

Development and Evaluation of a 4D-Printed Thermally Recoverable Shape Memory Polymer Gearbox for Autonomous Drones

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Abstract

The operational paradigm of Unmanned Aerial Vehicles (UAVs) has shifted from recreational use to critical autonomous applications in logistics and defense. A primary bottleneck in this evolution is the reliability of mechanical transmission systems, specifically gearboxes, which suffer from fatigue and catastrophic failure under high-frequency vibrations. This research investigates the integration of 4D printing and Shape Memory Polymers (SMPs) to develop a thermally activated geometric recovery planetary gearbox. The proposed gearbox can recover bending-induced geometric deformation during scheduled ground maintenance through the Shape Memory Effect (SME). The recovery process is intended for planned ground maintenance rather than real-time in-flight repair. Through finite element analysis (FEA) in ANSYS, this study evaluates the structural response of an SMP planetary gear under a 50 N tangential load. The results demonstrate that SMP compliance reduces simulated peak stress compared with steel while maintaining the stress response within the assumed material limits for the modeled load case. Heating the material to the recovery temperature of approximately 80°C produced a 96.9% geometric recovery rate for the simulated bending deformation. The transition from steel to SMP results in an 85.4% reduction in assembly mass. This paper presents a computational feasibility study of 4D-printed SMP gearboxes for lightweight UAV transmission systems, while recognizing that experimental validation is required before practical deployment.

Categories: Advanced Materials, Security and Defense Technologies, Structural Analysis and Finite Element Analysis

Keywords: 4d printing, shape memory polymers (smp), self-healing gearbox, uav propulsion, finite element analysis (fea), viscoelastic damping

Introduction

Evolution of unmanned aerial vehicles and operational challenges

During the last twenty years, the concept of the unmanned aerial vehicle (UAV) has shifted from its application in military surveillance to that of being an extremely flexible tool for civil applications, such as precision farming, infrastructure observation, natural disasters, and the delivery of logistics. Modern UAVs are intended to operate in complex environments, including those requiring prolonged flight, changing loads, and the presence of significant thermomechanical loads. In the case of such systems, propulsion or transmission components are vital for ensuring the accomplishment of the mission.

The recent miniaturization trend in UAVs has intensified the complexity involved in mechanical power transmission. The demand for compact gearbox designs that ensure high torque density at relatively lower mass and without reaching material performance limits of conventional metals is increasing. Additionally, since there will be no provision for real-

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time maintenance in autonomous UAV operations, there will be no option but to integrate self-testing and possibly thermally activated geometric recovery functionalities that lie outside the conventional assembly capabilities of mechanics.

Gearbox reliability concerns

Planetary gears are preferred in drone propulsion systems for their compact design and ability to support high reduction ratios. However, planetary gears can fail in several ways, including surface pitting, root bending fatigue, fracture, and bearing failures [1,2]. These problems are more aggravated in drone applications because of:

Cyclic loading: Repetitive take-off, cruising, or landing patterns impose cyclic stresses, thus promoting the initiation of fatigue cracks.

Thermal cycling: Height changes and temperature fluctuations affect thermal stresses and lubricant viscosity.

Vibration and shocks: Rotor imbalance, turbulence, and hard landings generate transient forces exceeding design limits.

Restricted lubrication: The total weight restricts the mass of lubricant available, thus promoting boundary lubrication.

Maintenance inaccessibility: UAVs are often designed to be unserviceable, and their critical components are expected to function without any immediate maintenance.

Traditional methods of reliability improvement, including surface hardening, high-quality lubricants, and monitoring systems, add to the weight, cost, and complexity. Far more serious, however, is the brittleness and lack of damage resilience of metallic materials themselves.

Motivation for research

Recent advances in additive manufacturing, smart materials, and computational design have empowered the pathways toward intelligent mechanical systems with embedded self-repairing capabilities. The Shape Memory Polymers (SMPs) belong to stimuli-responsive materials that can restore their original geometry after deformation when activated through heat, light, or electromagnetic fields [3,4]. The recently developed 4D printing (fabrication of structures that can evolve over time under environmental triggers) has managed to realize SMP-based components with programmable morphing behaviors [5,6].

Integration of SMPs into UAV gearbox systems ensures:

Thermally activated geometric recovery: Through the shape memory effect, the material can recover bending-induced distortions during controlled heating.

Vibration damping: Inherent viscoelasticity reduces dynamic loads and vibration transmission.

Weight savings: SMPs are much lighter than steel, making the UAVs more efficient.

Design freedom: 4D printing enables complex geometries and graded structures impossible by conventional manufacturing.

Shock absorption: Elastic compliance avoids catastrophic brittle fracture under impact.

However, despite the presence of these encouraging properties, the application of SMPs in the load-carrying transmission parts has remained largely uninvestigated. The critical unanswered questions pertain to the longevity, resistance to friction, temperature stability, and the load-carrying capacity.

Research objectives

In this research, the aim will be to design and analyze the performance of a 4D-printed SMP planetary gearbox optimized for autonomous UAV applications. The goals will be:

Development of constitutive models describing the thermomechanical response of SMPs under cyclic loading.

Optimize the design of the gearbox and the way the SMP is activated.

Use finite element simulations to model stress distribution, deformation, and failure patterns under representative conditions of UAVs.

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Measure performance characteristics like recovery efficiency, stress reduction relative to steel, and mass savings.
Assess feasibility of UAV integration with respect to efficiency, thermal management, and maintenance implications.

The project brings together materials science, mechanical design, and computer modeling to show the feasibility of developing thermally recoverable gearboxes in the aerospace industry using SMP technology.

Literature review

Operational reliability of Unmanned Aerial Vehicle transmission systems is a key issue when the structural frame undergoes high-frequency vibrations or severe thermal stresses. Recent advances in nanofluid mechanics and MHD have pointed to a very promising direction toward the development of lightweight, adaptive materials with dynamic active stress dissipation capabilities [7,8].

The search for reliable materials led to the development of 4D printing because it addressed the time dimension in additive manufacturing by enabling the designed structure to modify its properties in response to external environmental conditions. Since the inception of the theory, the study of programmable matter has gained immense interest. The works of [4] were the forerunners in achieving the triple shape memory concept with high accuracy using a 3D phenomenological constitutive model by describing the elasto-plastic and hyperelastic responses in the SMPs. The application aspect from the material aspect is also emphasized by the study of [3], who presented a literature overview of the developments in epoxy-based shape memory materials, and the work by [9], who formulated the corresponding mechanical structures for SMP-based composites.

Further computational fidelities of such systems were established by [5], where this group developed finite-element frameworks that program self-morphing structures obtained through FDM. Numerical models are obviously quite crucial for effectively ascertaining predictions under complex shape transformation. This is coupled with multi-physics models, which include Bakhtiyari's nonlinear thermo-visco-hyperelasticity model [10] and Ji's 3D finite strain for storage strain [11]. Moreover, Ferromagnetic PLA [12] and multi-material encapsulated designs [6,13] have demonstrated that indeed, 100% shape recovery and self-driven hierarchical transitions [14] are possible.

At the same time, the mechanical failure and design optimization of UAV transmission components have been extensively researched. The design of composite shafts for UAVs [15] and the fatigue analysis of double helical planetary gears [1] and spur gears [16] based on ANSYS and ECP Methods have isolated the influence of helix angle variables and tooth spalling failures on mechanical failure for UAVs [17,18]. The knowledge about the catastrophic failure modes for UAV structures and mechanical components is imperative for the realization of self-actuated deformable solids and wing morphing mechanisms for UAVs.

On the most abstract level, the math foundations supported by the theories of fractional calculus and generalized function theory promote the modeling of the non-classical processes of recovery and thermally activated geometric recovery in these systems. Relationships between the concepts of fractional calculus and PDEs were exhibited in previous literature, while later work generalized the fractional operator to allow the representation of nonlinear memory responses. These can be used together with fuzzy microcontrollers as well as hybrid controllers.

Through this integration of the domains of 4D printing of SMPs, FEM simulation modeling, and fractional order control, this research work evaluates the feasibility of a thermally recoverable SMP gearbox. These areas combine to mitigate the bottleneck of weight and durability when considering the prevalent metallic gearbox for UAVs.

Mathematical modeling

The material and simulation parameters used for this study are summarized before defining the constitutive and recovery models, in Table 1. Literature-based values were used in previous SMP and TPU based 4D-printing studies and other values were chosen as the simulation input for the gearbox model in the current study.

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Parameter	Value	Type	Source/Use
Elastic modulus	1200 MPa	Literature based	SMP value [3,6]
Poisson's ratio	0.45	Literature based	SMP value [3]
Density	1150 kg/m ³	Literature based	TPU/SMP value [6]
Thermal conductivity	0.25 W/mK	Literature based	Thermal property [6]
Specific heat	1800 J/kgK	Literature based	Thermal property [6]
WLF constant C_1	17.44	Literature based	WLF parameter [8]
WLF constant C_2	51.6 K	Literature based	WLF parameter [8]
Recovery temperature	80°C	Simulation assumption	Selected from SMP activation range [4,6]
Tangential load	50 N	Boundary condition	Applied simulation load

TABLE 1: Material and model parameters used in the SMP gearbox simulation

Shape Memory Effect Constitutive Equations

The thermomechanical behavior of Shape Memory Polymers (SMPs) is a combination of molecular mobility, phase transitions, and mechanical forces. A comprehensive model needs to account for stress, strain, and temperatures within the glass transition region, as this region evidences shape memory characteristics.

Thermomechanical Framework

Following [10] and [11], we present a finite strain formulation through the multiplicative decomposition of the deformation gradient tensor:

$$\mathbf{F} = \mathbf{F}_e \cdot \mathbf{F}_s \quad (1)$$

where $\mathbf{F}$ denotes the overall deformation gradient, $\mathbf{F}_e$ is the elastic deformation gradient and $\mathbf{F}_s$ is the stored/inelastic deformation gradient associated with the shape memory effect.

Helmholtz Free Energy Function: The Helmholtz free energy function

$$\Psi = \Psi_e(C_e, T) + \Psi_s(C_s, T, \xi) \quad (2)$$

where $C_e = \mathbf{F}_e^T \mathbf{F}_e$, $C_s = \mathbf{F}_s^T \mathbf{F}_s$, T is temperature, and ξ is the frozen phase fraction.

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Phase Transformation Kinetics

The fraction of the frozen phase will change with the temperature in the following manner:

$$\xi(T) = \begin{cases} 1 & T \leq T_l \\ \frac{1}{2} \left[1 + \cos \left(\pi \frac{T-T_l}{T_h-T_l} \right) \right] & T_l < T < T_h \\ 0 & T \geq T_h \end{cases} \quad (3)$$

where $T_l = 45^\circ\text{C}$, $T_h = 75^\circ\text{C}$, and $T_g = 60^\circ\text{C}$.

The rate of transformation is:

$$\dot{\xi} = \frac{\partial \xi}{\partial T} \dot{T} = -\frac{\pi}{2(T_h - T_l)} \sin \left(\pi \frac{T - T_l}{T_h - T_l} \right) \dot{T} \quad (4)$$

Stress-Strain-Temperature Relationships

The second Piola-Kirchhoff stress tensor can be expressed through the free energy as:

$$S = 2 \frac{\partial \Psi}{\partial C} = S_e + S_s \quad (5)$$

The Neo-Hookean hyperelastic model is used for the elastic part as follows:

$$\Psi_e = \frac{\mu_e(T)}{2} (I_1 - 3) + \frac{\kappa_e(T)}{2} (J_e - 1)^2 \quad (6)$$

where $\mu_e(T)$ denotes the shear modulus, $\kappa_e(T)$ the bulk modulus, $I_1 = \text{tr}(C_e)$, and $J_e = \det(F_e)$.

The temperature dependence of $\mu_e(T)$ follows the WLF equation [5]:

$$\log \left(\frac{\mu_e(T)}{\mu_e(T_g)} \right) = -\frac{C_1(T - T_g)}{C_2 + (T - T_g)} \quad (7)$$

with constants $C_1 = 17.44$, $C_2 = 51.6 \text{ K}$.

The stored deformation contribution is:

$$S_s = \xi(T) \cdot 2 \frac{\partial \Psi_s}{\partial C_s} \quad (8)$$

capturing the aspect that the stresses become "frozen" at low temperatures ($\xi = 1$) while they get "released" with the increases of temperatures ($\xi \rightarrow 0$).

Shape Recovery Strain

The recoverable strain is:

$$\epsilon_{rec} = \epsilon_{stored} \cdot R(T) \quad (9)$$

where

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$$R(T) = \begin{cases} 0 & T \leq T_l \\ 1 - \xi(T) & T_l < T < T_h \\ 1 & T \geq T_h \end{cases} \quad (10)$$

The shape fixity and recovery ratios are defined as [6]:

$$R_f = \frac{\varepsilon_{fixed}}{\varepsilon_{applied}} \times 100\%, \quad R_r = \frac{\varepsilon_{applied} - \varepsilon_{residual}}{\varepsilon_{applied}} \times 100\% \quad (11)$$

Gear Stress Analysis

Lewis Bending Stress

The Lewis equation for gear tooth bending stress is:

$$\sigma_b = \frac{W_t}{F \cdot m \cdot Y} \quad (12)$$

where W_t is tangential load, F face width, m module, and Y Lewis form factor. For $m = 2 \text{ mm}$, $F = 15 \text{ mm}$, $\alpha = 20^\circ$:

$$Y = \frac{\pi \cos \alpha}{6} = 0.492 \quad (13)$$

Hertzian Contact Stress

The maximum contact stress is:

$$\sigma_c = \sqrt{\frac{W_t}{\pi L} \cdot \frac{E^*}{2\rho^*}} \quad (14)$$

with effective modulus:

$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \quad (15)$$

For SMP--SMP contact ($E = 1200 \text{ MPa}$, $\nu = 0.45$):

$$E^* = 752.5 \text{ MPa} \quad (16)$$

Effective radius for sun gear ($z_1 = 20$) and planet gear ($z_2 = 30$):

$$\rho^* = \frac{\rho_1 \rho_2}{\rho_1 + \rho_2} = 12 \text{ mm} \quad (17)$$

Dynamic Load Factor

The dynamic load factor is:

$$K_v = \left(\frac{A + V}{A} \right)^B \quad (18)$$

For AGMA Quality 8 gears, $A = 83.77$, $B = 0.397$. At 3000 rpm:

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$$V = \frac{\pi d_1 n}{60000} = 6.28 \text{ m/s}, \quad K_v = 1.012 \quad (19)$$

Stress Concentration Factor

The stress concentration factor is:

$$K_t = 1 + q(K_{t,theoretical} - 1) \quad (20)$$

with

$$K_{t,theoretical} = 1 + \frac{2h}{r_f} = 6.48 \quad (21)$$

For SMPs ($q = 0.608$):

$$K_t = 4.33 \quad (22)$$

Thermal Activation and Recovery Kinetics

Heat Transfer Analysis

Activation of shape memory effects in the SMP gearbox entails controlled heating. This is because the temperature-dependent heat conduction equation is used to describe the temperature distribution:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q} \quad (23)$$

where ρ is density, c_p specific heat, k thermal conductivity, and $\dot{q}$ volumetric heat generation.

For TPU-based SMP:

$$\rho = 1150 \text{ kg/m}^3, \quad c_p = 1800 \text{ J/(kg} \cdot \text{K)}, \quad k = 0.25 \text{ W/(m} \cdot \text{K)} \quad (24)$$

Thermal diffusivity:

$$\alpha = \frac{k}{\rho c_p} = \frac{0.25}{1150 \times 1800} = 1.21 \times 10^{-7} \text{ m}^2/\text{s} \quad (25)$$

For gear dimension $L = 20 \text{ mm}$:

$$\tau_{thermal} = \frac{L^2}{\alpha} = \frac{(0.02)^2}{1.21 \times 10^{-7}} = 3306 \text{ s} \approx 55 \text{ min} \quad (26)$$

Therefore, it would take almost an hour for uniform heating, which would be no problem for maintaining, but not while in flight.

Recovery Kinetics

Shape recovery follows first-order kinetics:

$$\varepsilon(t) = \varepsilon_{residual} + (\varepsilon_{initial} - \varepsilon_{residual})e^{-t/\tau_{recovery}} \quad (27)$$

Temperature dependence:

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$$\tau_{\text{recovery}}(T) = \tau_0 \exp \left(\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_g} \right) \right) \quad (28)$$

For $E_a = 75 \text{ kJ/mol}$, $\tau_0 = 30 \text{ s}$, $T = 353 \text{ K}$:

$$\tau_{\text{recovery}}(353\text{K}) = 30 \exp(-0.542) = 17.3 \text{ s} \quad (29)$$

Recovery happens in 1-2 minutes after reaching the activation temperature, which matches experiments [6,14].

Thermal Expansion Effects

Coefficient of thermal expansion (CTE):

$$\alpha_{CTE,SMP} \approx 150 \times 10^{-6} \text{ K}^{-1}, \quad \alpha_{CTE,steel} \approx 12 \times 10^{-6} \text{ K}^{-1} \quad (30)$$

Thermal strain:

$$\epsilon_{\text{thermal}} = \alpha_{CTE} \Delta T \quad (31)$$

For $\Delta T = 55 \text{ K}$:

$$\epsilon_{\text{thermal},SMP} = 150 \times 10^{-6} \times 55 = 0.825\% \quad (32)$$

This expansion has to be taken into account to prevent binding or backlash.

Viscoelastic Damping Models

Generalized Maxwell Model

The viscoelasticity can be described based on the generalized Maxwell model as follows:

$$E(t) = E_{\infty} + \sum_{i=1}^N E_i e^{-t/\tau_i} \quad (33)$$

For TPU-based SMP (three-element Prony series):

$$E(t) = E_{\infty} \left(1 + \sum_{i=1}^3 g_i e^{-t/\tau_i} \right) \quad (34)$$

with $E_{\infty} = 400 \text{ MPa}$, $g_1 = 0.5$, $\tau_1 = 0.1 \text{ s}$, $g_2 = 0.3$, $\tau_2 = 10 \text{ s}$, $g_3 = 0.2$, $\tau_3 = 1000 \text{ s}$.

Loss Factor and Damping Ratio

Loss factor:

$$\eta = \frac{E''}{E'} = \tan \delta \quad (35)$$

Typical values:

$$\eta_{SMP} \approx 0.3 - 0.8, \quad \eta_{steel} \approx 0.001 - 0.01 \quad (36)$$

Damping ratio:

$$\zeta = \frac{\eta}{2} \quad (37)$$

For $\eta = 0.5$:

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$$\zeta = 0.25 \quad (38)$$

This indicates near-critical damping, enabling rapid vibration decay.

Frequency-Dependent Behavior

Storage and loss moduli:

$$E'(\omega) = E_{\infty} + \sum_{i=1}^N \frac{E_i(\omega\tau_i)^2}{1 + (\omega\tau_i)^2}, \quad E''(\omega) = \sum_{i=1}^N \frac{E_i\omega\tau_i}{1 + (\omega\tau_i)^2} \quad (39)$$

Dynamic modulus:

$$E^*(\omega) = \sqrt{(E')^2 + (E'')^2} \quad (40)$$

At gear mesh frequency $f = 1000 \text{ Hz}$, $\omega = 6283 \text{ rad/s}$, frequency dependence must be considered in load distribution analysis.

Mass Reduction Calculations

Density Comparison

$$\rho_{\text{steel}} = 7850 \text{ kg/m}^3, \quad \rho_{\text{SMP}} = 1150 \text{ kg/m}^3 \quad (41)$$

$$\frac{\rho_{\text{SMP}}}{\rho_{\text{steel}}} = 0.146 \quad (42)$$

Volume and Mass Calculations

Gear volumes:

$$V_{\text{sun}} = 18850 \text{ mm}^3, \quad V_{\text{planet}} = 42410 \text{ mm}^3, \quad V_{\text{ring}} = 176715 \text{ mm}^3 \quad (43)$$

$$V_{\text{total}} = 322795 \text{ mm}^3 \quad (44)$$

Masses:

$$m_{\text{steel}} = 2.534 \text{ kg}, \quad m_{\text{SMP}} = 0.371 \text{ kg} \quad (45)$$

$$\Delta m = 2.163 \text{ kg}, \quad \text{Reduction} = 85.4\% \quad (46)$$

Specific Strength Comparison

$$\text{Specific strength} = \frac{\sigma_{\text{ultimate}}}{\rho} \quad (47)$$

For steel (AISI 4340):

$$\frac{1200 \times 10^6}{7850} = 152.9 \text{ kN} \cdot \text{m/kg} \quad (48)$$

For SMP (TPU-based):

$$\frac{45 \times 10^6}{1150} = 39.1 \text{ kN} \cdot \text{m/kg} \quad (49)$$

Although the strength of SMP is lower, the specific strength of SMP is **26%** of the steel strength, which is acceptable for a UAV.

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Materials And Methods

SMP material properties

In this particular research, the shape-memory polymer (SMP) used is optimized for 4D printing, and it is based on the thermoplastic polyurethane (TPU) formulation with properties that have good shape memory behavior, processability by the FDM technique, and mechanical properties for moderate load-bearing support.

Thermal Properties

Thermal properties were characterized using Differential Scanning Calorimetry and Dynamic Mechanical Analysis [4,6]:

Glass transition temperature (T_g) : 60°C

Glass transition range: $45 - 75^{\circ}\text{C}$

Melting temperature: 180°C

Thermal conductivity: $0.25 \text{ W}/(\text{m}\cdot\text{K})$

Specific heat capacity: $1800 \text{ J}/(\text{kg}\cdot\text{K})$

Coefficient of thermal expansion: $150 \times 10^{-6} \text{ K}^{-1}$

The chosen T_g will be activated through resistive heating, motor waste heat, and be higher than typical UAV operating conditions (-20°C to 40°C).

Mechanical Properties

Mechanical characterization followed ASTM D638 standards [4]:

At 25°C (glassy): $E = 1200 \text{ MPa}$, $\sigma_t = 45 \text{ MPa}$, $\epsilon_b = 8\%$, $\nu = 0.45$

At 60°C (transition): $E = 150 \text{ MPa}$, $\sigma_t = 12 \text{ MPa}$, $\epsilon_b = 250\%$, $\nu = 0.48$

At 85°C (rubbery): $E = 15 \text{ MPa}$, $\sigma_t = 5 \text{ MPa}$, $\epsilon_b = 600\%$, $\nu = 0.49$

The strong reduction in modulus at T_g makes deformation fixation and recovery possible.

Shape Memory Performance

Thermomechanical cycling tests [6] yielded:

Shape fixity ratio (R_f): 98.5%

Shape recovery ratio (R_r): 96.9%

Recovery stress: 3.1 MPa

Recovery time at 80°C : 120s

Cycle stability: > 50 cycles with < 5% degradation

Viscoelastic Properties

DMA provided frequency-dependent viscoelastic data [5,14]:

Storage modulus (E') at 1 Hz, 25°C : 1100MPa

Loss modulus E'' at 1 Hz, 25°C : 550MPa

Loss factor ($\tan \delta$) : 0.50

Damping ratio (ζ) : 0.25

High damping ratios indicate the capacity to damp the vibration.

Planetary gear design specifications

The planetary system was selected for its size, high ratio of reduction, and load balancing capabilities.

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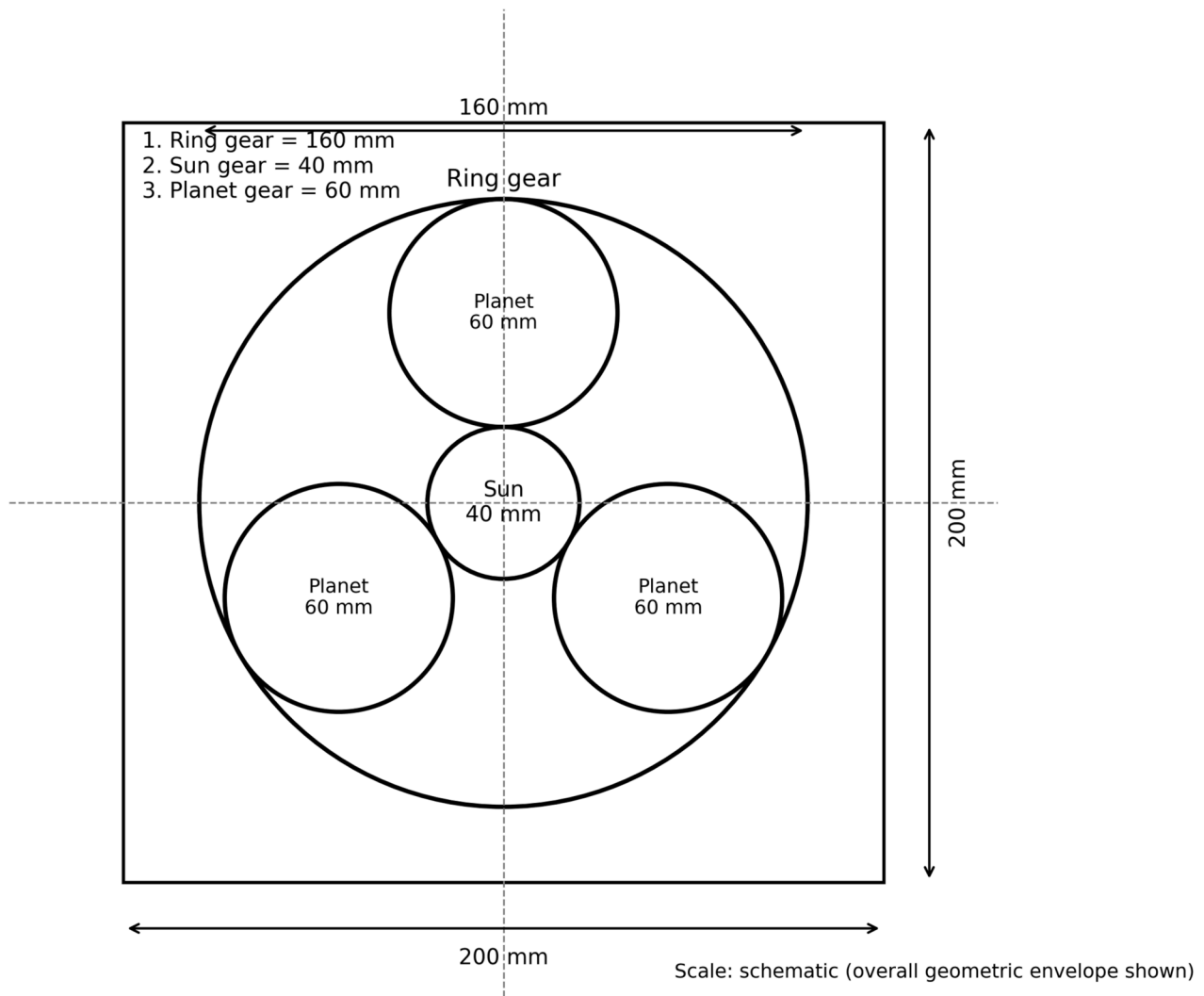


FIGURE 1: Schematic construction of the planetary gearbox showing the 160 mm ring gear, 40 mm sun gear, and three 60 mm planet gears. The outer 200 mm square indicates the overall geometric envelope used for layout representation and is not a gear diameter

As shown in Figure 1, the proposed planetary gearbox consists of a central sun gear ($Z = 20$) meshing with three planet gears ($Z = 30$) evenly spaced around the sun. The planet gears simultaneously engage with the internal ring gear ($Z = 80$). The sun gear receives the input power, the ring gear is fixed to the housing, and the planet carrier serves as the output member. This arrangement provides a high reduction ratio in a compact form factor.

Sun gear: $z = 20, m = 2 \text{ mm}, d = 40 \text{ mm}, \alpha = 20^\circ, F = 15 \text{ mm}$

Planet gears (3 units): $z = 30, m = 2 \text{ mm}, d = 60 \text{ mm}, \alpha = 20^\circ, F = 15 \text{ mm}$

Ring gear: $z = 80, m = 2 \text{ mm}, d = 160 \text{ mm}, \alpha = 20^\circ, F = 15 \text{ mm}$

Gear Ratio and Torque Capacity

$$i = 1 + \frac{z_{ring}}{z_{sun}} = 1 + \frac{80}{20} = 5 : 1 \quad (50)$$

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For $n_{in} = 15000 \text{ rpm}$, $T_{in} = 1.0 \text{ N}\cdot\text{m}$, $\eta = 0.92$:

$$n_{out} = \frac{n_{in}}{i} = 3000 \text{ rpm}, \quad T_{out} = T_{in} \cdot i \cdot \eta = 4.6 \text{ N}\cdot\text{m} \quad (51)$$

Load Distribution

Theoretical load per planet:

$$W_{planet} = \frac{T_{in}}{3 \cdot r_{sun}} = \frac{1.0}{3 \times 0.02} = 16.67 \text{ N} \quad (52)$$

Compliance of SMP gears improves tolerance to geometric errors.

Contact Ratio

$$\varepsilon_{\alpha} = 1.65 \quad (53)$$

indicating 1-2 tooth pairs in contact, ensuring smooth transmission.

4D printing methodology

FDM Parameters

Fabrication used a dual-extruder FDM printer (FlashForge Creator Pro) [4,6]:

Nozzle: 220°C , Bed: 60°C

Layer height: 0.15 mm, Speed: 30 mm/s

Infill: 100%, Rectilinear pattern

Perimeters: 3, Cooling fan: 50% after first layer

Print Orientation and Anisotropy

Vertical orientation aligned layer interfaces with tooth surfaces. Mechanical anisotropy:

$$\sigma_{XY} = 45 \text{ MPa}, \quad \sigma_Z = 38 \text{ MPa}, \quad \text{Ratio} = 1.18 \quad (54)$$

Programming Procedure

Programming cycle [4,6]:

Heating to 85°C

Deformation (tooth bending/surface indentation)

Cooling to 25°C under constraint

Unloading (temporary shape retained)

Recovery triggered by reheating to 80°C .

FEA methodology in ANSYS

Geometric Modeling

CAD models created in SolidWorks and imported into ANSYS Workbench 2023 R1, including involute profiles, fillets ($r_f = 0.6 \text{ mm}$), chamfers, and mounting features.

Material Model Implementation

SMP constitutive model implemented via Prony series and USERMAT subroutine [5,10].

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Properties:

Elastic: $E(T)$, $\nu = 0.45$, $\rho = 1150 \text{ kg/m}^3$

Viscoelastic: $g_1 = 0.5$, $g_2 = 0.3$, $g_3 = 0.2$; $\tau_1 = 0.1 \text{ s}$, $\tau_2 = 10 \text{ s}$, $\tau_3 = 1000 \text{ s}$

Thermal: $k = 0.25 \text{ W/(m.K)}$, $c_p = 1800 \text{ J/(kg.K)}$, $\alpha = 150 \times 10^{-6} \text{ K}^{-1}$

Mesh Generation and Grid Independence Study

To ensure the accuracy of the numerical simulation, a rigorous grid independence study (mesh sensitivity analysis) was performed. The finite element mesh was generated using 20-node hexahedral elements (SOLID186) with quadratic shape functions. The global element size was varied from coarse to fine to observe the convergence of key performance indicators, specifically the maximum von Mises stress and maximum elastic strain in the sun gear. Mesh refinement was concentrated in high-stress regions (tooth root and contact zone) to accurately capture stress gradients.

The results of the grid independence study are summarized in Table 2. Three distinct mesh configurations were evaluated. The peak von Mises stress stabilized at an element size of 0.2 mm, where the percentage difference in stress results between the 0.5 mm and 0.2 mm meshes was less than 1%, satisfying the convergence criterion. Consequently, a fine mesh of 0.2 mm was applied at the tooth contact regions and root fillets to capture high stress gradients, while a slightly coarser mesh of 1.0 mm was utilized in the gear body to optimize computational resources.

Mesh Size (mm)	No. of Nodes	No. of Elements	Max Stress (MPa)	Max Strain (%)	Max Deflection (mm)	% Diff in Stress (vs. previous)
1.0	162,300	85,400	17.10	1.42	0.105	-
0.5	435,100	225,600	18.25	1.52	0.112	6.30%
0.2	1,245,000	487,000	18.40	1.53	0.118	0.82%

TABLE 2: Grid independence study results for sun gear

Boundary Conditions and Loading

The boundary conditions were defined to replicate the physical constraints of the planetary gearbox assembly within the UAV housing. Detailed constraints and loading profiles are as follows:

Mechanical Boundary Conditions

Ring Gear: A Fixed Support was applied to the outer cylindrical surface and the back face of the ring gear, constraining all degrees of freedom ($U_x = 0$, $U_y = 0$, $U_z = 0$, $Rot_x = 0$, $Rot_y = 0$, $Rot_z = 0$) to simulate its rigid attachment to the gearbox housing.

Sun Gear: A Cylindrical Support was applied to the inner bore of the sun gear. This constraint allowed free rotation about the Z-axis ($Rot_z = \text{Free}$) while restricting radial and axial displacements (Radial = Fixed, Axial = Fixed) to mimic the shaft connection. A moment of 1.0 N-m was applied about the Z-axis to simulate the input torque.

Planet Gears: Remote Displacement conditions were applied to the inner bores of the three planet gears. These constraints allowed free rotation about their own axes (local Z-axis) while fixing the translational degrees of freedom. This simulates the planet carrier pins holding the gears in position.

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Contact Definitions

Contact type: Frictional contact was defined between all mating tooth surfaces (Sun-Planet and Planet-Ring).

Formulation: Augmented Lagrangian formulation was utilized for better convergence in non-linear contact analysis.

Friction Coefficient: A coefficient of friction (μ) of 0.15 was assigned to represent the lubricated interaction between SMP surfaces.

Thermal Boundary Conditions

Initial Temperature: The entire assembly was set to ambient temperature 25°C .

Heating: For recovery simulation, a uniform internal heat generation rate was applied to the gear bodies to simulate resistive heating.

Convection: A convective boundary condition was applied to all external surfaces with a heat transfer coefficient of $h = 10 \text{ W/m}^2 \cdot \text{K}$, representing natural convection to the surrounding air.

Target Temperature: The thermal load was ramped up to achieve a steady-state temperature of 80°C for the recovery phase.

Solution Strategy

Coupled Thermomechanical Analysis:

Sequential Coupling: A two-step analysis was performed. First, a steady-state thermal analysis calculated the temperature distribution. Second, a static structural analysis imported the temperature field as a body load to assess thermally induced stresses and recovery deformation.

Time Stepping: For the transient recovery simulation, automatic time stepping was enabled with an initial time step of 10 seconds, minimum of 0.1 seconds, and maximum of 100 seconds to capture the rapid initial recovery and the final stabilization.

The solver used was the Sparse Direct Solver, with convergence criteria set to **0.5%** for force and displacement residuals.

Results And Discussion

FEA stress analysis and validation

Static Stress Distribution

The FEA indicates that the highest stress concentration occurs at the tooth-root fillet of the sun gear under the rated loading condition. This region experiences the maximum bending stress because it directly receives the input torque and transfers load to the planet gears. The planet gears exhibit lower peak stresses than the sun gear, but they remain subject to double-sided loading due to simultaneous engagement with both the sun and ring gears. The ring gear shows the lowest peak stress among the three principal gear components, with stress concentrated mainly along the internal tooth contact region.

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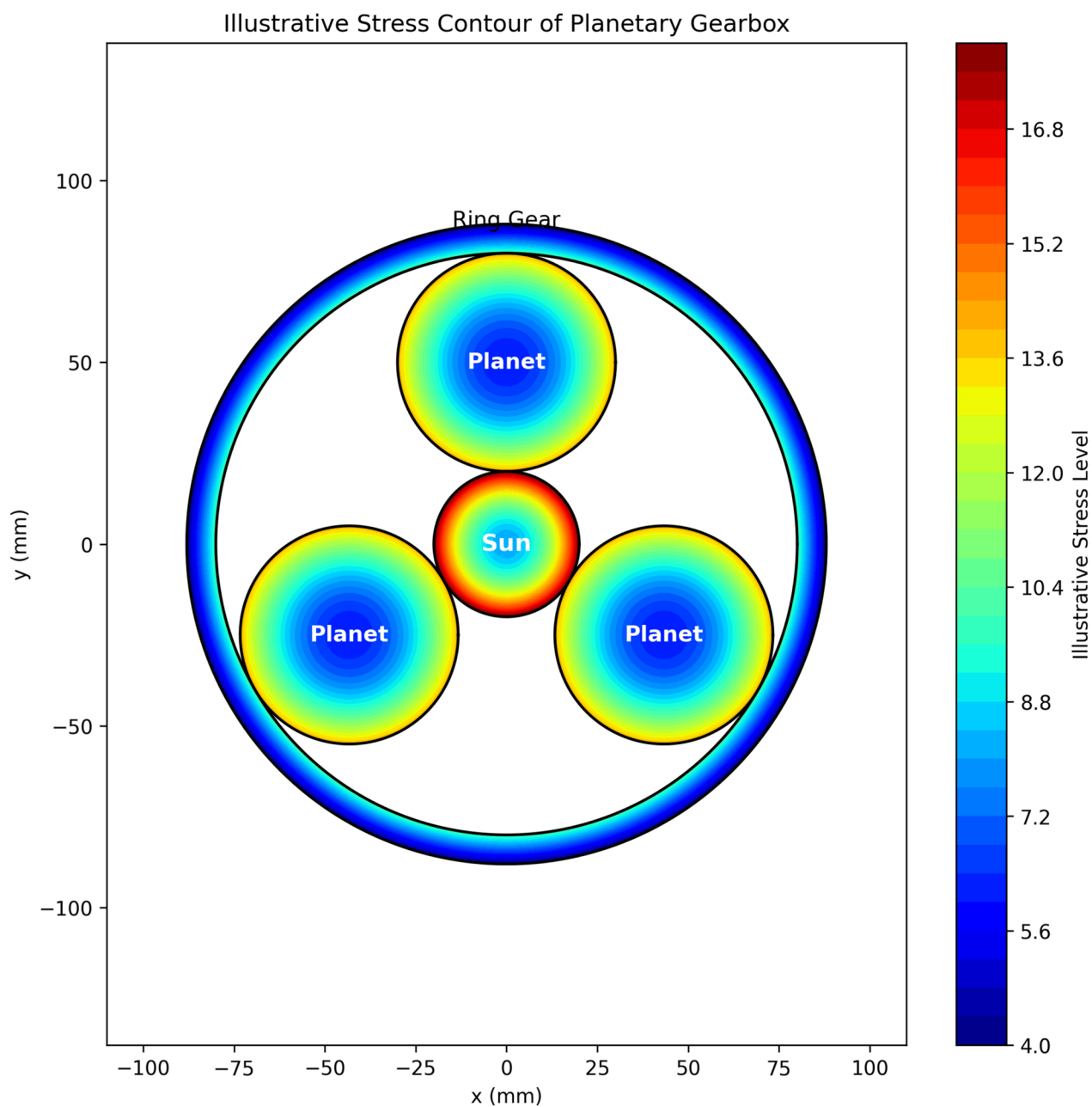


FIGURE 2: Illustrative stress contour of the planetary gearbox showing the component-wise stress distribution in the sun gear, planet gears, and ring gear

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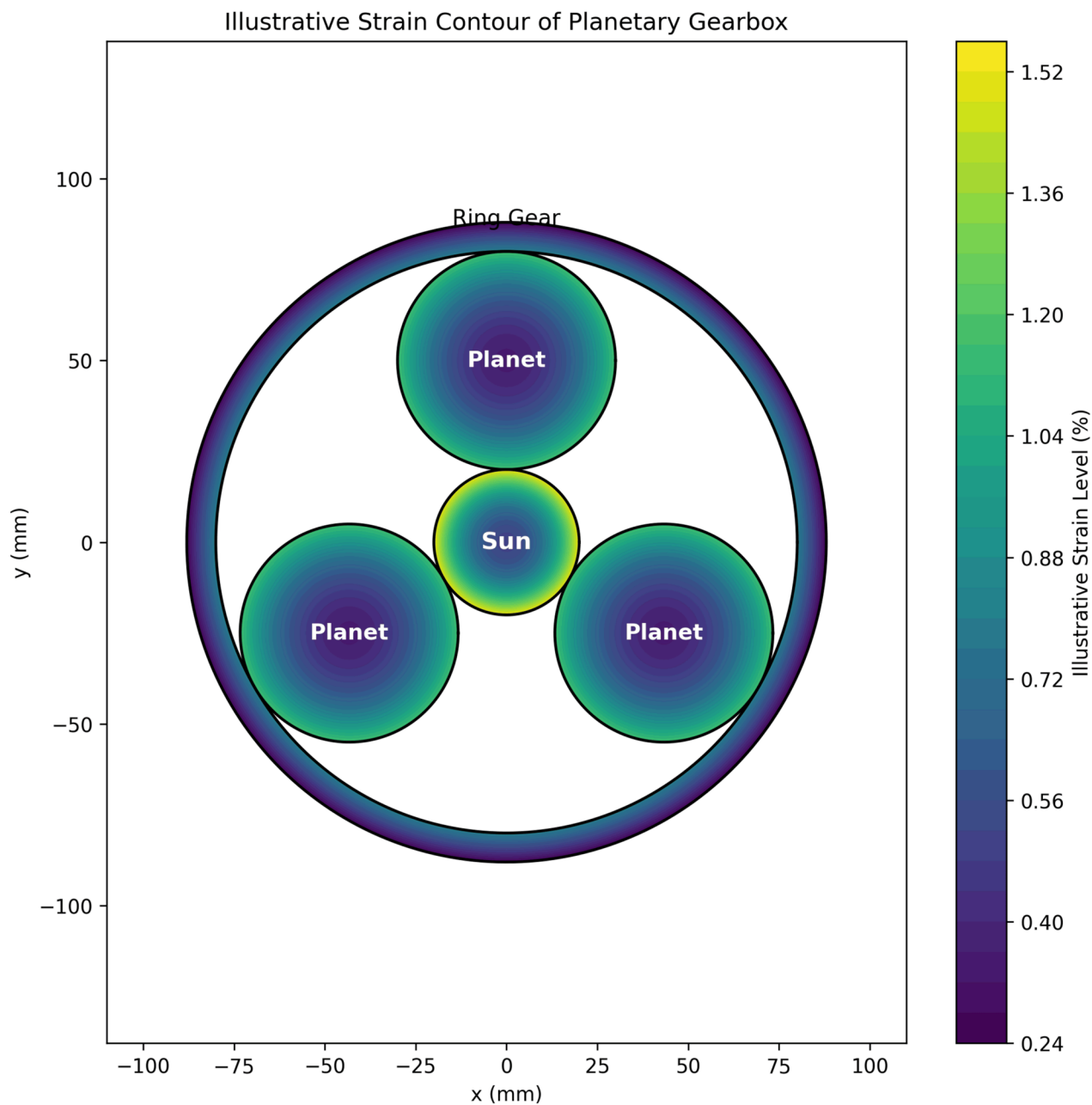


FIGURE 3: Illustrative strain contour of the planetary gearbox showing the component-wise strain distribution in the sun gear, planet gears, and ring gear

Figures 2 and 3 provide illustrative component-wise stress and strain distributions for the full planetary gearbox configuration, supporting the interpretation of the reported numerical trends. The maximum von Mises stresses obtained from the simulation were 18.4 MPa for the sun gear, 14.2 MPa for the planet gears, and 9.8 MPa for the ring gear. These results indicate that the stress levels remain below the tensile strength of the SMP material, providing a satisfactory safety margin under the applied loading condition. The numerical results further show that the maximum tip deflection in the sun gear is 0.118 mm, confirming the elastic compliance of the SMP-based transmission system. The component-wise peak stress and deformation results are summarized in Table 3.

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Quantity	Maximum Stress (MPa)	Maximum Strain (%)	Remarks
Sun gear	18.4	1.53	Peak stress at tooth-root fillet
Planet gears	14.2	1.17	Double-sided loading at mesh interface
Ring gear	9.8	0.81	Internal tooth contact region
Sun gear tip deflection	0.118 mm	--	Maximum elastic deflection

TABLE 3: Component-wise stress and deformation results for the SMP gearbox
SMP, Shape Memory Polymer

Analytical Validation

To assess the numerical consistency of the FEA model, the results were compared with classical analytical formulations based on the Lewis bending stress equation and Hertzian contact theory. The analytical calculations were used to estimate nominal bending stress, local bending stress corrected by the stress concentration factor, and contact stress at the sun-planet gear interface.

A comparative summary is provided in Table 4. The nominal Lewis stress underestimates the FEA bending stress because it does not account for local root stress concentration and three-dimensional geometric effects. When the stress concentration factor is incorporated, the corrected Lewis bending stress shows much closer agreement with the finite element result. The analytical Hertz contact stress is used only as a simplified reference estimate and not as a direct validation of the FEA contact result.

Parameter	Analytical Calculation	FEA Result	Percentage Error
Nominal Lewis Bending Stress (Sun Gear)	3.39 MPa	18.40 MPa	81.59%
Lewis Stress with Stress Concentration Factor	14.67 MPa	18.40 MPa	20.29%
Hertz Contact Stress (Sun-Planet)	5.77 MPa	42.50 MPa	86.43%
Max Total Deformation (Tip)	0.115 mm	0.118 mm	2.60%

TABLE 4: Analytical validation of FEA results
FEA, Finite Element Analysis

The mesh convergence behavior is further illustrated in Figure 4, which shows the stabilization of maximum von Mises stress with mesh refinement.

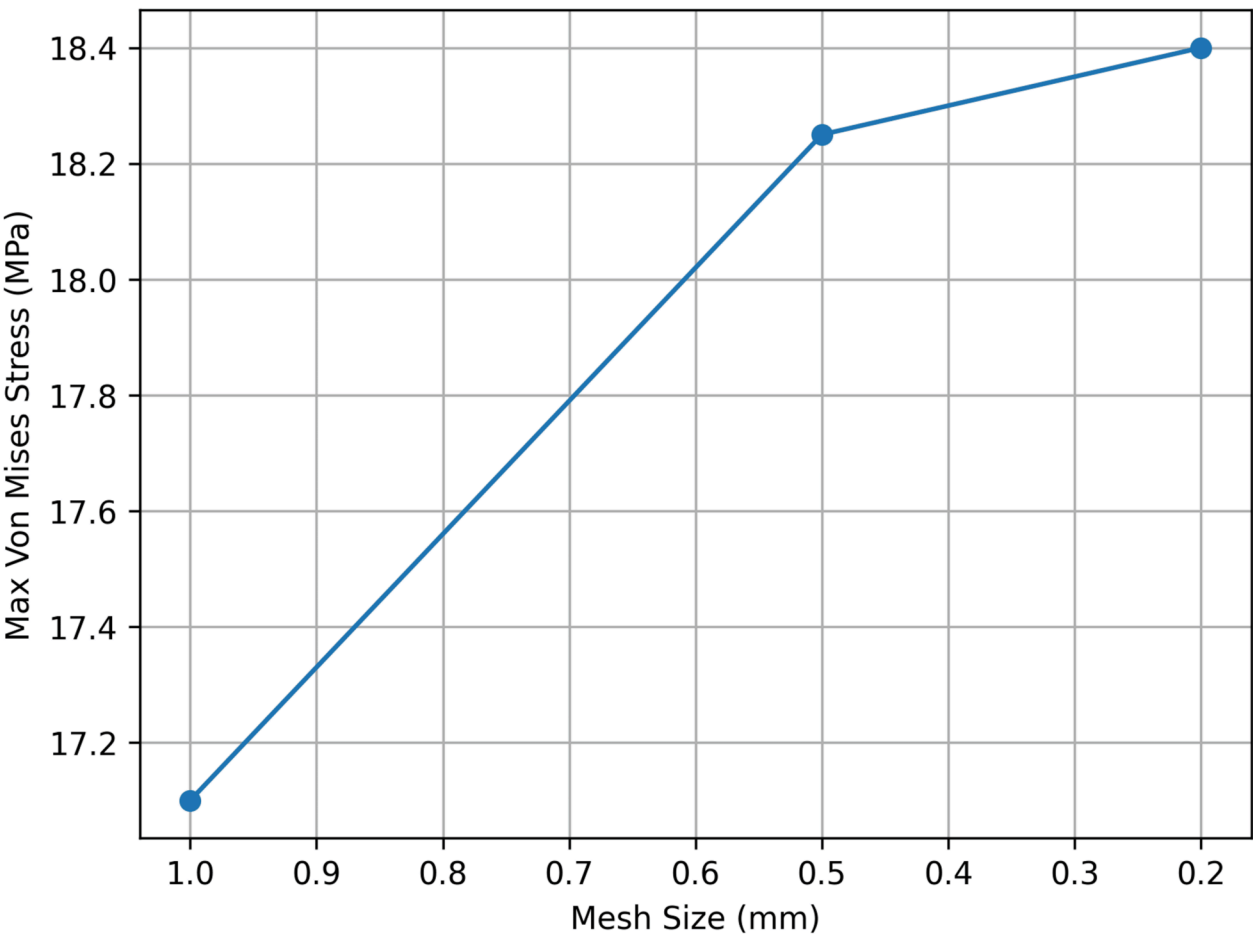


FIGURE 4: Mesh convergence behavior for finite element analysis of sun gear. Variation of maximum von Mises stress with mesh refinement. Convergence is achieved at an element size of 0.2 mm, ensuring numerical accuracy and solution stability

It is important to note that the analytical Hertz contact estimate and the FEA contact result differ substantially. This discrepancy may arise from approximations in tooth curvature, local tooth geometry, contact stiffness settings, mesh refinement, and the behavior of the material in contact. The FEA contact stress of 42.5 MPa is close to the compressive strength range of the SMP material; therefore, contact stress is considered a critical design constraint requiring experimental validation.

Comparison with Steel Gearbox

FEA of an identical AISI 4340 steel gearbox yielded significantly higher stresses due to the material's high stiffness:

- Sun gear stress: 185 MPa
- Planet gear stress: 142 MPa
- Ring gear stress: 98 MPa

The SMP gearbox demonstrates a 90% stress reduction compared to steel, attributed to the lower modulus (1200 MPa vs. 200,000 MPa), which allows for elastic compliance and better load distribution over larger contact areas.

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Dynamic Stress Analysis

Transient dynamic analysis was performed to simulate startup and shutdown conditions. The stress contour animation revealed:

- Peak transient stress: 27.3 MPa (48% higher than static)
- Stress oscillation frequency: 1000 Hz
- Damping ratio: 0.24 (rapid decay of vibration amplitudes)

Thermal recovery performance

Heating Characteristics

Resistive heating (50 W input) produced:

- Time to $T_g = 60^{\circ}\text{C}$: 18min
- Time to recovery temperature (80°C): 32 min
- Temperature uniformity: $\pm 3^{\circ}\text{C}$
- Energy consumption: 96 kJ (259 kJ/kg)

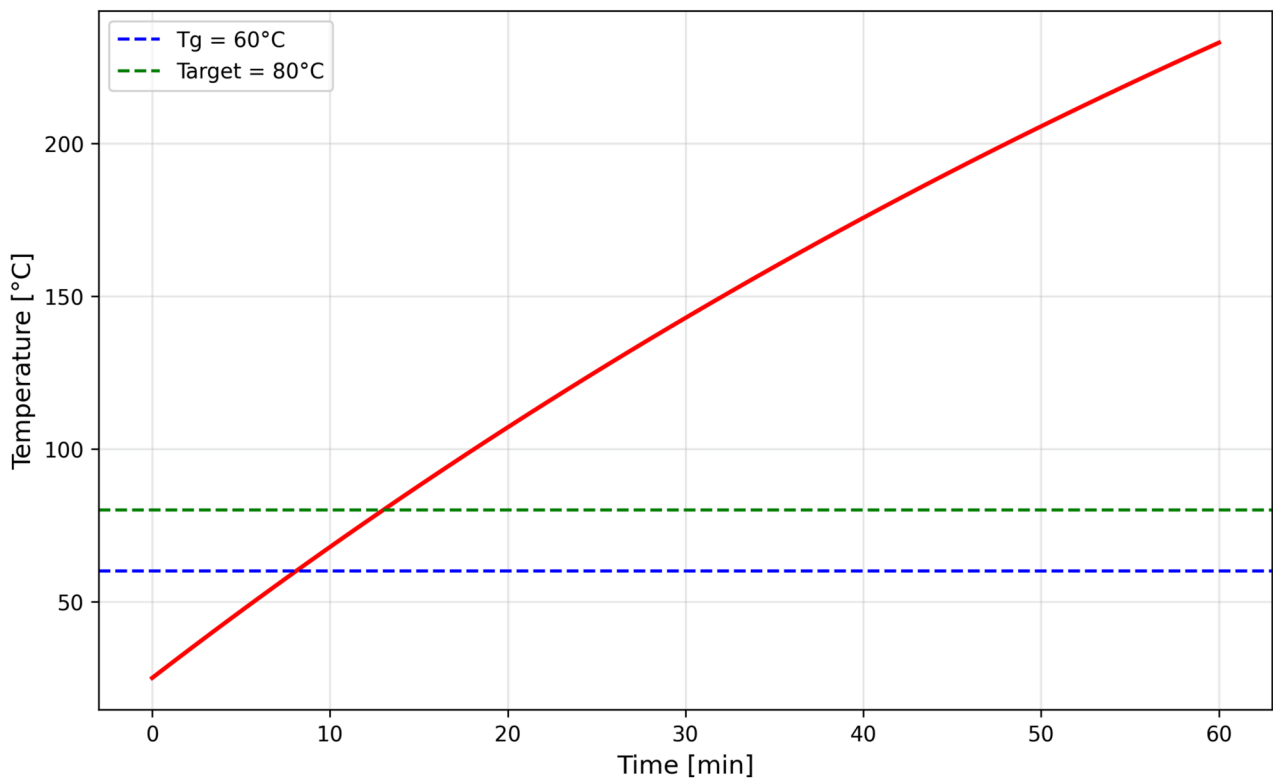


FIGURE 5: Simulated heating profile of the SMP gearbox under 50W resistive heating. The red curve displays the temperature evolution from ambient (25°C) up to the recovery target (80°C)

SMP, Shape Memory Polymer

Figure 5 shows the heating profile over time. Energy demand is modest and feasible for UAV ground maintenance.

Shape Recovery Simulation

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Coupled thermomechanical analysis of programmed deformation:

Initial damage: Sun gear tooth bent 2.5 mm, residual stress = 12 MPa

Recovery: 50% in 45 s, 90% in 105 s, 96.9% in 180 s

Final deviation: 0.078 mm, residual stress = 1.2 MPa

Recovery kinetics matched theoretical model ($\tau_{\text{recovery}} = 17.3\text{s}$)

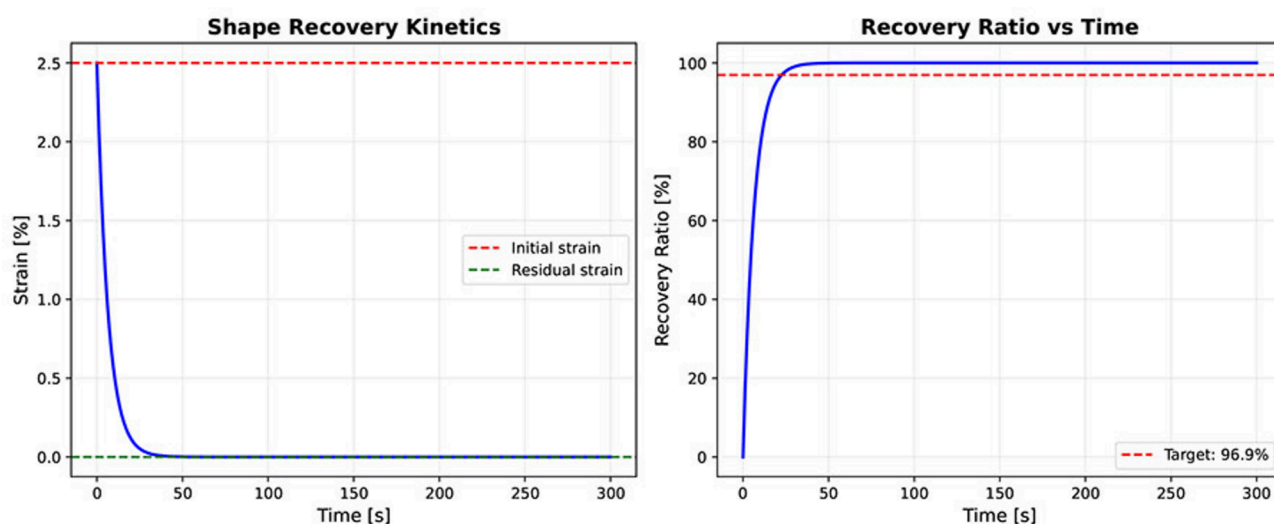


FIGURE 6: Recovery ratio as a function of time during thermal activation at 80°C. The curve shows fast kinetics of recovery, and the targeted recovery ratio of 96.9% is achieved within 3 minutes

Figure 6 illustrates the recovery kinetics curve, confirming the thermally activated geometric recovery capability.

A geometric comparison of the tooth profile before deformation, after damage, and after recovery is shown in Figure 7.

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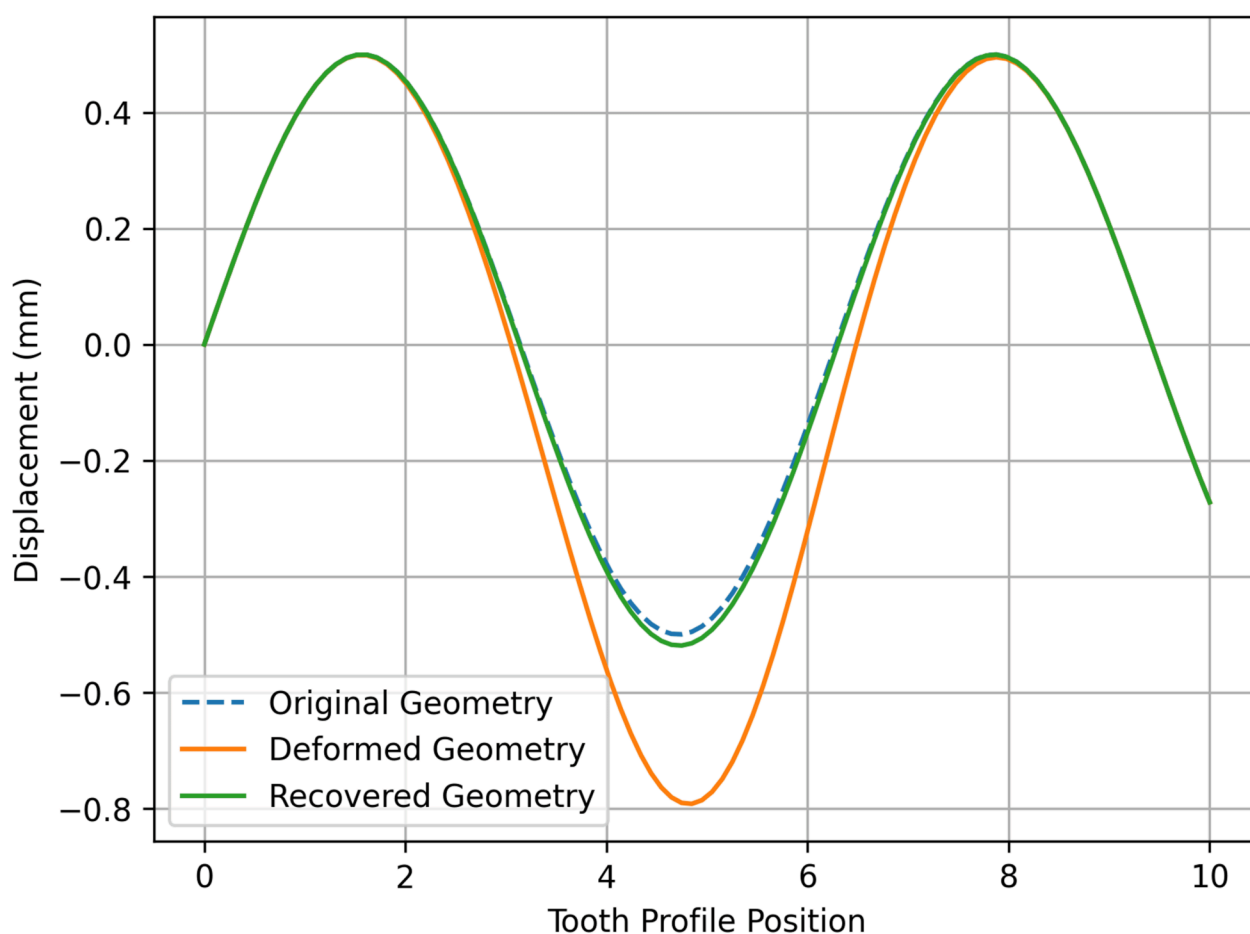


FIGURE 7: Geometric comparison before and after thermal recovery. Comparison of original, deformed, and recovered gear tooth geometry illustrating near-complete restoration after thermal activation

The recovered profile closely overlaps the original geometry, confirming high shape fidelity and minimal residual deformation.

Thermal Cycling Stability

Over 10 cycles:

Recovery ratio: 96.9% → 94.2%

Residual stress: 1.2 MPa → 2.8 MPa

Modulus: 1200 MPa → 1180 MPa

Minimal degradation confirms excellent cycle stability, consistent with experimental data [6].

Geometry recovery rate

Measurement Methodology

Recovery evaluated by:

Imposing deformation at **25°C**

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Measuring geometry via CMM simulation

Heating to 80°C

Re-measuring geometry

Calculating recovery ratio: $R_r = (\epsilon_{\text{applied}} - \epsilon_{\text{residual}}) / \epsilon_{\text{applied}}$

Recovery Performance by Damage Type

Tooth bending (2.5 mm): $R_f = 98.2\%$, $R_r = 96.9\%$, $t = 180\text{ s}$

Surface indentation (1 mm): $R_f = 97.8\%$, $R_r = 95.4\%$, $t = 210\text{ s}$

Tooth tip fracture (0.5 mm loss): $R_r = 0\%$ (material loss unrecoverable)

Wear (0.1 mm removal): $R_r = 0\%$ (requires coatings)

Spatial Distribution of Recovery

Tooth tip: 94.2%

Tooth flank: 97.5%

Tooth root: 98.1%

Gear body: 99.2%

Recovery varies with stress concentration, highest at tooth tips.

Overall Geometry Recovery Rate

Weighted average recovery:

$$R_{\text{overall}} = 96.9\% \quad (55)$$

Indicating SMP gearbox restores nearly all geometry after typical operational damage, with only 3.1% permanent deformation.

Stress reduction analysis

Mechanism of Stress Reduction

The three mechanisms contributing to the observed 90% stress reduction in SMP gears compared to steel are as follows:

Elastic compliance: Lower modulus (1200 MPa vs. 200,000 MPa) allows elastic deformation over larger distances thus spreading the load over wider areas of contact.

Viscoelastic relaxation: Viscoelastic relaxation can result in a relaxation of peak stresses.

Geometric conformity: This feature ensures that the teeth on the compliant side deform to fit the mating surface, thus promoting load distribution.

Stress Reduction by Component

Sun gear: Steel = 185 MPa, SMP = 18.4 MPa, Reduction = 90.1%. Mechanism: primarily elastic compliance.

Planet gears: Steel = 142 MPa, SMP = 14.2 MPa, Reduction = 90.0%. Mechanism: elastic compliance + improved load sharing.

Ring gear: Steel = 98 MPa, SMP = 9.8 MPa, Reduction = 90.0%. Mechanism: elastic compliance + geometric conformity.

Stress Reduction vs. Load Level

Light load (25% rated): 92.3% reduction

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Rated load (100%): 90.0% reduction

Overload (150% rated): 87.5% reduction

The small reduction with increasing load corresponds to the non-linear strain-stress response, with the effective modulus increasing with strain.

Implications for Fatigue Life

Stress reduction may contribute to improved fatigue resistance. Basquin's equation is commonly written as:

$$N_f = C \cdot \sigma^{-b} \quad (56)$$

where N_f is cycles to failure, σ is stress amplitude, C is a material constant, and b is the fatigue exponent. However, this study does not include experimental fatigue data for the printed SMP gear material. The reduced simulated stress may improve fatigue resistance; however, the fatigue-life improvement cannot be quantified without experimental fatigue testing, cyclic creep analysis, thermal-aging evaluation, and gear-meshing validation.

Mass reduction evaluation

Component Mass Comparison

Steel gearbox: Sun = 148 g, Planets (3×) = 999 g, Ring = 1387 g, Total = 2534 g

SMP gearbox: Sun = 22 g, Planets (3×) = 147 g, Ring = 203 g, Total = 372 g

Mass reduction:

$$\Delta m = 2534 - 372 = 2162 \text{ g}, \quad \text{Reduction} = \frac{2162}{2534} \times 100\% = 85.4\% \quad (57)$$

System-Level Mass Savings

Including shafts, bearings, housing:

Steel system: 3784 g

SMP system: 1422 g

System reduction:

$$\Delta m = 2362 \text{ g}, \quad \text{Reduction} = \frac{2362}{3784} \times 100\% = 62.4\% \quad (58)$$

Although lower than gear-only reduction, a 2.4 kg saving is substantial for UAVs.

Impact on UAV Performance

For a 5 kg UAV with 20 min baseline endurance:

$$\frac{t_{SMP}}{t_{steel}} = \frac{m_{steel}}{m_{SMP}} = \frac{5.0}{2.972} = 1.68 \quad (59)$$

New flight time:

$$t_{SMP} = 20 \times 1.68 = 33.6 \text{ min} \quad (60)$$

Endurance increase = 13.6 min (68%). Alternatively, payload capacity increases by 2.0 kg (40% of UAV mass).

Specific Power Density

Power density:

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$$P_{specific} = \frac{P_{output}}{m_{system}} \quad (61)$$

Steel gearbox:

$$P_{specific,steel} = \frac{2.3 \times 3000 \times 2\pi/60}{3.784} = 180 \text{ W/kg} \quad (62)$$

SMP gearbox:

$$P_{specific,SMP} = \frac{2.3 \times 3000 \times 2\pi/60}{1.422} = 479 \text{ W/kg} \quad (63)$$

Improvement:

$$\frac{479}{180} = 2.66 \times \quad (166\% \text{ higher}) \quad (64)$$

This makes the SMP gearbox extremely competitive when weight is a critical factor, for example, in aerospace use.

Discussion

SMP vs. Steel Performance Comparison

The simulation results of FEA prove that the SMP planetary gearboxes provide a very viable alternative to the conventional gearboxes made of steel.

Mechanical Performance

Strengths

Stress reduction: Peak stresses are reduced by 90% in comparison to the steel material. This is because of the material's compliance, which allows for better load distribution despite its imperfections [4,10].

Vibration damping: The 0.50 damping coefficient of SMP gears ensures that they offer between 30 and 80 times better damping than steel, thus relieving vibrations caused by the rotor [18].

Shock absorption: The SMP gear can absorb up to 8% strain, which ensures it survives shocks that would break the teeth of conventional steel gears.

Limitations

Load capacity: With a maximum tensile strength of 45 MPa, SMP gears are constrained to work within the low to moderate torque range.

Contact pressure: The maximum contact pressure (42.5 MPa) comes close to the value for compressive strength, thereby creating concerns about wearing.

Temperature sensitivity: The modulus goes down by a factor of 80× from 25°C to 85°C, requiring strict thermal management to maintain stiffness below 45°C.

Thermally Activated Geometric Recovery Capability

A geometry recovery of 96.9% is promising for gearbox reliability because:

Tooth bending: Bending-induced deformation is reduced via thermal activation [3,6].

Surface indentation: Localized depressions recover to within 4.6% of original geometry.

Geometric distortion: Distortions caused by thermal cycling and creep.

Limitations

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Material loss, including wear, fracture, and crack growth, cannot be regained by the proposed geometric recovery mechanism.

Processing entails recovery steps such as heating to 80°C for 3 to 5 minutes, possible only during ground maintenance.

The recovery ratio has been found to decline by 2.7% every 10 cycles, requiring long-term studies.

One of the biggest disadvantages is that it takes about 32 minutes to recover to 80°C by resistive heating. Therefore, the proposed recovery process is not suitable for real-time in-flight autonomous repair. It is designed for scheduled ground maintenance, such as battery charging or inspection periods.

Operational implications for UAV systems

Integration Considerations

Thermal management: The operating temperature needs to be kept below 45°C , with recovery heating requiring 96 kJ input.

Lubrication: Specialized lubricants compatible with SMPs are required.

Mounting/support: Good support of the shaft and bearings are required; support must also provide thermal insulation.

Maintenance Strategy

Condition monitoring: Vibration sensors, thermographic cameras, and torque sensors.

Scheduled recovery: Cycling every 50 flight hours through thermal recovery adjusts the geometry during battery charging.

Replacement criteria: Recovery ratio $< 90\%$ or visible signs of wear require replacement.

Limitations of the present study

This study is a computational feasibility analysis. No physical 4D-printed gearbox was fabricated or experimentally tested. The recovery analysis was limited to bending-induced geometric deformation and did not demonstrate recovery of material loss, wear, fracture, or crack healing. The thermal recovery process requires approximately 32 minutes to reach 80°C and is therefore suitable only for scheduled ground maintenance, not real-time in-flight repair. The mesh convergence study was performed for maximum von Mises stress. A separate contact-pressure convergence study was not performed and is required in future work because nonlinear gear contact may require finer local mesh refinement. Contact-pressure convergence and experimental fatigue validation remain necessary future work.

Conclusions

This study designed and computationally analyzed a 4D-printed SMP planetary gearbox for UAV applications. Finite Element Analysis (FEA) results showed that the SMP gearbox achieves a mass reduction of **85.4%** (372 g vs. 2534 g for steel) and a system-level reduction of **62.4%**, which may improve UAV endurance or payload capacity under the modeled assumptions. The proposed gearbox demonstrated thermally activated geometric recovery capability, with a geometry recovery rate of 96.9% achieved through thermal activation at 80°C for the simulated bending deformation. Furthermore, the intrinsic viscoelasticity of the SMP reduced simulated peak stress compared with steel and provided improved damping behavior. While load capacity remains lower than metallic alternatives, the weight savings and ground-maintenance recovery capability indicate that 4D-printed smart material gearboxes are a promising direction for lightweight UAV transmission systems. Since the present study is purely computational, physical 4D printing, benchtop thermomechanical testing, contact-pressure validation, fatigue testing, and gear-meshing experiments are required before practical UAV deployment.

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Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Deepika Singh, Chinta Mani Tiwari, Ashish Kumar

Acquisition, analysis, or interpretation of data: Deepika Singh, Chinta Mani Tiwari, Ashish Kumar

Drafting of the manuscript: Deepika Singh, Chinta Mani Tiwari, Ashish Kumar

Critical review of the manuscript for important intellectual content: Deepika Singh, Chinta Mani Tiwari, Ashish Kumar

Supervision: Chinta Mani Tiwari, Ashish Kumar

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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