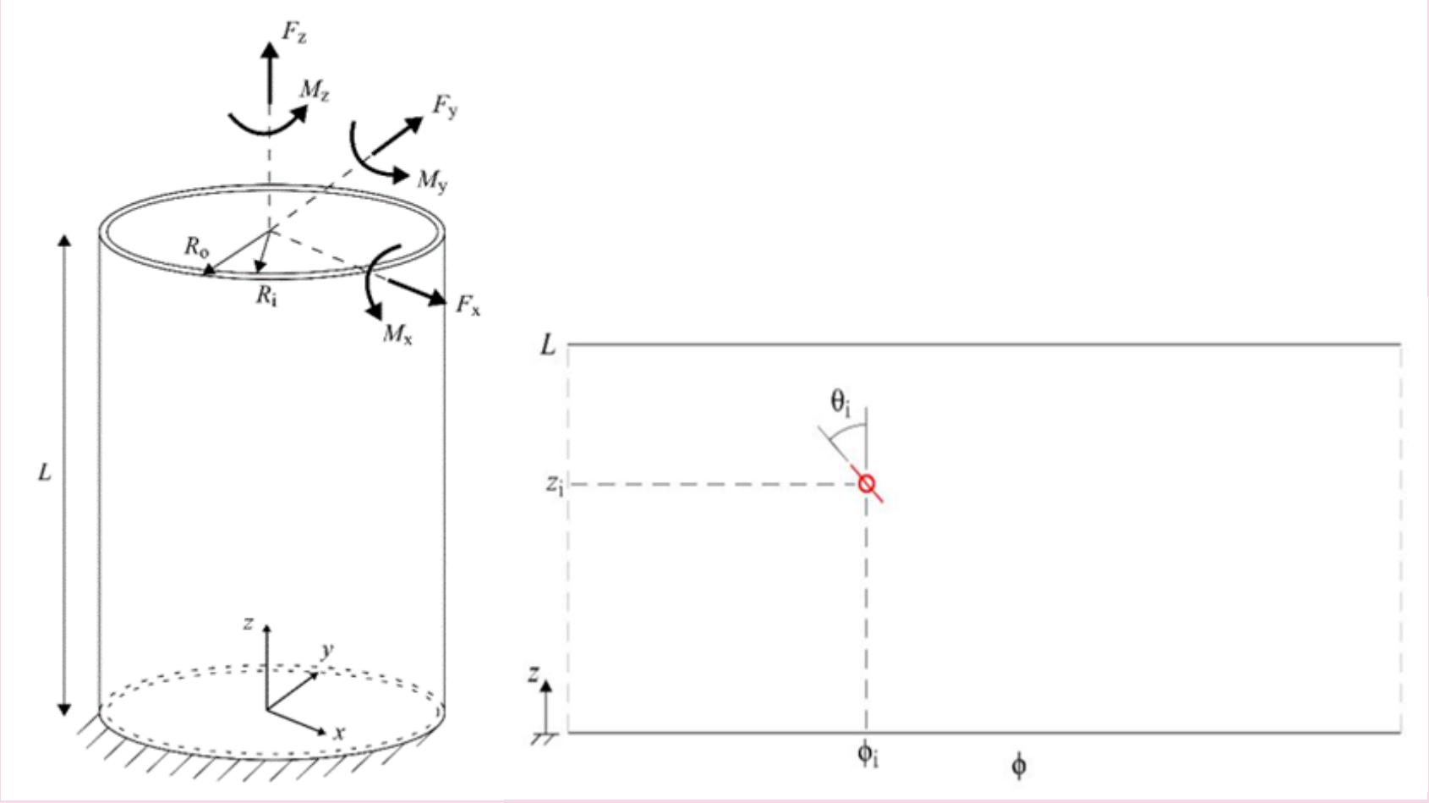


Figure 2: Adopted analytical model framework, featuring 3D and 2D "roll-out" schematics used to simulate and analyse the response of the structure under a six DOF load case with simultaneous uniform temperature changes.

Sensor Calibration And Grading Using Machine Learning

The relationship between force **f** (sensor **outputs**) and strain **u** (sensor **inputs**) is characterised by compliance matrix **C:**

$$\mathbf{u} = \mathbf{C}\mathbf{f}.$$

The sensor was calibrated numerically using machine learning. Linear regression model **"Multi-Task-Lasso"** was used to map sensor outputs and inputs and thus define C. The accuracy of the calibration procedure, quantified using an **R^2 "score"**, was used as the main analytical performance metric. ***A cut-off score of 0.99 was used for the sensor accuracy threshold.***

At least seven distinct strain measurements, corresponding to seven FBGs, are required to constitute a compatible system of equations. ***A redundant approach, using 8 or 9 FBGs, was adopted to increase the likelihood of achieving an $R^2 \geq 0.99$.*** The advantage of this method is **"drop-out" capability**:

- only the most discriminant inputs are used in the regression
- non-informative inputs are ignored or "dropped-out" from the calibration

QUALITATIVE ANALYSIS OF SENSOR PERFORMANCE USING EARLY PROTOYPING

Sensor Layout Design

Three base patterns were produced to gain insight on practical sensor design qualities relating predominantly to ease of manufacturing. Vertical FBGs were incorporated to maximise sensor sensitivity. Graphical representations of 2 exemplar layouts, Pattern 1 (left) and 2 (right) are shown in Figure 3, where the red semi-circles represent pivots.

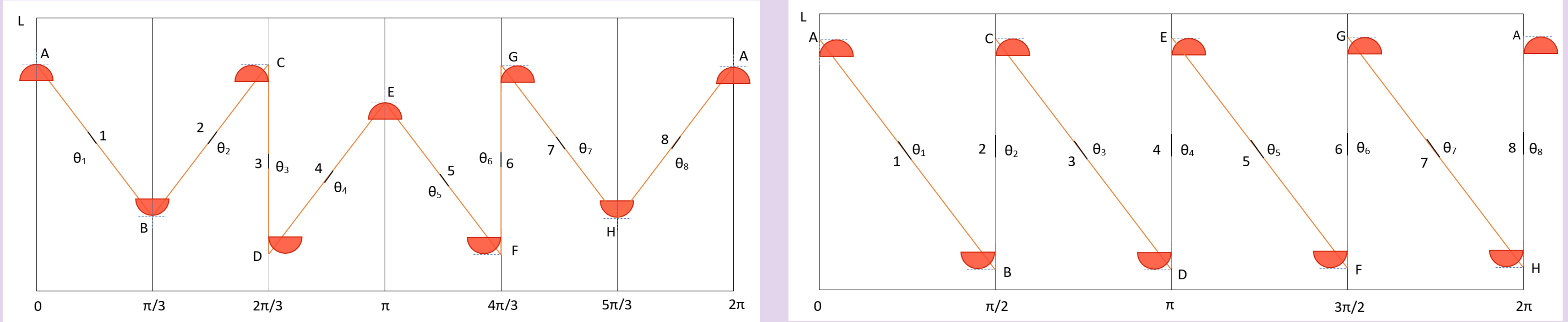


Figure 3: Graphical representation of two different patterns, used as references to build early prototype models.

Layout Testing

Prototypes for the sensor layouts were built using 3D printed cylinders and pivots and nylon thread as a cheaper fibre optic cable substitute (having similar flexibility and stiffness properties). An example prototype, corresponding to the layout pattern on the left of Figure 3 for a common FBG angle of 45° (to achieve equal FBG spacing in cable), is photographed in Figure 4.

Figure 4: Photographs of a prototype model for Pattern 1, for $\theta_i = 45°$.

Results

The layouts were tested to gather qualitative data relating to manufacturing ease and other practical design characteristics, paying particular attention to FBG alignment, pivot placement and fixability to structure, and time taken to implement the select layout by looping the cable around the cylinder.

The main finding was the efficiency and effectiveness of the implementation method:

- The pivots worked well to achieve the desired pattern & the layout was easy to implement on the cylinder
- Instrumentation of the cable on the fully manufactured host structure was extremely rapid for a 6DOF sensor:
  - FBG sensor design = 10 seconds to completely instrument the sensor
  - ERSG sensor design = 40-60 minutes per Wheatstone Bridge and typically up to a day for the sensor as a whole

QUANTITATIVE ANALYSIS OF SENSOR PERFORMANCE USING VIRTUAL SENSOR AND MACHINE LEARNING MODELS FOR OPTIMISATION

Grid Search Optimisation

The sensor design was optimised via a controlled grid search of orientations, used to identify the FBG layouts resulting in optimal R^2 scores. The search parameters and increments were carefully selected to enable an optimisation of the analytical sensor performance without losing practical design qualities.

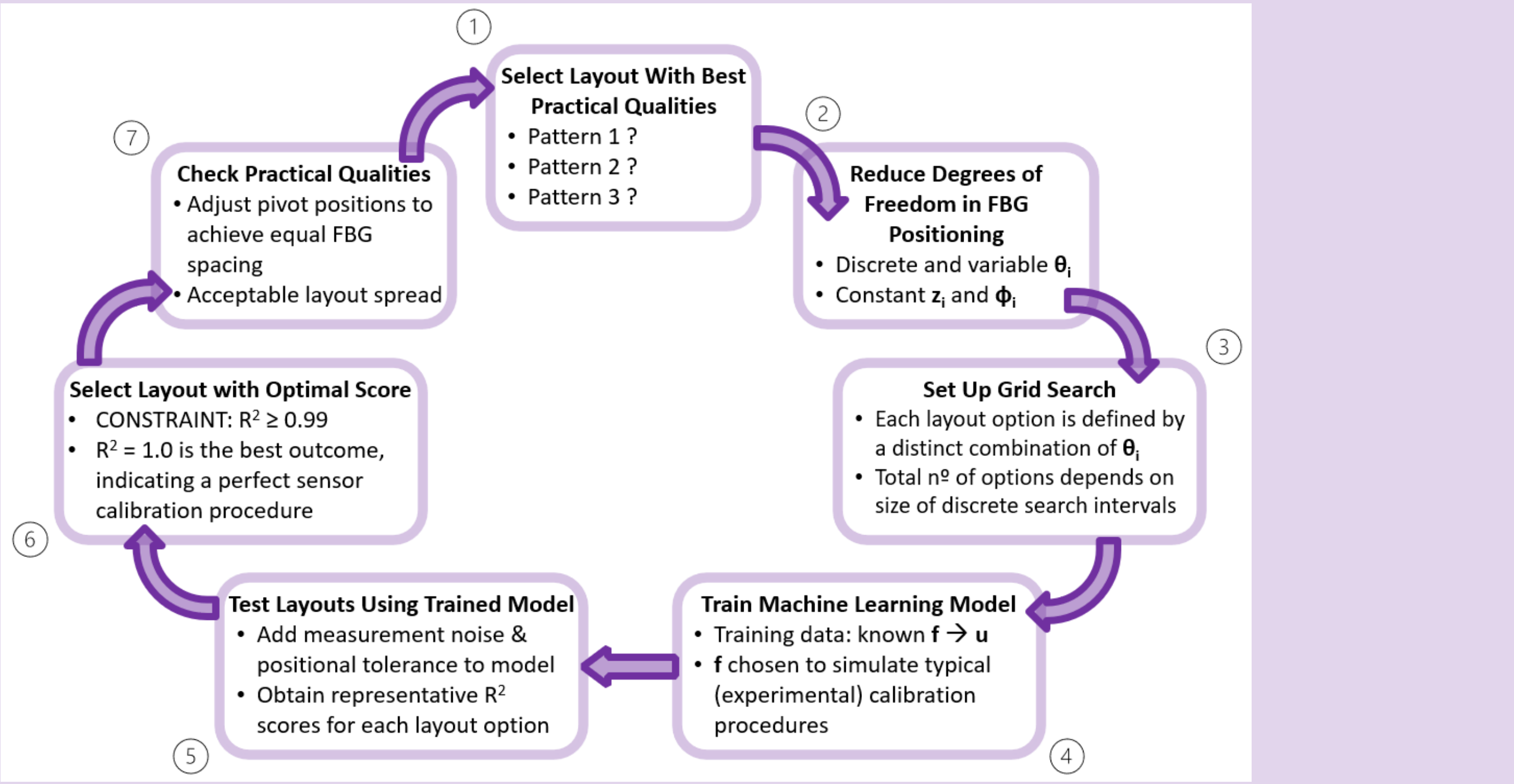


Figure 5: Flowchart outlining layout optimisation and selection procedures.

Sensor performance was tested by running the Virtual Sensor and MTL models for 1,000 consecutive trials of random load cases **(F_x, F_y, F_z, M_x, M_y, M_z, ΔT)** and under simulated sensor operation conditions, i.e. ***considering the effects of noisy strain measurements and potential offsets in intended FBG positions caused by manufacturing errors***.

RESULTS

- Success rate of 92% of layout options scoring $R^2 \geq 0.99$ under ideal conditions
- Success rate of 20% considering imperfections and noise
- Positioning offsets arising from manufacturing tolerances caused negligible reductions in R^2 scores
- Some well-performing & highly symmetrical layouts (good practical qualities)

IMPLICATIONS

- Sensor performance is noise-dominated
- Sensor performance is robust to FBG positioning. For a L=70mm, R= 27.5mm structure, tolerances of: **(1) $\theta_i = 5°$, (2) $z_i = 7$mm (↑), (3) $\phi_i = 2$mm (⟶)**
- Extensive range of well-performing layout options: 880 (out of an original 4,375 for the search gride size used) & layouts possessing manufacturing advantages

Conclusion

SENSOR DESIGN SUMMARY

A method for sensor design has been developed and optimised. It features:

- Scalability and adaptability with flexible FBG positioning & instrumentation
- Novel, autonomous & reliable "smart" calibration using AI techniques
- Excellent accuracy performance, rivalling existing sensor designs'
- Advantageous practical qualities

IMPLICATIONS

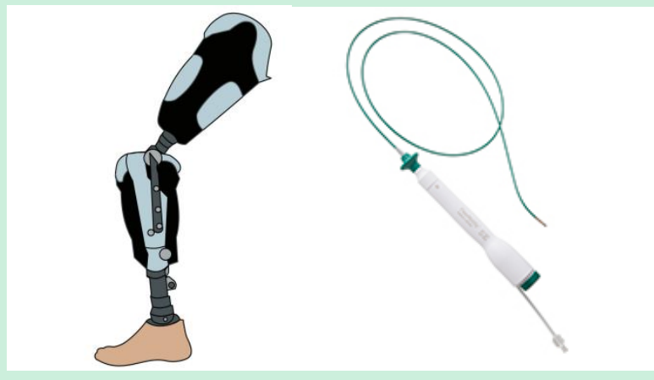
The state-of-the-art sensor design enables:

- Bespoke sensor design
- Increasing simplicity and functionality of sensor → quick & straightforward operation & integration into application systems
- Cheap and versatile manufacturing → optimal sensor turnaround time
- An extensive range of interesting existing and potential sensor applications!

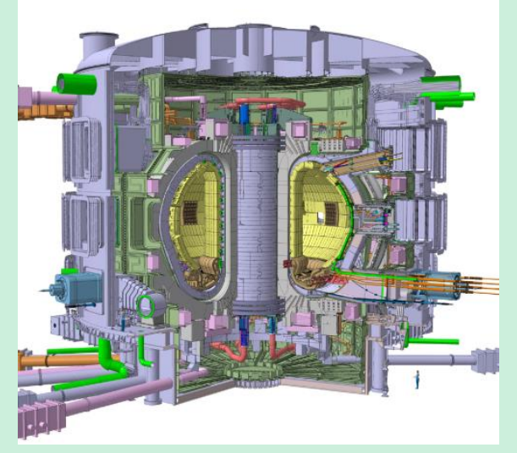
Some Sensor Application Examples

Tunnel and pipeline monitoring

Prosthetic limbs and skin



Minimally invasive surgical tools



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References
[1] Malekzadeh, M. (2014). Structural health monitoring using novel sensing technologies and data analysis methods.

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