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# Research Abstract

*B. subtilis Spore Hygromorphs as a Novel Smart Material*

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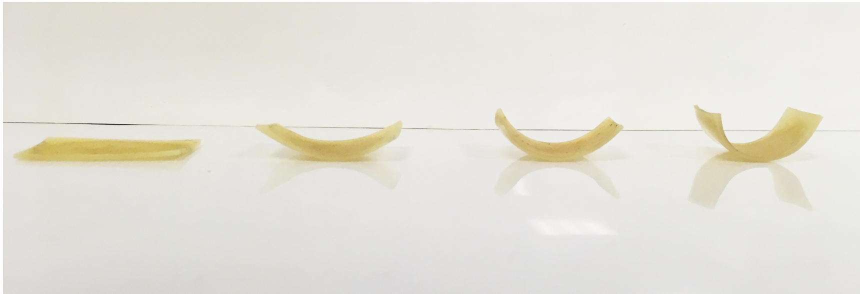
We are living in a world increasingly dictated by adverse climate change and a growing pressure on limited resources, one of which is shelter from those environmental extremes[1]. Arguably one of mankind's most successful evolutionary techniques is harnessing our intellect to allow us to colonise non-ideal environments by building shelter. Whether this shelter is built in the form of an igloo or a modern day skyscraper there are certain requirements it must achieve; to protect the user from extreme temperatures (both low and high), to provide sufficient ventilation, light and moisture control[2]. If any one of these requirements are not fulfilled it can have a detrimental effect on the users' health and wellbeing[3]. Our current methods of achieving this requires huge amounts of electricity, fossil fuels and non-renewable energy sources to make our static buildings react to their changing environments[4]. *Our quest is to rethink how we achieve internal environmental stability, sustainably.* To do this we are looking closely at how natural systems such as the perceivably static plant kingdom, utilise complex biomechanics to achieve dynamic motion in response to their environment[5]. We will be applying this mechanical principle to the hygromorphic phenomenon observed in some bacterial spores[6,7,8,9] for the development of complex smart materials capable of both sensing, responding and interacting with their local environments[2,10] to begin to allow us to produce 'living' architectures.

The principle aim of this research is 'To develop the potential of using *B. subtills* spore hygromorphs as a novel smart biomaterial by utilizing an understanding of passive, nastic movement mechanisms to amplify deflection, enhance programmability and develop fabrication techniques.' To achieve this we will be following three clear objectives, each representing an avenue of this interdisciplinary project.

The first aim is '*To optimise Bacillus subtilis spore actuator properties to maximise their hygromorphic performance'* by harnessing the natural modifications that the environment triggers in sporulation, thus influencing the biological make-up of the spores to improve their hygromorphic properties at a cellular level[11,12]. This includes laboratory experiments to investigate the effect of culture conditions, temperature, pH etcetera on the developing spores structural make up, providing a greater or lesser hygromorphic response. It is hypothesised that the hygromorphic response can be programmed at the cellular level during the sporulation process if the conditions are optimised.

The second aim is '*To investigate plant-inspired adaptive structures and materials for morphing and actuation and identify those able to amplify the hygromorphic response of the Bacillus subtilis spores*.' This utilises the biomechanical principles of non-growth related motion to respond to the environment within the plant kingdom[13,14] to allow a biomimetic design approach to be adopted. This includes histological investigations to isolate the specific morphology capable of shape changes driven by cellular expansion[15]. It is hypothesised that such structures can be isolated, recreated and applied in a synthetic structure utilising the bacterial spores' cellular expansion as the actuation.

The third aim is '*To develop fabrication techniques which are capable of combining the complex structures and materials required in passive nastic movement mechanisms with the bacterial spores to produce 'live' hygromorphically active 4D structures as a showcase of material capabilities*.' This third aim follows a material tinkering approach to gain a better understanding of structures and materials formed though objectives one and two, with the aim of producing a material fabrication technique capable of producing such complex synthetic 'living' smart materials. These investigations will not only investigate the fabrication technique but the final form of these materials in relation to their function. It is hypothesised that to fabricate such complex smart materials traditional fabrication techniques will have to be tailored and advanced from 3D to 4D as the material develops.



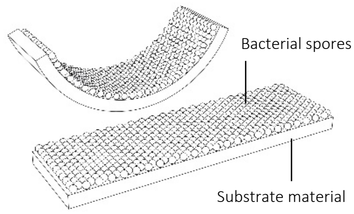



Figure 1. a) Initial Bacterial spore actuators deforming under a changing relative humidity b) schematic of actuator formation and deformation.

A literature review has, and is, being conducted to reflect the three key lines of inquiry within this research as discussed earlier. This has been split therefore into '*Bacillus subtilis Spores as Hygromorphic Actuators'* covering everything from the bacteria's evolutionary advantage to current *B. subtilis* spore actuator experiments within the literature; '*Biomimetics in Architecture'* which covers nastic plant motion and its current biomechanical utilisation within biomimetic design; and finally '*4D Advanced Fabrication Techniques*'. This includes specific fabrication techniques which have, or show potential, for producing complex bimorph and multi-morph structures capable of shape change post fabrication.

The proposed methodologies have been developed through rigorous interrogation of the multidisciplinary literature to provide tailoring to each line of inquiry. This ensures the most appropriate research mentality is adopted for each phase. These range from meticulous laboratory protocols; biometric inspired design approach featuring a bottom up focus and development of innovative shape-change fabrication technology and protocols.

Laboratory work has commenced on investigating objective one with some primary results of sporulation rates already recorded. Significant time has been spent learning new techniques and protocols to ensure safety and competency whilst conducting laboratory experiments unsupervised. These initial results gathered have helped to rationalise the sporulation protocol and provide knowledge of time taken to reach early exponential phase. This will prove vital for the next phase of investigation as it provides an accurate time frame the sporulation process. Investigations into objective two have provided knowledge of plant biomechanics of the Venus fly trap and the sundew plant which either aid movement or protect vital structures during motion without adding additional resistance. These findings have begun to aid design and form for utilisation in objective three, providing a bottom up design ethos. Initial 3D prints with flexible filaments have begun to recreate the forms capable of such complex shape change. Working on both the two dimensional and three dimensional planes we are beginning to develop our understanding of the formation process, and material properties required for such structures prior to the application of *B.subtilis* spores to form a biohybrid bimorph or multi-morph. To further this complex fabrication, utilisation of computer aided design such as a Generative Design within Fusion 360 will allow the internal structures and stresses to be accurately predicted providing the most innovative structure to harness the hygromorphic force demonstrated by the bacterial spore actuators to create 4D multi-morphs.

Figure 2. Initial flexible 3D printed prototypes

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