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# Auto-Inflatables: Chemical Inflation for Pop-Up Fabrication\*

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**ABSTRACT**

This research aims to utilize an output method for zero energy pop-up fabrication using chemical inflation as a technique for instant, hardware-free shape change. By applying state-changing techniques as a medium for material activation, we provide a framework for a two-part assembly process starting from the manufacturing side whereby a rigid structural body is given its form, through to the user side, where the form potential of a soft structure is activated and the structure becomes complete. To demonstrate this technique, we created two use cases: firstly, a compression material for emergency response, and secondly a self-inflating packaging system. This paper provides details on the auto-inflation process as well as the corresponding digital tool for the design of pneumatic materials. The results show the efficiency of using zero energy auto-inflatable structures for both medical applications and packaging. This rapidly deployable inflatable kit starts from the assumption that every product can provide its own contribution by responding in the best way to a specific application.

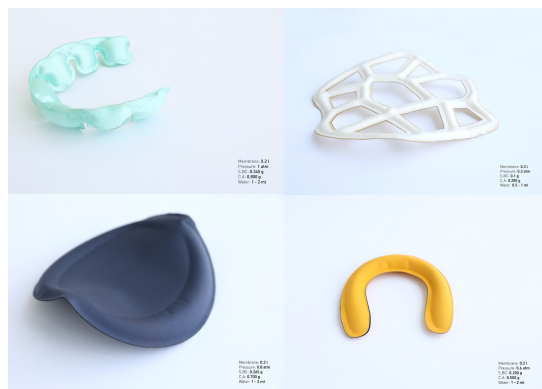
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**KEYWORDS**

Inflatable structure; membrane; chemical reaction; computational design; digital fabrication



**Figure 1. Auto-Inflatables.**

**Table 1. Calculated reagent quantities required to inflate bags of a specific volume to a predetermined pressure. Water quantities are the minimum amount of water needed to dissolve all powdered reagents.**

Volume (L)	Pressure (atm)	S.BC (g)	C.A. (g)	Water volume (ml)
0.1	1	0.345	0.800	1-2
0.05	1	0.173	0.285	0.5-1
0.01	1	0.035	0.080	0.5-1
0.1	0.5	0.175	0.400	0.5-1
0.05	0.5	0.085	0.200	0.5-1
0.01	0.5	0.018	0.040	0.5-1
0.1	0.1	0.035	0.080	0.5-1
0.05	0.1	0.018	0.029	0.5-1
0.01	0.1	0.004	0.008	0.5-1

**1 INTRODUCTION**

As a means to ignite curiosity within a material interface, behaviors that seem inherently unexpected or contrary to the material's innate properties can act as catalysts to expand functionality. For example, seeing a Cuttlefish transform to blend into its background seems somewhat magical when we observe it in comparison to our conceptual understanding of our own skin. Intriguing characteristics allow us to think outside the realms of possibility, thus inspiring unexpected thought and opportunity. Inflatable structures within the field of design have been explored in many capacities from structure, buoyancy, and air travel. In the scope of this paper, we will explore the use of self-inflating structures for two applications: as an emergency response material and as a self-inflating packaging system.

**2 RELATED WORK**

In the field of inflatable structures, several researchers investigated the potentials of using air as a morphing system [6]. Common examples are as follows: bubble wrap, invented in the 1950's by engineers as a product for greenhouse insulation; life-jackets and rafts, found within airplanes and boats to allow floatation in water; airbags in cars, designed for immediate shock absorbance in the event of an accident. Other examples include bike tires, balls for games, and hot air balloons. New academic research related to inflatables include: AeroMorph [10], developed at the MIT Media Lab, that utilizes a pneumatic system to reconfigure membranes and gives form and feedback in response to digital information. BMW and MIT's Self-Assembly Lab collaboration to design a 3D printable inflatable structure that can change its configuration and shape according to air flow [11]. Pneumatic Forming of Hardened Concrete is a project that was recently developed by researchers from Vienna University of Technology [8]. All of these projects are interesting because they utilize air as means to transform their shape. By reviewing this work a gap in the research was realized: all of them require an external air supply. Therefore, this paper focuses on a way to create shape changing membranes through chemical reactions that do not require external hardware and self-contain their air source.

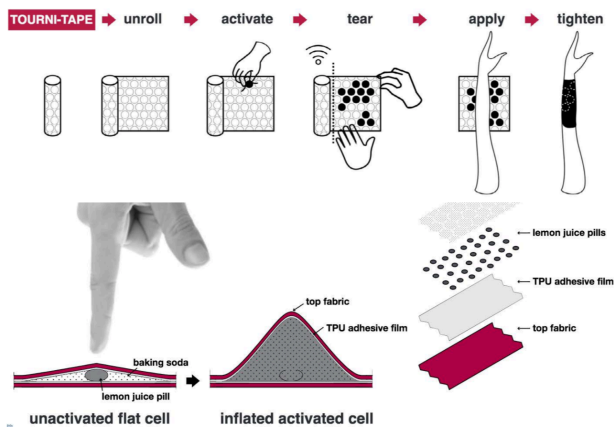
**3 TECHNICAL INSIGHTS**

To generate material transformations, we took advantage of the CO<sub>2</sub> output produced through the chemical reaction between Sodium Bicarbonate and Citric Acid to activate specific material behaviors [12]. By utilizing the structural movement generated by inflation, we have a number of characteristics that serve various functionalities. In this section, we will look at the use of inflation for hinging, folding, rigidity, small-to-large structural change, surface pattern, movement and insulation (Fig. 1). We will also give technical specifications for the chemical mixture [6].

3D Forms						
Movement						
Texture						
Pressure						
Membrane	Mylar	TPU	Nylon	Mylar + TPU	Mylar + TPU + Nylon	Mylar + TPU + Nylon + Outer fabric

Weak Strong

**Figure 2. Toolkit of primitive elements that can be combined to create a range of functionalities for self-inflating structures.**



**Figure 3. Tourni-tape project for first emergency response.**

**Hinging.** By applying the deformation gradient achieved by pressure buildup within an airtight membrane, hinging can be achieved through expansion by applying force on attached parts.

**Folding.** Origami techniques can be employed to generate a 2D to 3D structural change of more complex forms [5]. By applying pressure within specific points of a flat surface, structures can be automatically folded into place through pre-defined folding logic.

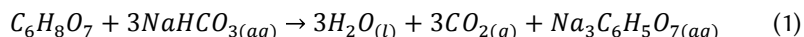
**Soft and rigid structure.** By combining a soft membrane with a rigid structure, large and strong, as well as complex structures can be assembled through the input of air.

**Surface pattern.** Surface patterns can be created by using a heat-pressing technique to create continuous tubular structures. To maintain airflow throughout a membrane, the patterns must be non-isolating, thus allowing a constant flow of air. The repetition of these patterns allows for structural changes that create textured and tactile patterning for both aesthetic and practical functions.

**Small-to-large shape change.** By optimizing airflow within a structure, for instance by decreasing the inner volume of a structure, structural form can be generated with minimal pressure. This technique is specifically beneficial for small-to-large structural change.

**Movement.** By controlling the time and order in which CO<sub>2</sub> is released into a membrane array, complex movements can be created in order to generate autonomous animation and motion. The examples below show how that by pushing airflow through channels via multiple valves and passageways, a single structure can obtain alternative movement possibilities.

**Chemical reaction.** Citric Acid (C<sub>6</sub>H<sub>8</sub>O<sub>7</sub>) and Sodium Bicarbonate (NaHCO<sub>3</sub>) react to form Sodium Citrate (Na<sub>3</sub>C<sub>6</sub>H<sub>5</sub>O<sub>7</sub>), water, and carbon dioxide (CO<sub>2</sub>):



**Pressurization.** The pressure inside the auto-inflatable structure and the inflation rate can be controlled by varying the ratio of sodium bicarbonate and citric acid and the amount of water in the reaction. While the final pressure is solely dependent on the concentration of citric acid (which is a limiting reactant in the reaction), assuming at least an equimolar acid concentration inflation rate is dependent on additional factors such as reagent solubility, water content and acid concentration.. For a 0.1L bag, 0.35g of sodium bicarbonate and ~0.8g of acid were used to obtain a pressure of 1 atmosphere.

**Insulation.** An air filled compartment provides good thermal insulation. By controlling thermal conduction with an inflatable compartment the temperature of that compartment and its contents can be regulated. Altering the sodium bicarbonate and citric acid ratio and quantities, controllable thermal insulation can be achieved. It is important to note that due to the fact that the reaction is endothermic, there is an initial drop in temperature when the chemicals react, however, this is only

temporary, and by taking this into consideration as a constraint, the system can be controlled to provide the required thermal regulation.

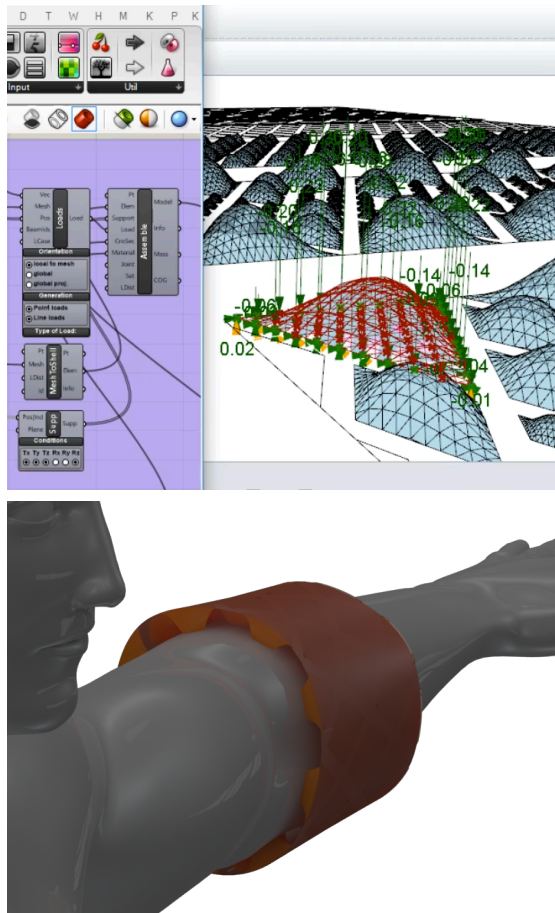


Figure 4. Tournitape parametric Finite Element model.

**Materials.** Through research we found that Mylar, the trade name for metalized BoPET, is the most efficient CO<sub>2</sub> barrier of the materials we tested, and provides a good membrane both by itself or as the inner layer of a composite membrane material.

BoPET (Biaxially-oriented polyethylene terephthalate) is a polyester film made from stretched polyethylene terephthalate (PET) and is used for its high tensile strength, chemical and dimensional stability, transparency, reflectivity, gas and aroma barrier properties, and electrical insulation. A variety of companies manufacture BoPET and other polyester films under different brand names. In the UK and US, the most well-known trade names are Mylar, Melinex and Hostaphan. Mylar comes with many different coatings that can add both aesthetic and mechanical properties to the material. We found that Mylar and, more specifically, metalized Mylar (commonly used in helium balloons) with a matte outer coating, has the ability to maintain a pressurized state for many weeks after initial CO<sub>2</sub> inflation.

To provide an airtight seal, we use a Thermoplastic Polyurethane (TPU) film on the internal surface of the inflatable cushion.

**Primitives toolkit for auto-inflatables.** A Primitives Toolkit for the design exploration of inflatable structures is presented in Figure 2 to show the different design variables of the system.

## 4 DESIGN EXPLORATION

Inflatable assembly can be applied in various ways, from structural primitives such as pre-programmed material elements, to geometric forms with multi-state structural potential. In the context of this paper we are focusing on small-to-large structural change, with elemental control of structural form. From an application perspective, space utilization is one of the most useful traits of this technique, given that volume can be generated out of air, thus providing a light-weight solution to the storage and transportation of physical artifacts.

### 4.1 Tournitape

One of the key applications we developed is a tape for first responders and people in war zones to apply instant pressure to wounds using the chemical activation cells within a bandage. This first aid kit has been implemented in order to create a structural transformation utilizing the minimum inflation necessary to add an inflated frame to a soft structure. The final configuration will have an overall rigidity which in emergency situations can provide a lightweight emergency material for both compression as well as cushioning, protection and thermal insulation (Fig. 3).

The Tournitape project has been parametrically designed in Rhinoceros and Grasshopper to explore different patterns [2]. The algorithm based model reads the 2D pattern lines and automatically recognizes them as boundary condition lines for the inflation simulation. Therefore, through a Finite Element analysis, in Grasshopper–Karamba [9], of the membrane, it is possible to estimate the deformations of several patterns considering the soft and rigid parts of the bandage.



**Figure 5. Emergency auto-inflatable bandage.**

The analysis output enables us to compare resulting textures and physical deformations before proceeding with the fabrication process.

In Figures 4 and 5, the resulting structural analysis of the inflatable structures are shown considering the elastic module of the TPU membrane that provides the airtightness property and a uniform internal pressure of about 1 atm. The final designs have been realized through different digital fabrication techniques taking into account various textiles and materials in order to compare their wearable performance [4].

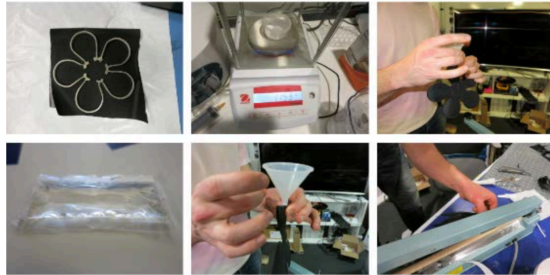
The fabrication process requires 6 main steps: laser cutting the membrane shape; partially heat sealing the laser cut membrane; pre-dissolving the citric acid in water; filling the polypropylene bag with the water mixture and heat sealing; placing measured quantity of sodium bicarbonate and water-citric acid capsule in the pre-sealed membrane; heat sealing the airtight membrane. An added benefit of our system is that by using chemical reactions, the inflation can be very immediate with no external hardware required, thus there is no additional weight or rigid surfaces from valves and other openings. The main issue we encountered with the fabrication process was dealing with very small components by hand. This aspect made measuring and sealing the membranes problematic as we lacked some of the precision we could have if this were an industrialized process.

Aside from functionality, the aesthetic properties of inflated membranes provide a unique quality to a structure. With the development of soft structures becoming a prevalent feature in the field of soft robotics, we can see that there is a clear desire for an aesthetic push in the direction of texture diversity within transformable artifacts. Through the research done in this paper, we have found a number of appropriate solutions to surface membranes which will provide functionality as well as character for CO<sub>2</sub>-retaining inflatable structures.

#### 4.2 Packaging

The design of everyday artifacts that minimize packaging volume, transportation cost and, therefore, carbon footprints in the environment represents one of the main challenges.

In order to meet the required substantial reductions in greenhouse gas (GHG) emissions, changes in consumption patterns are increasingly recognized as an important pillar to address the global climate change mitigation challenge, and have also become increasingly relevant in recent policy debates. Therefore, different patterns of both consumption and daily life are central to addressing the global mitigation challenge. In this research the design of a new type of packaging has been explored whereby contained chemical reactions provide a way to transport fragile goods with a smaller footprint, as packaging will only inflate upon impact (Fig. 6). This design experiment shows that complex geometries can be easily implemented, fabricated and triggered through this chemical reaction, meaning that packaging can be customized for goods with various shapes [3].



**Figure 6. Auto-inflatable flower project: fabrication and inflation triggering.**

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#### 5. CONCLUSIONS

In conclusion, the utilization of chemical bi-products for the purpose of shape-change and material augmentation provides a useful resource for hardware-free inflation methods. Limitations to the system rest in the fact that the process provides a one-time activation mode, which in the context of HCI does not allow for the fidelity of applications that pneumatically controlled system would. However, the advantage of this one-time use system can be applied to other areas such as construction, fabrication and emergency response without the need of energy consuming devices. Our approach, as shown in the Tournitape and packaging examples, requires a preliminary computational design for predicting the inflation deformation shape that will create the shape change. Beyond our applications, other use cases can be realized at a larger architectural scale, for example enabling a pop up emergency shelter after a catastrophic event. Therefore, by utilizing chemical reactions for construction purposes, we give way to a unique and light-weight fabrication method that can be self-evolving and human controlled, allowing us to think of new type of pre-programmable structures with built in energy potential. This process is giving life to otherwise inert materials through shape-change transformation, providing an added dimension and texture to otherwise flat membranes.

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