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# Optimal integration of pneumatic artificial muscles with vacuum-jammed surfaces to characterise a novel reconfigurable moulding system

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ABSTRACT

Producing mould tooling systems is a considerable proportion of manufacturing cost and time, especially for low volume productions. Producing a reconfigurable mould to shape surfaces into complex geometries with multiple curvatures would obviate the need to design and fabricate individual moulds for different products. Current reconfigurable mould tooling systems are mainly variations on a 'bed of pins' design through differing patterns of actuated pins. These systems are heavy, mechanically complex and expensive to manufacture. Soft pneumatic actuators such as Mckibben muscles, also known as pneumatic artificial muscles (PAMs) are recognised for their high strength to weight ratio, ease of manufacture and low cost. In this work, PAMs are used to influence a soft elastomeric surface, allowing the formation of spatial curved profiles. This thin, hollow surface is packed with a granular medium that exhibits jamming under the negative pressure of a vacuum. This allows the flexible surface to transform to a rigid surface of greatly increased stiffness with a specific geometry for moulding purposes. This paper presents the design, experimental development and experimental performance of two sample prototypes to actualizes the idea of such adaptable moulding tools. The prototypes contain different actuator arrangements to form jamming surfaces into diverse, simple-to-complex 3D profiles. In addition, the kinematic performance for one of the prototypes is shown by a numerical model. Future work on this system will tailor it for production of fibre carbon composites.


## 1. Introduction

A reconfigurable mould that can be used to shape parts of differing geometries is a highly desirable prospect in a number of areas of manufacturing. The most important reason for this is the factor of cost as the construction of these parts, often of limited number of uses before a new mold is required, can represent a significant proportion of the total cost per part, especially for low volume productions. Additionally, related costs are also incurred for storage, maintenance and logistics of using a large number of different moulds. This is particularly true for the aerospace industry, with tooling representing over 10% of the cost per part in some cases [1]. The development of a low-cost solution that reduces the need for these conventional moulds has many potential benefits to both the aerospace industry and numerous other manufacturing areas. Previous work in the area of reconfigurable tooling has primarily consisted of reconfigurable pin-matrix based systems such as that presented in the works of Peters and Marion [2] and Koc et al. [3]. Most commonly used in the incremental forming of sheet metal structures, these systems consist of a number of individual pins, actuated in a variety of manners which can be individually positioned to create a 3-dimensional replication of the input. Use of an interpolator layer is necessary to maintain an acceptable surface profile. Common methods of actuation utilised in these systems include: shaft driven lead screws, hydraulic actuation and sequential pin set up methods [4]. Problems with current reconfigurable tooling methods such as complexity, cost and difficulty in obtaining high tolerances due to the nature of the interpolator layer, have prevented the uptake of this technology and have limited the application of a reconfigurable tool within areas such as composites processing [5]. In the context of improving such systems, there are several further studies that mainly present the use of various mechanisms for actuated discrete pins with application to sheet

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metal forming [6–8]. However, the fundamental problems with these systems in terms of cost and complexity remain.

An area that provides the starting point for an alternative to the discrete pin based systems in the work discussed above is the newly emerging technology of granular jamming. Media such as sand, beads or grains contained within a volume, exhibit the reversible phenomenon of jamming when subjected to compressive stress such as the negative pressure of a vacuum. This allows vacuum-jammed volumes to transition between a flexible, reconfigurable state and a pseudo-solid, jammed state, in which it exhibits increased stiffness and an ability to hold its shape [9]. This characteristic of tunable stiffness gives rise to the concept of a jammable surface which can form shapes when flexible and then increase stiffness to lock in place. The relative stiffness of vacuum jammed surfaces is a product of a number of factors. At comparative levels of compressive stress, the stiffness is governed by the relative motion ability of the granular medium. This is dependent on particle shape, size, material and homogeneity and surface texture [10]. The potential for exploitation of this controllable phase change has been explored in a work by Steltz et al [11] on the use of jamming as an enabling technology for soft robotics. The concept presented involved utilising vacuum-jammed structural elements as a method of achieving locomotion in a mobile robot. This work illustrates the potential for use of the vacuum jamming principles within the context of a controllable volume and highlights manufacturing techniques which have proved successful in the creation of an effective vacuum-jammed surface.

Consideration of the actuation methods for a vacuum-jammed surface included the review of solutions previously utilised in reconfigurable systems such as those discussed above. These included shape memory alloys, electro-active polymers, tension cable systems and servo motors [4,12]. However, a more suitable alternative to these conventional, rigid actuation methods could be pneumatic artificial muscles (PAMs). These actuators, also commonly known as McKibben muscles were developed in artificial limb research in the 1960s and consist of an internal bladder surrounded by an expandable braided mesh sleeving fastened at either end [13]. Pressurizing the internal bladder causes an increase in volume of the muscle in a direction prescribed by the nature of the braided mesh. Conventional PAMs expand circumferentially causing an axial contraction [14]. However they can also be made to extend axially reducing in diameter. The soft nature of these actuators allows them to produce interesting non-linear motions when arranged or joined in specific ways, where for the purposes of a reconfigurable mould it is desirable to produce surface curvature. Combining two extensible PAMs in parallel in a fashion analogous to a bi-metallic strip or a pair of agonist-antagonist muscles allows the creation of a curving actuator set. Where the extended PAM forces deformation around a bend to maintain continuity at the fixed end points. This ability to produce uniform curvature, combined with the high strength to weight ratio, soft nature and low cost of these actuators make them an attractive choice for use within a reconfigurable surface over methods such as shape memory alloys, electro-active polymers, tension cable systems and servo motors.

This paper looks to an optimal integration of these two technologies, granular jamming surfaces and PAMs, to present a prototype reconfigurable manufacturing mould. The nature of this lightweight and rapidly reconfigurable surface enables a variety of potential applications to industry. A primary focus for this technology is to integrate into the composite materials market, this industry often has a requirement for rapid mould geometries with single, double or multiple curvatures. The reconfigurable surface technology presents the potential to enable rapid development of bespoke composite components to industries such are aerospace, marine and energy technology, while providing a relatively low-cost and repeatable tooling method.

The developed prototypes will also underpin a significant step towards advancing the understanding and ability to design, model and control actuated Large Displacement Continuum Surfaces (LDCS) that have been used previously in soft robotic systems [15–18]. Although to date the integration of both an actuated deformable surface and on-demand surface stiffening system has not been done. In Section 2 the conceptual model of the integrated system will be presented. Section 3 will then illustrates the optimisation of the actuators through experimental characterisation of the parameters pressure, curvature, length and force. Section 4 presents aspects of design, fabrication and optimisation of the vacuum-jammed surfaces used in this work. Finally the development and performance of two prototype examples of the reconfigurable mould consisting of optimally characterised PMAs (one with 4 and the other with 16 PAMs) and an optimised vacuum-jammed surface to shape deformable composite sheets will be described in Section 5.

## 2. Conceptual model of an actuated deformable surface system

The optimal integration of these two technologies (vacuum jamming and PAMs) into a unique solution to the problem of achieving a reconfigurable, cost-effective moulding system was inspired by examples of projects in the respective technological areas. It was also informed by prior art on reconfigurable mould solutions and the gap in the market for a low-cost solution that would reduce the significant cost of single-component tooling.

The proposed concept involves a thin, flexible elastomeric surface with a densely packed granular media internal to this surface. The even distribution of this medium within the surface is maintained via division of the cavity into cells. This ensures that the granular medium will not move during deformation, before the vacuum is pulled. Sets of PAM actuators are integrated into the edges of the surface to allow formation of uniform curvature. Fig. 1 shows a model of the system concept with an enlarged internal view of the surface. In the model shown in Fig. 1, only one axis of curvature is considered. However, multi-axis deformation can be achieved through the integration of actuators along additional axes or even across the surface. In the operation shown here the lower PAM of each actuator set is pressurised, causing it to extend and forcing the surface to deform around a curvature due to the lack of similar deformation by the upper PAM. When the desired shape is achieved, the air is removed from the surface, jamming the granular medium and forming a rigid shape that can then be used for moulding. As the performance of the system is dependent upon both the surface and the actuator capabilities, these two elements are studied and optimised separately before the integrated system's function will be presented in this work.

## 3. Actuator optimisation

Optimisation of the actuators involved modifications to the design of the PAMs to achieve operation up to 5 bars. Characterisation of the curvature and force abilities was achieved through experimentation with the optimised design.

### 3.1. Design and fabrication of actuators

As with typical PAMs, the design consists of an internal bladder and a braided mesh sleeving. Conventionally, PAMs will contract or expand when pressurised due to circumferential expansion of the internal bladder against the outer material creating force along