Sensor integration

A Precision Method for Integrating Shock Sensors in the Lining of Sports Helmets by Additive Manufacturing

Aferdita Xhameni, Runbei Cheng, and Tristan Farrow

1Department of Electronic and Electrical Engineering, University College London, London WC1E 7JE, U.K.
2Department of Engineering, University of Oxford, Oxford OX1 3PJ, U.K.
3Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, U.K.

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Abstract—A method is presented for embedding sensors into the lining of sports helmets for the purpose of monitoring head impact in contact sports. Additive manufacturing was used to embed optical fiber-based pressure sensors inside thermoplastic polyurethane (TPU), a material used for lining and shock-dampening that fills the space between a helmet’s hard outer shell and the head. A proof-of-concept has successfully demonstrated sensitive shock-monitoring capabilities, thus avoiding the inaccuracies in existing systems. The sensors can be embedded into additively manufactured parts in new or existing helmets and are unobtrusive to the wearers. This proposed system can be powered by readily available medical-grade cell batteries and requires less maintenance.

Index Terms—Sensor integration, additive manufacturing for photonic sensor integration, fiber Bragg grating (FBG), fused filament fabrication (FFF), stereolithography apparatus (SLA).

I. INTRODUCTION

Athletes with a history of repetitive head impacts and multiple traumatic brain injuries (TBI) risk long-term neurological sequelae and premature cognitive decline. Protective headgear is a crucial factor in reducing head trauma, but there are still a significant number of injuries every year with 1.7–3 million concussions recorded annually across sports in the US [1], with 300,000 in all sports [2] and approximately one third of these occurring during American football games [3], [4]. Research has shown that regular small impacts to the skull can lead to long-term brain damage, with a 10–20% prevalence in retired National Football League players [5]. There is a need for objective monitoring methods that can better help to safeguard athletes. Head impact monitoring can be valuable for providing data to develop safer techniques during training which can help players avoid collisions, as well as support medical professionals determine when to withdraw a player during a competition. Existing systems involve accelerometers and gyroscopes but have yet to demonstrate their viability in the trial phase because they can suffer from inaccuracy. Low-intensity and detrimental impact can go undetected, while the force of a collision can often be overestimated by 6% [6], [7]. Additionally, existing helmet-sensor solutions require replacing batteries in a factory at least once over the course of an American football season, and mouthguard systems can suffer from poor coupling to the head during impact when athletes’ jaws relax [7].

Fiber Bragg grating sensors (FBGs) are versatile optical sensors that can measure various physical properties, such as strain and temperature. They are widely used in fields such as aerospace and civil engineering due to their robustness to environmental factors such as moisture, rust, and electromagnetic interference, unlike their electrical counterparts. FBGs can achieve sampling rates in the range of 100 kHz [8], which is excellent compared to electrical sensors, which sample at about 10 kHz [7]. Unlike electrical sensors, FBGs can measure strain along a single direction, making them more suitable for structural health monitoring and health care applications [9]. In low power, portable strain sensing applications, FBGs have been used to measure strain using LED light sources powered by medical grade batteries with typical powers of less than 0.25W [10] compared to piezoelectric accelerometers, which use 0.15–1 W [11].

FBGs consist of sections with different refractive indices called Bragg reflectors. The Bragg reflectors can reflect light at a specific wavelength, depending on the refractive index, as well as on the size and separation of the grating. When the fiber changes length due to either an applied mechanical tension or heat expansion, the grating separation changes, causing a proportional shift in the reflected (Bragg) wavelength. The total shift due to strain and temperature can be modeled as [12]

\[
\Delta \lambda_B = \left[1 - \frac{P^{ref}}{P_{ref}}\right] \frac{\varepsilon_m}{\alpha_m} + \left[1 - P^{ref}\right] \alpha_t + \frac{1}{n_0} \frac{dn}{dT} \Delta T
\]  

(1)

where \(\Delta \lambda_B\) is the change in Bragg wavelength from the initial Bragg wavelength \(\lambda_{B0}\), \(1 - P^{ref}\) is the strain sensitivity of the FBG, \(\varepsilon_m\) is the mechanical strain due to tension, \(\alpha_t\) is the thermal strain due to thermal expansion, and \(n_0\) is the initial refractive index.

When attached to mechanical objects, FBGs can be used to detect deformation and vibration. The accuracy of such measurements depends on the bonding strength between the FBGs and the measured objects. In practice, FBGs are often glued to the surface of the objects of interest. However, embedding FBGs inside objects can create stronger bonds and allow the objects’ structural health to be monitored more accurately and with more information [13].

Additive manufacturing, commonly known as 3-D printing, offers the freedom to rapidly prototype complex structures. Most additive manufacturing printing methods produce parts by laying down materials layer by layer. This mechanism allows the possibility of embedding FBGs inside printed structures during the printing process. A well-established method for embedding FBGs into additively manufactured metal structures has already been realized [14]. However, there have
only been few attempts to embed them into 3-D printed polymer structures with varying degrees of success [13], [15], [16].

Two of the most common polymer additive manufacturing methods are fused filament fabrication (FFF) and stereolithography apparatus (SLA). Three-dimensional printers employing these methods are widely available commercially and affordable. Most modern machines can achieve layer resolutions in the sub-millimetre range, with more advanced models being capable of 50 and 25 μm layer resolution for FFF and SLA, respectively. With such a resolution, it is possible to produce complex parts with securely embedded FBGs reproducibly. Being able to manufacture such objects with relative ease through additive manufacturing creates new possibilities in a wide range of fields. Hence, it is of great interest to standardize and validate such embedding processes.

While optical fibers are tough and resilient to harsh conditions, the engraved sections of FBGs are, however, very fragile in comparison and can be damaged when high heat is applied during the embedding process [13], [14]. This temperature restriction eliminates most metal additive manufacturing methods as candidates for FBG embedding. One low temperature 3-D printing method is ultrasonic additive manufacturing (UAM), where metal sheets are welded together using high power ultrasound [14]. UAM has been adapted as the industry gold standard method for embedding FBGs in metal parts used for high-value tasks by organizations like NASA but remains prohibitively expensive for niche consumer products [17]. Integrating FBG sensors in helmets and other consumer applications via polymer additive manufacturing (FFF, SLA) as shown here presents an opportunity for cost-effective manufacturing at scale.

II. EMBEDDING METHODS

A. Fused Filament Fabrication

FFF is a layer-by-layer printing method using thermoplastic materials, polymers that can be reshaped with heat. During printing, thermoplastic filaments are pushed through a heated nozzle, which softens the filaments upon contact, turning the filaments into a molten liquid. This liquid is then deposited onto a build platform layer by layer and quickly solidified by cooling air, forming predesigned parts. There is a large variety of materials available for FFF printing, such as polyactic acid (PLA), acrylonitrile butadiene styrene (ABS), high-impact polystyrene (HIPS), thermoplastic polyurethane (TPU), and nylon, making it ideal for printing functional parts.

During FFF prints, polymer filaments leave the print nozzle in a softened liquid-like state. Thus, FBGs can be embedded by placing the fiber on an unfinished surface halfway through the print. The softened polymer adheres to the fiber forming a tight bond between the fiber and the printed parts. FFF print nozzles generally operate at 200°C, and such high heat could damage the fiber if the nozzle were to make direct contact with the fiber [13], [14], [18], [19]. This is commonly mitigated by designing the printed parts with grooves for fiber placement (see Fig. 1). In addition to protecting the fiber from the print nozzle, this also facilitates a precise alignment of the fiber.

B. Stereolithography

Unlike FFF which reshapes solid plastic filaments to produce parts, SLA uses photopolymer resin to produce higher-quality prints. To produce prints with this method, an upside-down build platform is submerged into a resin tank. The bottom of the resin tank has a UV light source, with wavelength 405 nm, that cures the resin onto the build platform, layer by layer. Prints are only partially cured fresh out of the printer, and a further UV bath is required to cure them fully. SLA machines have an even more extensive selection of materials than FFF, ranging from hard materials such as ceramic to flexible materials like rubber, offering unique solutions in many fields.

The challenges with using these printers to embed FBGs are the spatial limitations imposed by the resin tank and screen wiper, and the upside-down geometry of the build platform. We modified the platform such that the fiber is held in place against the drag from the viscous resin and aligned in the groove, without damage.

This method performed consistently for multiple test prints with silica fibers. The fibers were securely embedded inside the SLA blocks without fail with the correct groove size. However, when polymer (polyimide) fibers were used, the resins used could no longer cure fully, even after extensive exposure to UV in the post-curing UV bath. Polyimide has a low acid resistance while SLA resins are acidic. Their unfavorable chemical interaction is likely to have released contaminants into the resin and inhibited curing. More research is needed to investigate this behavior in-depth to control it.

In addition to the interaction between the resin and polyimide, there are other concerns with this method. Photopolymer resin is highly toxic. Partially cured and uncured resin can poison the operator if mishandled. Additionally, photopolymer resin is cured using a UV light source, and since FBG fibers are also photosensitive to the UV spectrum, FBG fibers could potentially be damaged during printing and post curing. A preliminary UV damage test was carried out during optical testing, the results of which are discussed below.

III. RESULTS

To evaluate the embedded sensors, 10 mm³ cuboid prototypes with optical fibers embedded were manufactured and tested. Two types of optical fibers were embedded: plain fibers and FBGs. The plain fibers were 242 μm in diameter, and the FBGs were 125 μm in core diameter at the grating and 242 μm in diameter throughout the rest of the fiber. 125 μm is the smallest layer thickness compatible with the FFF machine, and 50 μm is the smallest layer thickness for the SLA machine. Both were used to maximize the print quality.

Optical fibers were also embedded in a rigid and flexible cheek pad (see Fig. 2) modeled from a Schutt Vengeance Pro American football helmet (Schutt Sports, Litchfield, Illinois, United States) using an FFF printer. Such segments can be printed for the whole helmet, comprising a sensor array.

A. Optical Analysis

A LUNA 4600 optical backscatter reflectometer (OBR) (Luna Innovations, Roanoke, VA, USA) was used to measure the signal...
amplitude as a function of the distance traveled by the signal in the fiber. Comparing a 2 cm long FBG embedded by FFF to the reference signal from a 5 cm long nonembedded FBG (see Fig. 3), we observe a square wave signal in both cases. The position of the signal shifts in a proportional manner to the mechanical deformation of the fiber.

High temperatures in the range of 200°C can completely extinguish the change in refractive index in the bare FBG [19]. However, the high amplitude reflections in the FBG generating the square-wave signal are still present after embedding. Hence, we can conclude that temperature did not damage the grating during embedding.

In Fig. 3, the embedded signal amplitude (red) rises gradually compared to the sharp rise in the reference signal (blue). We hypothesise that the tension is held in the embedded portion of the fiber due to the pinch points [see Fig. 6(b)] located at each end of the printed block.

The strain this induces in the fiber changes the period of the grating and results in weak reflections of wavelengths outside the design range. These show up as flatter tails in the tails of the square wave signals from embedded fibers (see Fig. 4).

To confirm this, we coiled FBGs around cylinders and recorded the reflected signal after bending, as this would result in a similar extension of the grating under tension. We observe that tension under bending increases the curvature in the signal, compared to the signal prior to bending. This led us to confirm our hypothesis that tension is held in the embedded fiber at pinch points where it enters and exits the block.

The issue can be minimized by printing support blocks on both ends of the structure, at the same height as the groove.

We exposed a silica coated FBG embedded by FFF to the same UV bath used in the SLA process to investigate the effects of 405 nm UV on the gratings (see Fig. 5). As the whole fiber is exposed to unfocused UV light from all angles during curing, any UV damage would degrade the characteristic FBG signal entirely [20]. This was not observed hence it is unlikely that any localized UV damage occurred which would affect only a portion of the signal.

### B. Mechanical Testing

To measure the strain experienced by the structure the FBG is embedded in, there needs to be a high degree of adhesion at the
interface between them. A hanging-weights experiment was carried out to measure the workload required to cause slippage between the embedded fibers and the printed parts [see Fig. 6(a)]. FFF printed PLA and TPU blocks embedded with silica-coated fibers were used. The blocks were clamped to a metal pole with the fiber hanging vertically under the block while masses were incrementally added. A section of the fiber was allowed to protrude the top of the block and was marked as a reference point to measure the slippage. The experiment showed that the assembly was slippage-free up to 1 kg for PLA and TPU, which exceeds a typical use-case scenario and provides a robust test of durability.

IV. DISCUSSION

FBGs are versatile sensors that are reliable and resilient under demanding environmental conditions. By embedding them inside complex structures, they can be used to monitor vibration and structural health [21, 16]. This study validated the use of FFF to embed FBGs inside complex polymer structures such as pannelling elements for American football helmets. In addition to validating the potential for embedding FBGs with FFF, we demonstrated a new technique using SLA. While SLA delivers higher quality prints than FFF, it cannot be used to embed polyimide fibers due to their chemical interaction with the SLA resin. SLA is more costly than FFF and has a longer print time, which are trade-offs that need to be balanced against the higher quality prints depending on the application use-case.

V. CONCLUSION

This letter paves the way for field-testing prototypes of FBGs embedded in the lining of sports helmets under in-situ workloads and real-time strain response. Prototypes with multiple fibers for temperature correction can also be fabricated to enhance accuracy where needed. Other types of sensors can be embedded using 3-D printing, such as coaxial cables, for example, using SLA, which we embedded during our development phase. With printable FBGs on the horizon [22], we anticipate the printing of polymer structures with built-in FBG sensors for a range of new applications that need precise in-situ monitoring, such as the structural health of materials used in aviation, civil, and medical engineering in life-saving technologies.

VI. COMPETING INTERESTS

The authors have filed GB patent applications no. 2107898.5 and PCT/GB2022/051410.

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REFERENCES

[1] T. Covassin, J. L. Savage, A. C. Bretzin, and M. E. Fox, “Sex differences in sport-related concussion long-term outcomes,” Int. J. Psychophysiol., vol. 132, pp. 9–13, 2018.
[2] M. Aynsley et al., “Ice hockey summit II: Zero tolerance for head hits and fighting,” PM&R, vol. 7, no. 3, pp. 283–295, 2015.
[3] Centers for Disease Control, Prevention, et al. “Sports-related recurrent brain injuries—United States,” MMWR: Morbidity Mortality Weekly Rep., vol. 46, no. 10, pp. 224–227, 1997.
[4] D. J. Thurman, C. M. Branche, and J. E. Snizek, “The epidemiology of sports-related traumatic brain injuries in the United States: Recent developments,” J. Head Trauma Rehabil., vol. 13, no. 2, pp. 1–8, 1998.
[5] I. R. Casson, D. C. Viano, E. M. Haacke, Z. Kow, and D.G. LeStrange, “Is there chronic brain damage in retired NFL players? Neuroradiology, neuropsychology, and neurology examinations of 45 retired players,” Sports Health, vol. 6, no. 5, pp. 384–395, 2014.
[6] J. G. Beckwith, R. M. Greenwald, and J. J. Chu, “Measuring head kinematics in football: Correlation between the head impact telemetry system and hybrid III headform.” Ann. Biomed. Eng., vol. 40, no. 1, pp. 237–248, 2012.
[7] A. D. Patton, “A review of instrumented equipment to investigate head impacts in sport,” Appl. Bionics Biomech., vol. 2016, 2016, Art. no. 7049743.
[8] J. Bentell et al., “500 KHz sampling rate FBG interrogator with strong anti-aliasing signal processing,” in Proc. 26th Int. Conf. Opt. Fibre Sensors, 2009, vol. 7503, pp. 695–698.
[9] D. Tosi, “Review of chirped fiber Bragg grating (CFBG) fiber-optic sensors and their applications,” Sensors, vol. 18, no. 7, 2018, Art. no. 2147.
[10] M. Maheshwari, Y. Yang, T. Chaturvedi, and S. C. Tijn, “Chirped fiber Bragg grating coupled with a light emitting diode as FBG interrogator,” Opt. Lasers Eng., vol. 122, pp. 59–64, 2019.
[11] S. Elies, “Performance analysis of commercial accelerometers: A parameter review,” Sensors Transducers, vol. 193, no. 10, 2015, Art. no. 179.
[12] C. Daniel, G. Betz, B.T. Culshaw, and W.J. Staszewski, “Advanced layout of a fiber Bragg grating strain gauge rosette,” J. Lightw. Technol., vol. 24, no. 2, pp. 1019–1026, 2006.
[13] R. J. Maier et al., “Embedded fiber optic sensors within additive layer manufactured components,” IEEE Sensors J., vol. 13, no. 3, pp. 969–979, Mar. 2013.
[14] J. J. Schomer, A. J. Hehr, and M. J. Dopino, “Characterization of embedded fiber optic strain sensors into metallic structures via ultrasonic additive manufacturing,” in Proc. Sensors Smart Struct. Technol. Civil, Mech., Aerosp. Syst., 2016, vol. 9803, pp. 587–596.
[15] M. G. Zubel, K. Sugden, D. J. Webb, D. Sáez-Rodríguez, K. Nielsen, and O. Bang, “Embedding silica and polymer fibre Bragg gratings (FBG) in plastic 3D-printed sensing patches,” in Proc. Micro-Struct. Specialty Opt. Fibres IV, 2016, vol. 9886, pp. 78–89.
[16] N.R. Manzo, G. T. Callado, C.M.B. Cordeiro, and L. C. M. Vieira Jr., “Embedding optical fiber Bragg grating (FBG) sensors in 3D printed casings,” Opt. Fiber Technol., vol. 53, 2019, Art. no. 102015.
[17] A. Hehr et al., “Integrating fiber optic strain sensors into metal using ultrasonic additive manufacturing,” Jom, vol. 70, no. 3, pp. 315–320, 2018.
[18] D. Grobnic, C. Hnatovsky, S. Dedynia, R. B. Walker, H. Ding, and S. J. Mihailov, “Fiber bragg grating wavelength drift in long-term high temperature annealing,” Sensors, vol. 21, no. 4, pp. 1454–1481, 2021.
[19] H. Yang, Y. Liu, and T. Gu, “Fabrication and experiment of a FBG strain sensor in high temperature environment,” in Proc. 16th Int. Conf. Opt. Commun. Netw., 2017, pp. 1–3.
[20] Y. Leng, Y. E. Yun, and J. Goldhar, “UV laser fabrication and modification of fiber Bragg gratings by stitching sub-gratings with in situ fluorescence monitoring,” Appl. Opt., vol. 56, no. 24, pp. 6977–6981, 2017.
[21] L. Liu, H. Zhang, Q. Zhao, Y. Liu, and F. Li, “Temperature-independent FBG pressure sensor with high sensitivity,” Opt. Fiber Technol., vol. 13, no. 1, pp. 78–80, 2007.
[22] C. Hong, Y. Zhang, and L. Borana, “Design, fabrication and testing of a 3D printed FBG pressure sensor,” IEEE Access, vol. 7, pp. 38577–38583, 2019.