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Lightweight design and integrated method for manufacturing hydraulic wheel-legged robots

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Section S1

In the topology optimization process, the design domain is discretized into N finite elements. Each element can be represented by an optimization variable $\rho_e \in \left(0,1\right]$ to represent its relative density, where $\rho_e = 1$ denotes a material-filled element, $\rho_e \to 0$ denotes an void cell, and $e \in 1,\ldots,N$. These optimization variables can be aggregated into a vector $\boldsymbol{\rho}$. The equilibrium equation for optimization $\boldsymbol{\rho}$ can be described as:

$$\boldsymbol{K}(\boldsymbol{\rho})\boldsymbol{u} = \boldsymbol{f}, \tag{S1}$$

where $\boldsymbol{K}(\boldsymbol{\rho})$ is the global stiffness matrix of the structure, $\boldsymbol{u}$ represents the global nodal displacement vector, and $\boldsymbol{f}$ represents the external loads acting on the component under the ultimate working condition.

To obtain well-defined structural boundaries, i.e., to confine the final design outcome to encompass solely material and void regions, it becomes imperative to introduce a penalization scheme targeting intermediate values of the optimization variables, aiming to enforce their proximity to the limiting values. The topological optimization problem can be written as:

$$\begin{aligned}
\min_{\boldsymbol{\rho}} \quad & \sum_{e=1}^{N} m_e\left[\rho_e + \alpha\rho_e(1-\rho_e)\right] + \left(\boldsymbol{S}_{\mathrm{w}}\boldsymbol{\rho}\right)^2 + \left(\boldsymbol{S}_{\mathrm{b}}\boldsymbol{\rho} - \boldsymbol{I}\right)^2, \\
s.t. \quad & \boldsymbol{K}(\boldsymbol{\rho})\boldsymbol{u} = \boldsymbol{f}, \\
& F(\sigma_e) \le \sigma_{\mathrm{y}}, \\
& \boldsymbol{S}_{\mathrm{w}}\boldsymbol{\rho} = \boldsymbol{0}, \boldsymbol{S}_{\mathrm{b}}\boldsymbol{\rho} = \boldsymbol{I}, \\
& \varepsilon \le \rho_e \le 1,
\end{aligned} \tag{S2}$$

where m_e is the mass of the material-filled element, and α is a penalty factor to produce a non-zero term when the density is at an intermediate value. σ_{y} is the material yield strength, and the material failure function $F(\sigma_e)$ can be obtained from the von Mises failure criterion:

$$\begin{aligned}
F(\sigma_e) &= \rho_e^{1/2}\sigma_{\mathrm{vm}}, \\
\sigma_{\mathrm{vm}}^2 &= \frac{1}{2}\left[(\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{33}-\sigma_{11})^2\right] \\
&\quad + 3(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2),
\end{aligned} \tag{S3}$$

The use of selection matrices $\boldsymbol{S}_{\mathrm{w}}$ and $\boldsymbol{S}_{\mathrm{b}}$ is to confine the material distribution within specific regions, thereby enabling the resulting topological optimization to adhere to essential constraints such as the placement of oil lines and installation dimensions. As a result, we can obtain a 3D conceptual model, but whether the model meets the load conditions requires further finite element analysis. Then the topology structure is modified repeatedly until the part meets the load conditions.

Reference

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