Automated design of pneumatic soft grippers through design-dependent multi-material topology optimization

Josh Pinskier\textsuperscript{1}, Prabhat Kumar\textsuperscript{2}, Matthijs Langelaar\textsuperscript{3}, and David Howard\textsuperscript{1}

Abstract—Soft robotic grasping has rapidly spread through the academic robotics community in recent years and pushed into industrial applications. At the same time, multimaterial 3D printing has become widely available, enabling the monolithic manufacture of devices containing rigid and elastic sections. We propose a novel design technique that leverages both technologies and can automatically design bespoke soft robotic grippers for fruit-picking and similar applications. We demonstrate the novel topology optimisation formulation that generates multi-material soft grippers, can solve internal and external pressure boundaries, and investigate methods to produce air-tight designs. Compared to existing methods, it vastly expands the searchable design space while increasing simulation accuracy.

I. INTRODUCTION

Soft robotic grasping has emerged as a safe and effective means for grasping fragile, flexible and fluctuating objects. Their inherent deformability enables them to conform to fit the objects’ shape and distribute gripping force, hence gently grasping even soft objects.

These soft grippers are often inspired by human hands, which are seen as the gold standard in soft and dexterous grasping. However, there is an increasing trend towards non-anthropomorphic designs, which enable diverse grasping strategies and require controllable fewer degrees of freedom (DOFs) \cite{1}. Several mechanisms have been investigated for their actuation including pneumatic \cite{2}, tendon-driven \cite{3}, and granular (vacuum) jamming \cite{4}, \cite{5}.

Despite the diversity of grasping and actuation paradigms available in the literature, most existing grippers are hand-designed. They draw on human experience and biomimicry to navigate the complexity of designing deformable devices to generate high-quality designs \cite{6}. The resulting generic designs emphasise universal approaches rather than bespoke designs \cite{4}. However, real-world applications frequently require designs which are tailored to the specifics of their task. Clearly, a fruit-picking robot requires a different end effector to an assembly line robot or a human assistance robot, and an apple-picking end-effector has different requirements to a fruit-picking end-effector.

Despite this obvious need to produce bespoke soft end-effectors, existing automated design tools are limited and underexplored. Methods including simulated and in-materio evolution have recently proven successful in designing granular jamming grippers \cite{7}, \cite{8}. More generally, an impressive and diverse array of soft robotics have been evolved in simulation \cite{9}, \cite{10}. However, because of the large number of evaluations required these require very cheap simulators, which are unable to capture multiphysics interactions and have a large simulation to reality gap \cite{11}.

In contrast, Topology optimization (TO) is a general purpose design tool, suitable to numerous actuation techniques and physical domains \cite{12}. It distributes material inside a meshed (or pixelized/voxelized) space to identify the topology with the best performance, and has designed both pneumatic and tendon-driven soft grippers. \cite{13}, \cite{6}, \cite{14}. However, the methods presented in these works require significant assumptions about the design domain and actuation, limiting both the accuracy of the simulation and the range of realisable designs.

A. Topology Optimisation of Soft Grippers

The current state-of-the-art in topology optimised soft grippers broadly falls into two categories. Either externally actuated grippers which use an exogenous displacement to drive their grasping behaviour (an externally routed cable or moving surface) \cite{15}, \cite{13}, or pressure-actuated soft fingers without design dependency \cite{16}, \cite{17}. In both cases, the
actuation source is prespecified and does not form part of
the optimisation problem. Whilst convenient, these assump-
tions do not reflect best-practice design methods which use
complex pneumatic chambers and internal cable routing.
To capture these features, the loading point (magnitude,
direction and location) should be free to move with each
iteration of the topology optimisation solver. This design-
dependency problem increases the solver complexity and
requires auxiliary physics equations to solve and additional
constraints to enforce physical limits. A small number of
topology optimised soft grippers have investigated design-
dependent pressure optimisation, but their coarse physics
approximations result in unrealisable designs, with discon-
nected pressurised regions [18], [19].

The above methods have been demonstrated only in
single-material optimisation. However, improvements in 3D
printing technology, enable the monolithic manufacture of
arbitrarily complex multi-material soft robots. With two or
more materials it becomes possible to strike a trade-off
between the flexibility and strength of the material, and
increase the overall strength of the device without com-
promising on its workspace. For a detailed review of soft
robotic topology optimisation see [6], [20]. To the best of
the authors’ knowledge, there is currently no method for
creating multi-material pneumatically activated soft robots
using topology optimization.

B. Pressure-Loaded Topology Optimisation

Pressure-loaded topology optimisation is a problem that
extends beyond soft robotics. It has applications in the
design of pneumatically and hydraulically loaded structures
like pressure vessels, dams, pumps and ships. In these
problems, the fluid-solid boundary and hence the loading
must move during the optimisation. In density-based topol-
ygy optimisation, mesh elements are allowed to occupy a
continuum between solid and void [12]. Hence, the problem
is commonly approached either by attempting to explicit-
ly identify a fluid-solid boundary, or using a mixed fluid-
solid formulation [21], [22]. In contrast, the current state
of the art method treats the continuous density material as
a porous media, and uses the Darcy method to estimate
fluid penetration as a function of density [22], [14]. This
allows the boundary to be located implicitly without the
need to explicitly separate the fluid-filled and void regions.
However, generating airtight in pressure-actuated compliant
mechanisms remains challenging as the contiguous, closed
surfaces required to hold pressure also reduce compliance.
Hence, the problem and cost function design are critical to
prevent leaky designs. The issue can be resolved using a
material filtering scheme, which forces a solid layer between
the high and low pressure regions [23], such a scheme is
heavily dependent on the optimiser’s initial conditions and
prevents the formation of beneficial internal cavities.

C. Contributions

In this work, we present a novel method to design 3D
multi-material pressure-actuated soft grippers using topology
optimization. The method builds on our previous work into
pressure-loaded topology optimization using Darcy’s law
[22], [14] and the extended solid-isotropic material with
penalisation (SIMP) material model for the multi-material
modeling [24]. An example of a soft gripper designed using
this method is shown in Figure 1, it uses three materials with
stiffnesses of 1 MPa, 10 MPa and 100 MPa. Using the
multimaterial Darcy formulation, the solver converges to a
soft gripper which clamps together using several compliant
hinges. The main contributions of this work are:

1) The first presentation of a multi-material topology
optimisation formulation for pneumatic soft robots with
design-dependent loading conditions.
2) The development and investigation two new formul-
ae to generate sealed pneumatic actuators, based on
pressure regions and an energy penalty, respectively.
3) The design of several new multimaterial pressure-
actuated soft grippers.

We focus on the application of this methodology to soft robotic
grasping, but it is generalisable to other pneumatic compliant
mechanism and soft robots.

II. TOPOLOGY OPTIMISATION FORMULATION

In this work, we use the density based SIMP method for
topology optimisation. The goal of topology optimisation is
to find a discrete material layout where each region contains
a unique material or is left void. To simplify the problem,
SIMP allows the design variable \( \rho \) to occupy a continuum
from 0 to 1, and a penalty \( p = 3 \) applied to drive the results
towards a binary solution. For a single material problem this
is done using the SIMP interpolation law:

\[
E_i = (1 - \bar{\rho}_i)E_{\min} + \bar{\rho}_i E_1
\]

(1)

where \( E_{\min} \) is a small, non-zero constant used to prevent
singularities in material voids and \( E_1 \) is the elastic modulus
of the material used.

A. Multimaterial Modeling

We apply the extended SIMP interpolation technique to
model multiple materials for the gripper mechanisms [24].
In this formulation, one design variable is assigned to each
material. For example, in the two-material case, the scheme
with the modified SIMP formulation can be written as:

\[
E_i = (1 - \rho_i)E_{\min} + \rho_i((1 - \rho_2)E_1 + \rho_2 E_2)
\]

(2)

where \( E_1 \) and \( E_2 \) are moduli of material 1 and material 2,
respectively. \( \rho_i \) denotes the physical variable corresponding
to design variable \( \rho_i \). \( \{\rho_1 = 1, \rho_2 = 0\} \) gives the second
material, whereas \( \{\rho_1 = 0, \rho_2 = 1\} \) provides the first
material. Thus, \( \rho_1 \) is called the topology variable. It decides
the topology of the evolving design, whereas \( \rho_2 \) decides
the candidate material. Similarly the three-material case can be
described by:

\[
E_i = (1 - \rho_i)E_{\min} + \rho_i(1 - \rho_2)E_1 + \rho_2 E_2
\]

(3)
where $E_3$ is the modulus of material 3. Using three materials, 
\[ \{\bar{\rho}_{i1} = 1, \bar{\rho}_{i2} = 0, \bar{\rho}_{i3} = 0\}, \{\bar{\rho}_{i1} = 1, \bar{\rho}_{i2} = 1, \bar{\rho}_{i3} = 0\}, \{\bar{\rho}_{i1} = 1, \bar{\rho}_{i2} = 1, \bar{\rho}_{i3} = 1\} \] give material 1, material 2 and material 3. To remove non-physical checkerboard patterns and intermediate (i.e non-binary) densities from the final design, we use a spacial density filter with hyperbolic projection as in [12], [25]. This takes a weighted averages of the elemental density with its neighbours, then uses a hyperbolic projection to drive towards 0/1.

**B. Pressure load modeling**

The method developed here for pneumatic soft robotic optimisations builds on our previous work into the Darcy method, a detailed description of which can be found in [22], [14]. It conceptualises the continuous design variable $\bar{\rho}$ as a porous medium, and uses Darcy’s law to calculate pressure losses. In it, the flux $q$ (volumetric fluid flow rate across a unit area) is defined by the flow coefficient $K(\bar{\rho})$ and the pressure difference $\nabla p$ as:

\[ q = -\frac{K}{\mu} \nabla p = -K(\bar{\rho}) \nabla p \]  \hspace{1cm} (4)

As the topology of the multimaterial structure (whether there is a material or void) is determined by $\bar{\rho}_i$, the flux solely depends on $\bar{\rho}_i$, regardless of the number of materials. Hence, the flow coefficient of element $i$ is calculated as:

\[ K(\bar{\rho}_i) = K_v \left( 1 - (1 - \frac{K_v}{K_v}) \mathcal{H}(\bar{\rho}_i, \beta_v, \eta_v) \right) \]  \hspace{1cm} (5)

where

\[ \mathcal{H}(\bar{\rho}_i, \beta_v, \eta_v) = \frac{\tanh (\beta_v \eta_v) + \tanh (\beta_v (\bar{\rho}_i - \eta_v))}{\tanh (\beta_v \eta_v) + \tanh (\beta_v (1 - \eta_v))} \]  \hspace{1cm} (6)

$K_v$ and $K_i$ are flow coefficients of solid and void phases, respectively, and $\eta_v$ and $\beta_v$ shape the distribution of $K(\bar{\rho}_i)$.

A drainage term, $Q_{\text{drain}}$, is added. It helps achieve the natural pressure field variation by draining pressure from internal cavities:

\[ Q_{\text{drain}} = -D_s \mathcal{H}(\bar{\rho}_i, \beta_{\text{dr}}, \eta_{\text{dr}})(\bar{\rho}_e)(p - p_{\text{atm}}) \]  \hspace{1cm} (7)

where $D_s$ is drainage coefficient and $p_{\text{atm}}$ is the atmospheric pressure. The net flow of the system is given by the equilibrium equation:

\[ \nabla \cdot q = -Q_{\text{drain}} = 0 \]  \hspace{1cm} (8)

Which is solved using the finite element method to find the equilibrium pressure distribution and transform the pressure distribution $p$, to a global force $F$ to solve the mechanical equilibrium equation:

\[ Ku = F = -Tp \]  \hspace{1cm} (9)

where $u$ and $K$ are the global displacement vector and stiffness matrix, and $T$ transforms elemental pressures to nodal forces. A linear system is used to facilitate a tractible and efficient solution. However, the resulting solution is accurate only for small deformations. By using two physical equation to solve for the equilibrium pressure and displacement, the formulation determines the pressure boundary at each iteration.

### C. Problem formulation

The final optimisation problem is formulated using:

\[
\begin{align*}
\min_{\rho} & -s - \frac{t_{\text{out}}}{(SE)^{1/n}} \\
\text{such that:} & \quad A p = 0 \\
& \quad Ku = F = -Tp \\
& \quad \sum_{i=1}^{\rho_{f1}} v_i \rho_{f1} \leq (v_f_1 + v_f_2 + v_f_3) \sum_{i=1}^{\rho_{f1}} v_i \\
& \quad \sum_{i=1}^{\rho_{f2}} v_i \rho_{f2} \leq v_f_2 \sum_{i=1}^{\rho_{f1}} v_i \\
& \quad \sum_{i=1}^{\rho_{f3}} v_i \rho_{f3} \leq v_f_3 \sum_{i=1}^{\rho_{f1}} v_i \\
& \quad 0 \leq \bar{\rho} \leq 1
\end{align*}
\]

where $t_{\text{out}}$ and $SE$ indicate output displacement and strain energy, respectively. $s$ is the consistent scaling parameter. $A$ is the global flow matrix, which is found by assembling (8). We use three linear volume constraints using the definitions $\rho_{f1}$, $\rho_{f2}$ and $\rho_{f3}$ described above. The first constraint controls the total amount of the solid state, whereas the second and third give the material amount of phase 2 and phase 3. $v_f_1$, $v_f_2$ and $v_f_3$ denote the volume fraction for material 1, material 2 and material 3, respectively.

The cost function is selected to balance the dual requirements of maximising the deformation of the gripper, and maintaining a design which is stiff enough to grasp and hold objects. Here $n = 8$ was selected after some initial studies to place a soft penalty on the design’s stiffness. In this work, $v_f_1 = 0.3$, $v_f_2 = 0.2$, and $v_f_3 = 0.2$ unless otherwise stated, hence the total material permitted is 70% of the volume of the design domain. Whilst it is desirable to minimise material usage, permitting more material is desirable for proof of concept. In each optimisation, the design variables are initialised with a constant density $\bar{\rho}_1 = v_f_1$ for material $n$. Finally, the input pressure is 50 kPa and the materials are given stiffnesses $E_1 = 1 \text{MPa}$, $E_2 = 10 \text{MPa}$, and $E_3 = 100 \text{MPa}$.

### III. Soft Grippers Design

To demonstrate the method and motivate the need for airtightness, this section investigates the design of pressure-actuated grippers using the multimaterial Darcy formulation. The design domain of the grippers is presented in Figure 2(a). Pressure is applied from the left face, with the output direction shown on the right. To simplify the domain and reduce computation time, 2 planes of symmetry are used, reducing workspace size.

The resulting design is illustrated in Figures 2(b) and 2(c), showing the design domain and undeformed configuration. The deformed configuration is show in Figure 2(d). In it, a solid face is formed on the left side, which absorbs the pressure. The internal strains are then transferred to the output face via a series of compliant hinges, one in the centre.
of the gripper, and four on the outer edges. Thin sections of
the stiffest material $E_3$ are used in each hing, and joined by
the softer materials $E_1$ and $E_2$. Although quite elegant, the
design illustrates two issues with existing pressure optimisation
methods. The first is that the optimiser frequently falls into a
local minimum in which the pressurised fluid is not
allowed to penetrate deeply into the structure, preventing the
formation of more complex, higher performing designs. The
second is that without careful consideration of the design
domain, the optimiser generates holes in the final design
which spuriously increases performance by reducing stiffness
in undesired locations. In this case, resealing the device
is fairly trivial, but in more complex designs, doing so
adversely affects performance. Hence, design methods are
needed which drive closed designs.

![Design domain](a) Undeformed Side-view (b) Undeformed Top-View
(c) Deformed Side-view (d) Deformed Top-View

Fig. 2. 3-Material optimised soft-gripper with stiffnesses: Red - 100MPa,
Green - 10MPa, Blue - 1MPa. (a) Design domain (b) Undeformed Side-view
(c) Undeformed Top-View

IV. AIRTIGHT DESIGN

To generate closed designs, we investigate and compare
three methods, and apply them to soft finger design. In
soft fingers, the pressure load is often applied via a central
channel in the design domain. This forces pressure deeper
into the design and enhances performance but also increases
its susceptibility to hole generation. Viewed from the per-
spective of the optimisation problem, sealed chambers reduce
compliance and restrict deformation. We propose two new
methods for generating sealed designs:

1) A heuristic approach, which adds material to the final
design along the median pressure contour.
2) A penalty approach, which adds an energy term to
the cost function and drives the optimisation to reduce
pressure loss.

The first approach leverages the advantages of the Darcy
method, which calculates the internal pressure distribution
between the inlet and outlet points. Where a face is unsealed,
a smooth pressure gradient will flow from the inlet to the
outlet. However, closed regions have a sharper pressure
boundary. Hence by adding material along the line $0.5(P_{in} - P_{atm})$ we close open regions without significantly impacting
regions which already have material.

The second approach is more rigorous, but remains sus-
cetible to local minima. Using the equilibrium flow from
the Darcy equation, we are able to calculate the energy
transferred from inlet to outlet. In a closed system, there
would be no flow, hence no energy transferred. However,
using the Darcy method, a small flow will always arise. We
use this energy value as a penalty term in the cost function,
such that we seek to minimise:

$$\min \rho \ E^s \ \frac{\rho \ u_{out}}{E^s (S^E)^{1/n}}$$

where $E_1$ is the total energy loss calculated at the boundaries
and $s$ is a constant.

V. AIRTIGHT SOFT FINGERS

The design domain of the soft fingers is presented in
Figure 3(a). It is fixed around the edges on the left side and
pressure enters via a central cavity, a single symmetry face
is used to reduce the problem size. The aim is to maximise
the bending on the right side.

A. Heuristic Skin

An example of the design of the soft bending finger
is shown in Figure 3. Without any closure method, the
material is distributed roughly from stiffest to softest, with
the stiffest material placed around the fixed side. Bending
is increased by placing holes at the top and sides of the
structure. However, a closed structure is easily regenerated
using the heuristic method.

B. With Skin

The surface can also be inserted as part of the optimisation
problem by creating a non-design domain on the boundary
of the optimisation region and assigning it to have stiffness $E_1$.
This guarantees air cannot leak, but will produce suboptimal
solutions as the external boundary must bend and expand
to generate deformation far from the neutral bending axis
(Figure 4). In contrast, Pneunets, a state of the art design
have a sinusoidal profile which localises bending in narrow
sections.

C. Energy Penalty

Finally, the same design is presented using the energy
penalty method. Here, the optimiser has reduced the overall
amount of air leakage by using the low stiffness material $E_1$
to close sections of the chamber which contribute least to
bending. As shown in Figure 5, the result is not a totally
closed design, but one where the open areas have been
greatly reduced. This uses the same design domain as the
heuristic skin. The efficacy of this penalty can be increased
by increasing the volume limit of the most elastic material
$E_1$. This is illustrated in Figure 6 in which the energy penalty
is evaluated with $V_{E_1} = 0.2$ and $V_{E_1} = 0.4$. When using
$V_{E_1} = 0.2$, there is insufficient material to meaningfully
close the design, but at $V_f = 0.4$ an almost sealed chamber emerges with only a small opening around the fixed side.

**D. Numerical Comparison**

We compare the two proposed closure methods by calculating their output displacement, strain energy, mechanical work done, and energy loss across 9 different output stiffnesses (springs placed at the output face) from $0.1 \text{ N m}^{-1}$ to $1000 \text{ N m}^{-1}$. The results are presented in Figure 7. A standard Pneunet design is included for comparison. It contains 7 inflatable chambers with a rectangular cross section, has total dimensions $17 \text{ mm} \times 15 \text{ mm} \times 72 \text{ mm}$ and is made of a single material with $E = E_1 = 1 \text{ MPa}$ and a constant wall thickness of $15 \text{ mm}$. Unsurprisingly, the unconstrained (no skin) optimisation produces the greatest bending, strain energy, work done and energy loss. Ignoring the energy loss, the design performs extremely well. In contrast, the closed design domain performs poorly. The heuristic gives the best performance of the methods discussed in this work, with a relatively large output displacement and low strain energy and energy loss. Of the methods discussed in this work, the heuristic gives the best performance, with a relatively large output displacement and low strain energy and energy loss. Whilst the energy penalty shows promise it is impeded by minimum length scales of topology optimisation, which prevent the formation of thin skins, and tends to become trapped in suboptimal local minima. In contrast, the Pneunet design gives a relatively large displacement across the entire range of output stiffnesses and can exert a significant amount of work on the output spring, but to do so it must take up large amounts of internal strain. This inherent softness is beneficial when acting in free space or on very soft objects but detrimental when grasping stiffer ones as its output work declines at higher output stiffnesses.

**E. Experimental Validation**

To validate the concept, a heuristic skin soft finger was 3D printed using a Stratasys Connex3 Polyjet printer. It allows blending of multiple base materials to produce soft elastomers ranging from Shore-A 30 to 95 as well as rigid materials. The three optimised materials are approximated as Shore-A 30, Shore-A 60 and Shore-A 85. Figure 8 shows the resulting printed finger in its undeformed state and during inflation. Although the printed material properties are only an approximation of the optimisation materials, the qualitative behaviour of the actuator matches the optimisation,
VI. CONCLUSION

 Guaranteeing closure in the topology optimisation of pneumatically actuated soft robots is a significant problem which has not been solved in existing research. We discussed two new methods for generated airtight or low-leakage soft robots. Of the two, the heuristic approach outperforms the rigorous optimisation method, but the latter approach is worthy of further investigation. In addition, this work presented a multi-material method for pneumatic topology optimisation and several new soft gripper designs. In numerical studies, the best optimised designs performed comparably to a Pneunet, a state of the art single material design. However, the topology optimisation method shows promise in generating bespoke designs for specific grasping challenges and can be generalised to any problem involving soft robotic motion. Nonlinearities including large-deformation, hyperelasticity and contact remain a challenge in topology optimisation. In future we aim to experimentally validate our designs in soft grasping and investigate the optimisation of non-linear mechanics.

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