Methods and materials

Software methodology

Materials

Compliant and elastic materials are commonly used in the construction of soft robots. Three specific silicon-based rubbers that are readily accessible and affordable were characterized by (Ellis). These rubbers are outlined with basic material properties in Table below.

Mold-Star 15 was selected as the primary material modeled and manufactured. Mold Star 15’s stiffness lies between EcoFlex and Smooth Sil’s.

Validation

Validation of simulated results generates confidence in the simulation approach. Future simulations do not need to be extensively verified if the method has been proven to be consistent and accurate. Constant verification of simulations is cumbersome, expensive and lengthy. It is desirable to avoid this where possible. To this end, validation of select units was carried out.

Units were selected according to their performance ranking, with better-performing units being more likely to be selected. Units were also selected according to manufacturability and testability. The casting process and testing process are outlined in the following sections.

Casting

Standard material casting was carried out as outlined in Section.

Modular moulds were designed to allow for the reuse of the moulds for different unit layouts. This reduces the complexity of manufacturing as well as the number of components required to be manufactured. Modular moulds consisted of a mould base, large mould cells and small mould cells. The mould base is a flat sheet of aluminium with a square depression 4mm deep. Large and small mould cells are 10 mm square aluminium blocks, 4mm and 2mm thick respectively. Figure illustrates the mould components. Aluminium was selected due to its availability, hardness, manufacturability and relatively low density.

To cast a unit, the mould cells are arranged according to the unit layout. Large mould cells are placed where elements have been removed from the unit. Small mould cells are placed where it is necessary for elements to be cast. Figure illustrates the unit layout, the mould packed according to the layout, and the mould with the cast material in.

The Finite Element Method (FEM) is an approach to numerically solving field problems. Field problems require the determination of one or more dependent variables' distribution in space. Field problems are mathematically described with differential equations or integral expressions. Finite elements can be expressed as small parts of a larger body. A field quantity within an element may only have a simple spatial variation, such as being described by polynomial terms no higher than the second order. FEM differs from calculus as calculus uses infinitesimal elements. FEM thus delivers approximate solutions. \cite{Cook2002}

**\subsection{Modeling Software}**

Several commercial software packages capable of realistically modeling soft bodies are available.

LSDyna is a FEM software package widely used in industry. It is owned by ANSYS and maintained by LSTC. The software's code is based on highly non-linear and transient dynamic FEM with explicit time integration \cite{LSDyna}.

Siemens NX 12 is an integrated software package capable of performing FEM analysis. The software package has a user-friendly interface for graphical design of components \cite{NX12}.

MSC.Marc Mentat is a pre- and postprocessing software for the MSC.Marc FEM solver. It is focused on nonlinear material modeling and analysis. It has an extensive set of options available for post-processing \cite{MSC}.

**\subsection{Material Modeling}**

The modeling of materials undergoing relatively large deformations is an active research field. Stored strain energy density may be used to compute stress in hyperelastic materials. The strain energy density is defined using invariants of strain. The three invariants are given as

\begin{equation}

I\_{1}=\lambda\_{1}^{2}+\lambda\_{2}^{2}+\lambda\_{3}^{2}

\end{equation}

\begin{equation}

I\_{2}=\lambda\_{1}^{2}\lambda\_{2}^{2}+\lambda\_{2}^{2}\lambda\_{3}^{2}+\lambda\_{3}^{2}\lambda\_{1}^{2}

\end{equation}

and

\begin{equation}

I\_{3}=\lambda\_{1}^{2}\lambda\_{2}^{2}\lambda\_{3}^{2}

\end{equation}

where $\lambda\_{1}^{2}$, $\lambda\_{2}^{2}$, and $\lambda\_{3}^{2}$ are three eigenvalues. The undeformed state is used as the frame of reference. The three invariants will not change when using different coordinate systems. The three invariants must be positive for the deformation to be valid. The square root of $I\_{3}$ measures the volume change of the material. $I\_{3}=1$ if the material is incompressible \cite{Kim2015}.

The distortional strain energy density is defined as

\begin{equation}

W\_{1}\left ( I\_{1},I\_{2} \right )=\sum\_{m+n=1}^{\infty}A\_{mn}\left ( I\_{1}-3 \right )^{m}\left ( I\_{2}-3 \right )^{n}

\end{equation}

The Ogden model uses the principal stretches to define the distortional strain energy density as

\begin{equation}

\**label{eq:om}**

W\_{1}\left ( \lambda\_{1}, \lambda\_{2}, \lambda\_{3} \right )=\sum\_{i=1}^{N}\frac{\mu\_{i}}{\alpha\_{i}}\left ( \lambda\_{1}^{\alpha\_{i}} + \lambda\_{2}^{\alpha\_{i}} + \lambda\_{3}^{\alpha\_{i}} \right )

\end{equation}

where $N$, $\mu\_{i}$, and $\alpha\_{i}$ are material parameters. $N$ is usually three. The principal stretches are the three eigenvalues of the deformation gradient. If the material is incompressible, the three principal stresses are not independent, meaning $\lambda\_{1}\lambda\_{2}\lambda\_{3}=1$. The shear modulus is

\begin{equation}

\mu=\frac{1}{2}\sum\_{i=1}^{N}\alpha\_{i}\mu\_{i}

\end{equation}

The Ogden model correlates well with simple tension test data that is elongated up to 700\%. The model accommodates for slightly compressible behaviour and a nonconstant shear modulus \cite{Kim2015}.

**\section{Document}**

**\subsection{Introduction}**

Define aim and objectives properly

-implement generative design process to construct basic elements

-implement generative design process to construct soft bodies from basic elements

-use generative design process to design soft actuator meeting some goal

-compare results to previous work

Define scope and assumptions properly

-hyper-elastic non-linear materials being inflated

-two dimensions

**\subsection{Literature Review}**

-define L-systems appropriately

-discuss and define CPPNs

-add illustrative diagrams where necessary

**\subsection{Material Testing}**

List other materials and given properties if applicable

-Smooth Sil 950

-Ecoflex 0030

Describe testing process in detail

-specimen preparation

--wear nitrile gloves

--sanitise workspace

--mix materials in 1:1 ratio

--mix until no streaks

--degas

--pour into tensile specimen and compression specimen mould

--degas

--even out surface

--leave to set for 4 hours

-specimen testing

--describe ISO standards appropriately

--use Instron machine

--100 kN load cell

--clamp grips vs roller grips

--long travel extensometer vs DIC

**\subsection{Software}**

Discuss coding approach in more detail

Discuss analysis of results in more detail

Refine layout and diagram quality

Eliminate unnecessary diagrams/translate to writing