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Conversion of Electromagnetic Force to Gravity in Curvature Engine Spacecraft

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Abstract

This paper presents a novel theoretical framework that bridges electromagnetic and gravitational fields through generalized gauge transformations. The author demonstrates how curvature tensor components, such as the antisymmetric Weyl tensor, can be derived from the electromagnetic antisymmetric tensor, offering a new perspective on the interaction between these fields. A systematic method for converting electromagnetic force into gravitational force is proposed, utilizing the theory of generalized gauge transformations. By regulating the Weyl tensor with electromagnetic fields, the need for negative curvature is circumvented, representing a significant advancement in curvature engine-type spacecraft theories. While current technology does not yet enable realization of this concept, the approach holds considerable potential for both theoretical and technological progress. Key insights include the direct conversion of electromagnetic fields into gravity via generalized gauge equations, the possibility of creating differential curvature for superluminal travel, and the potential for future advancements in electromagnetic control of spacetime curvature. This work may lay the groundwork for further exploration of engine technologies and human interstellar flight, with a focus on powerful electromagnetic field generation, nonlinear electromagnetic and gravitational field models, and precise control of the Weyl tensor.

Keywords

Grand Unification of Physics, Generalized Gauge Transformation, The Weyl Tensor, The Electromagnetic Antisymmetric Tensor, The Curvature Engine-Type Spacecrafts

1. Introduction

The interplay between electromagnetism and gravitation has long been a topic of profound interest in both theoretical and experimental physics. Electromagnetic fields, as carriers of energy and momentum, are inherently coupled to spacetime geometry through Einstein's field equations in the framework of General Relativity. This coupling raises an intriguing possibility: under extreme conditions, can electromagnetic fields induce significant gravitational effects, or perhaps mimic the behavior of gravitational sources? Recent theoretical developments and experimental advancements suggest this question is not merely speculative, but one grounded in physical principles and observable phenomena.

Electromagnetic fields contribute to spacetime curvature through their energy-momentum tensor, given by:

$$T_{\mu\nu}^{EM} = \frac{1}{\mu_0}\left(F_{\mu\lambda}F_{\nu\lambda} - \frac{1}{4}g_{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}\right) \tag{1}$$

where $F_{\mu\nu}$ is the electromagnetic field tensor, μ_0 is the vacuum permeability, and $g_{\mu\nu}$ is the metric tensor of spacetime. Substituting this tensor into the Einstein field equations,

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}^{EM} \tag{2}$$

reveals how the energy density and momentum density of an electromagnetic field generate spacetime curvature [1] [2]. While the gravitational effects of ordinary electromagnetic fields are negligible in most practical scenarios, extreme conditions such as those near neutron stars or black holes, or in laboratory-created high-intensity laser fields, can magnify these effects to measurable levels [3] [4].

Electromagnetic fields may influence spacetime geometry not only through direct energy-momentum coupling but also via dynamic processes. Rapidly varying fields, such as electromagnetic waves or intense laser pulses, can excite spacetime perturbations and even generate gravitational waves under specific conditions. These mechanisms are particularly relevant in high-energy astrophysical events, such as gamma-ray bursts or black hole mergers, where the coupling of electromagnetic and gravitational phenomena plays a crucial role [5] [6].

Furthermore, theoretical frameworks such as the Kaluza-Klein theory provide a geometric interpretation of the electromagnetic field as a manifestation of higher-dimensional gravity. This approach offers a unified perspective on the interaction between electromagnetic and gravitational fields, suggesting that, under certain conditions, electromagnetic phenomena may be regarded as a special form of gravitational effects in an extended spacetime [7] [8].

Despite the inherent differences between electromagnetism and gravitation—being a vector and tensor field, respectively—their mathematical and physical similarities have inspired a wealth of research on their interplay. For instance, the analogy between Maxwell's equations and linearized gravity highlights the potential for electromagnetic fields to mimic gravitational phenomena under specific conditions [9] [10].

These works explored the mechanisms through which electromagnetic fields can influence, mimic, or even partially convert into gravitational effects. It examines the role of extreme electromagnetic fields in generating spacetime curvature, the conditions under which dynamic electromagnetic fields can excite gravitational waves, and the implications of unified field theories that link electromagnetism and gravitation.

Beyond the classical framework, recent theoretical explorations have extended the scope of photon-graviton interactions into quantum field theory and extreme energy conditions. These studies investigate the possibility of converting electromagnetic forces, mediated by photons, into gravitational interactions, mediated by gravitons. Despite the profound differences between photons and gravitons, such as spin and interaction mechanisms, theoretical models suggest that under extreme conditions, such a conversion is not only theoretically plausible but also potentially significant for understanding the quantum-gravitational regime.

One potential mechanism for photon-to-graviton conversion lies in the nonlinear interactions inherent in quantum field theory. Photons, being spin-1 particles described by vector fields, can interact through quantum fluctuations or higher-order effects such as vacuum polarization. At extremely high energies, photon-photon interactions could form transient composite states, which might correspond to the excitation of gravitational perturbations, such as gravitational waves or even gravitons. These processes often involve high-order corrections in quantum electrodynamics (QED) or the introduction of effective field theory corrections. For instance, box diagrams in quantum field theory, which account for higher-order photon-photon interactions, suggest the possibility of inducing weak gravitational effects in extreme electromagnetic fields [11] [12].

Another promising avenue involves entangled photon pairs, which exhibit unique quantum properties such as nonlocality. When propagating in a strong gravitational background, these entangled states may interact with the spacetime fabric in nontrivial ways, potentially triggering gravitational perturbations. In frameworks such as quantum gravity or the AdS/CFT correspondence, entangled states might serve as a bridge between electromagnetic and gravitational phenomena. For instance, entangled photon pairs in highly curved spacetime could generate gravitons or gravitational waves through vacuum fluctuations and virtual particle creation [13] [14]. While this approach is still highly speculative, it provides a conceptual basis for linking quantum entanglement and spacetime curvature.

High-energy environments, such as those near black holes or neutron stars, may naturally facilitate the conversion of photons into gravitons. In particular, the strong electromagnetic and gravitational fields in such regions could amplify photon interactions, resulting in gravitational wave emission. Additionally, laboratory experiments using ultra-high-intensity lasers or future high-energy particle colliders might offer a controlled setting to test these mechanisms. For example, experiments involving photon-photon scattering at unprecedented energy scales could shed light on the feasibility of photon-graviton conversion [15] [16].

In the context of string theory, photons and gravitons are naturally related as different vibrational states of the same fundamental string. Photons correspond to open string modes, while gravitons arise from closed string vibrations. This inherent relationship implies that photon-to-graviton conversion could occur through string dynamics, such as open strings forming closed string loops. Additionally, D-brane dynamics in string theory may offer further insights into how photon-graviton interactions could be facilitated in higher-dimensional settings. Although string theory operates at energy scales far beyond current experimental reach, it provides a unified theoretical framework for understanding the electromagnetic-gravitational connection [17] [18].

Gauge invariance plays a central role in constraining the forms of interaction between electromagnetic and gravitational fields. In standard electromagnetism, the U (1) gauge symmetry governs the behavior of photons, while gravitational fields are described by diffeomorphism invariance in general relativity. Effective field theory (EFT) approaches introduce high-order correction terms that respect these symmetries, such as coupling terms involving the electromagnetic tensor $F_{\mu\nu}$ and the Ricci curvature tensor $R_{\mu\nu}$. For instance, terms like $R_{\mu\nu}F^{\mu\lambda}F_{\nu}^{\lambda}$ describe photon-gravitational field interactions and provide a framework for studying photon-to-graviton conversion under extreme conditions [19] [20].

Despite these theoretical advances, the direct detection of photon-to-graviton conversion remains an extraordinary challenge. The coupling between photons and gravitons is expected to be exceptionally weak, governed by the Planck scale ($M_{pl} \sim 10^{19}$ GeV). Achieving the energy and precision required to observe such interactions is currently beyond the reach of experimental physics. Nevertheless, advances in gravitational wave detectors (e.g., LIGO/VIRGO) and high-energy astrophysical observations, such as gamma-ray bursts or black hole mergers, may offer indirect evidence of these interactions in extreme cosmic environments.

Recently, the author published a series of five papers proposing a generalized gauge transformation framework based on the principal bundle and associated bundle manifold, which enables direct conversion between electromagnetic and gravitational interactions [21]-[25]. The author posits that electromagnetic force, gravity, and even the strong and weak fundamental interactions are essentially projections of the gauge potentials or curvatures of a principal fiber bundle onto the base manifold of our universe. These components can be interconverted through generalized gauge transformations. From this perspective, electromagnetic force can be directly transformed into gravity via such transformations.

In this research, the author will formulate a generalized formulation, demonstrating that curvature tensor components, such as the antisymmetric Weyl tensor, can be derived from the electromagnetic antisymmetric tensor through a generalized gauge similarity transformation. The paper further explores the application of this formulation and the potential corresponding physical processes, providing a novel theoretical framework for large-scale conversion between electromagnetic and gravitational fields, as well as their mutual interaction. Through these discussions, the author aims to provide a comprehensive perspective on the potential for electromagnetic fields to induce gravitational effects and their significance in both theoretical and experimental contexts.

The following text is divided into 9 sections. Section 2 discusses the four forms of the generalized gauge equation; Section 3 focuses on how to use the generalized gauge similarity transformation to convert the electromagnetic antisymmetric tensor into spatial curvature; Section 4 extends this discussion, demonstrating how the electromagnetic tensor can be transformed into the Weyl tensor through generalized gauge similarity transformations; Section 5 explores how to translate the aforementioned electromagnetic forces into gravitational effects and examines the potential applications of this transformation in curvature engine spacecraft, providing a comprehensive discussion on the theoretical and technological possibilities and prospects. In Section 6, a mathematical construction of Weyl Tensor control in warp Drive is given. In Section 7, the reason why our scheme avoids exotic matter has been analyzed and discussed. In Section 8, the potential feasibility and challenges are studied. Finally, in Section 9, summary and future research expectations are described.

2. Generalized Gauge Transformation

We have proposed the generalized gauge transformations that can span fundamental interactions [21]-[25], several forms of which can be expressed by the following generalized gauge equations for the connection or curvature [26], respectively.

In facts, there are three definitions of the connection between the principal bundle, namely the horizontal subspace H_p of the tangent vector at each point $p \in P$ of the principal bundle that satisfies a certain conditions, or the 1-form field $\tilde{\boldsymbol{\omega}}$ of a C^∞ Lie algebra value on the principal bundle P that satisfies a certain conditions, or in the bottom manifold, that is, the 1-form field $\boldsymbol{\omega}_U$ of a C^∞ Lie algebra $\mathcal{G}$ value on U specified by each local trivial T_U in our universe. If T_V is another local trivial, $U \cap V \neq \varnothing$, and the conversion function from T_U to T_V is g_{UV}, then the generalized gauge equation holds for both the cross basic gauge transformation and the basic gauge transformation:

$$\boldsymbol{\omega}_V\left(Y\right) = \mathcal{A}d_{g_{UV}(x)^{-1}}\boldsymbol{\omega}_U\left(Y\right) + L^{-1}_{g_{UV}(x)*}g_{UV*}\left(Y\right),\ \forall x \in U \cap V, Y \in T_x M \tag{3}$$

where $L^{-1}_{g_{UV}(x)}$ is the inverse mapping of left translation $L_{g_{UV}(x)}$ generated by $g_{UV}\left(x\right) \in G$, $L^{-1}_{g_{UV}(x)*} \equiv \left(L^{-1}_{g_{UV}(x)}\right)_*$, and $\mathcal{A}d_{g^{-1}_{UV}}$ is defined as a linear transformation on the Lie algebra of the structure group G, *i.e.* $\mathcal{A}d_g \equiv I_{g*e}$, $I_g\left(h\right) \equiv ghg^{-1}$, $\forall h \in G$, hence I_{g*e} is a mapping from V_e (the vector space of the unit element e of group G) to V_e, so $\mathcal{A}d_g : \mathcal{G} \to \mathcal{G}$ is a linear transformation on Lie algebra $\mathcal{G}$.

Furthermore, it can be proven that if the structural group G is a matrix group, then the generalized gauge Equation (3) can be simplified as follows:

$$\boldsymbol{\omega}_V = g^{-1}_{UV}\boldsymbol{\omega}_U g_{UV} + g^{-1}_{UV}\boldsymbol{d}g_{UV} \tag{4}$$

where $\boldsymbol{d}$ is defined as the exterior differential of g_{UV}.

The principal bundle structure composed of the structure group, principal bundle manifold, and base manifold has a principal bundle section as the gauge potential, a curvature as the gauge field strength, and satisfies the curvature gauge transformation relation between two different regions U and V. For example, in general, if $g_{UV}: U \cap V \to G$ is a local trivial conversion function from T_U to T_V, $\boldsymbol{\Omega}_V$ and $\boldsymbol{\Omega}_U$ are the curvatures of the bottom manifold in the V region or the U region, respectively, then on the base manifold $U \cap V$ has

$$\boldsymbol{\Omega}_V = \mathcal{A}d_{g_{UV}^{-1}} \boldsymbol{\Omega}_U \tag{5}$$

If the structure group is a matrix group, then Equation (5) can be further expressed as:

$$\boldsymbol{\Omega}_V = g_{UV}^{-1} \boldsymbol{\Omega}_U g_{UV} \tag{6}$$

Therefore, under the cross-sectional transformation σ, on the bottom manifold (*i.e.* the world we assume), $\boldsymbol{\omega}_U \to \boldsymbol{\omega}_V$ holds, that is, Equation (3) holds, and here g_{UV}^{-1} and g_{UV} are related by a gauge transformation.

Further, it can be proved that Equation (4) is equivalent to the following similarity transformation Equation (7) [22], namely, the following similar transformations are equivalent:

$$\boldsymbol{\Omega}_V = g_{UV}^{-1} \boldsymbol{\Omega}_U g_{UV} \Leftrightarrow \hat{F}'_{\mu\nu} = W^{-1} \hat{F}_{\mu\nu} W \tag{7}$$

where $\hat{F}'_{\mu\nu}$ is defined as the gravitational gauge field strength in region V on the bottom manifold; and $\hat{F}_{\mu\nu}$ is defined as the electromagnetic gauge field strength in region U on the base manifold. W^{-1} and W can be regarded as the matrix expression of a certain gauge transformation. The author suggests calling it a generalized gauge similarity transformation.

In fact, from the above formula (3) and (5), and then use the basis $\{e_r\}$ to expand the connection $\boldsymbol{\omega}$ and the curvature $\boldsymbol{\Omega}$ on the bottom manifold as $\boldsymbol{\omega} = e_r \boldsymbol{\omega}^r$ and $\boldsymbol{\Omega} = e_r \boldsymbol{\Omega}^r$ respectively, then $\boldsymbol{\omega}^r$ and $\boldsymbol{\Omega}^r$ are the (real-valued) 1-form and 2-form fields on the region U, respectively. Then ω^r_μ and $\Omega^r_{\mu\nu}$ represent the components of $\boldsymbol{\omega}^r$ and $\boldsymbol{\Omega}^r$ in the coordinate basis $\left\{\frac{\partial}{\partial x^\mu}\right\}$ in turn:

$$\omega^r_\mu = \boldsymbol{\omega}^r\left(\frac{\partial}{\partial x^\mu}\right) \tag{8}$$

$$\Omega^r_{\mu\nu} = \boldsymbol{\Omega}^r\left(\frac{\partial}{\partial x^\mu}, \frac{\partial}{\partial x^\nu}\right) \tag{9}$$

Then one can find [26]

$$\begin{cases} \omega^r_\mu = kA^r_\mu \\ \Omega^r_{\mu\nu} = kF^r_{\mu\nu} \end{cases} \tag{10}$$

That is, ω^r_μ and $\Omega^r_{\mu\nu}$ is k times of the gauge potential A^r_μ and the gauge field strength $F_{\mu\nu}^{r}$ respectively, so physically, the connection $\boldsymbol{\omega}$ and the curvature $\boldsymbol{\Omega}$ on the bottom manifold can represent the gauge potential and the gauge field strength respectively, so the formula (8) can be deduced which proves that formula (7) is correct, and vice versa. Later we can see that the W corresponding to this conversion function g_{UV} can be the product of different subgroups (for example, $U(1)\times SO(1,3)$), transforming the basic electromagnetic interaction into the basic gravitational interaction, which is the meaning of the gauge transformation becoming a generalized gauge transformation [25].

3. Electromagnetic Force Converted into Gravitational Force

From the above generalized gauge transformation for the grand unified theory, we can know that electromagnetic force can be converted into gravitational force under generalized gauge transformation. Here is an example: we know that the matrix expression of the electromagnetic antisymmetric tensor is:

$$(F_{\mu\nu})=\begin{pmatrix} 0 & -E_1 & -E_2 & -E_3 \\ E_1 & 0 & B_3 & -B_2 \\ E_2 & -B_3 & 0 & B_1 \\ E_3 & B_2 & -B_1 & 0 \end{pmatrix} \tag{11}$$

On the other hand, from the Schwarzschild metric solution of the Einstein equation, we know that there exists a spacetime metric g_{ab} whose line element expression in the coordinate system $\{t,r,\theta,\varphi\}$ is

$$\mathrm{d}s^2=-e^{2A(r)}\mathrm{d}t^2+e^{2B(r)}\mathrm{d}r^2+r^2\left(\mathrm{d}\theta^2+\sin^2\theta\mathrm{d}\varphi^2\right) \tag{12}$$

where $A(r)$ and $B(r)$ are pending functions respectively.

The above coordinate basis is orthogonal but not normalized. After normalizing it, we get the orthogonal normalized coordinate basis:

$$\begin{gathered}(e_0)^a=e^{-A}\left(\frac{\partial}{\partial t}\right)^a,\ (e_1)^a=e^{-B}\left(\frac{\partial}{\partial r}\right)^a \\ (e_2)^a=r^{-1}\left(\frac{\partial}{\partial\theta}\right)^a,\ (e_3)^a=(r\sin\theta)^{-1}\left(\frac{\partial}{\partial\varphi}\right)^a\end{gathered} \tag{13}$$

Its corresponding dual basis vector is

$$\begin{gathered}\left(e^0\right)_a=e^A(\mathrm{d}t)_a,\ \left(e^1\right)_a=e^B(\mathrm{d}r)_a \\ \left(e^2\right)_a=r(\mathrm{d}\theta)_a,\ \left(e^3\right)_a=r\sin\theta(\mathrm{d}\varphi)_a\end{gathered} \tag{14}$$

Finally, the matrix of the corresponding antisymmetric curvature tensor 2-form $\boldsymbol{R}_{\mu}^{\nu}$ can be obtained from the second structural equation of Cartan [26], namely

$$(R_{\mu}^{\nu})=\begin{pmatrix} 0 & R_0^1 & R_0^2 & R_0^3 \\ -R_0^1 & 0 & R_1^2 & R_1^3 \\ -R_0^2 & -R_1^2 & 0 & R_2^3 \\ -R_0^3 & -R_1^3 & -R_2^3 & 0 \end{pmatrix} \tag{15}$$

where notice 2-form $\boldsymbol{R}_{\mu}^{\nu}$ can be expressed as

$$\begin{aligned}
&\boldsymbol{R}_{0}^{1}=e^{-2B}\left(A''-A'B'+A'^{2}\right)\boldsymbol{e}^{0}\wedge\boldsymbol{e}^{1}\\
&\boldsymbol{R}_{0}^{2}=r^{-1}A'e^{-2B}\boldsymbol{e}^{0}\wedge\boldsymbol{e}^{2}\\
&\boldsymbol{R}_{0}^{3}=r^{-1}A'e^{-2B}\boldsymbol{e}^{0}\wedge\boldsymbol{e}^{3}\\
&\boldsymbol{R}_{1}^{2}=r^{-1}B'e^{-2B}\boldsymbol{e}^{1}\wedge\boldsymbol{e}^{2}\\
&\boldsymbol{R}_{1}^{3}=r^{-1}B'e^{-2B}\boldsymbol{e}^{1}\wedge\boldsymbol{e}^{3}\\
&\boldsymbol{R}_{2}^{3}=r^{-2}\left(1-e^{-2B}\right)\boldsymbol{e}^{2}\wedge\boldsymbol{e}^{3}
\end{aligned}\tag{16}$$

and A'' and A' are the second or first derivative of $A(r)$ with respect to r respectively [2], and the 2-form of the curvature tensor $\boldsymbol{R}_{\mu}^{\nu}$ is defined as:

$$\boldsymbol{R}_{ab\mu}^{\nu}=\frac{1}{2}R_{\rho\sigma\mu}^{\nu}\left(\boldsymbol{e}^{\rho}\right)_{a}\wedge\left(\boldsymbol{e}^{\sigma}\right)_{b}\tag{17}$$

Hence, by means of the generalized gauge similarity transformation (5), that is, for any given spacetime point $x\in U\cap V$, under the generalized gauge transformation W, the electromagnetic field antisymmetric tensor at this point and the (gravitational) the curvature tensor have the following similarity transformation relationship:

$$\left(R_{\mu}^{\nu}\right)_{V}=W^{-1}\left(F_{\mu\nu}\right)_{U}W\tag{18}$$

where the left side represents the Schwarzschild gravitational field strength and the right side represents certain electromagnetic field strength.

The mathematical and physical meaning of the above formula is that the diagonal matrix of the matrix $\left(F_{\mu\nu}\right)$ is equal to the diagonal matrix of $\left(R_{\mu}^{\nu}\right)$, that is, there exists a similarity transformation matrix W_1, belonging to the group $U(1)$ corresponding to the electromagnetic field, $\left(F_{\mu\nu}\right)$ can be diagonalized. Similarly, there can be another similarity transformation matrix $W_2\in SO(1,3)$ or $\in O(4)$ that can diagonalize $\left(R_{\mu}^{\nu}\right)$, and these two diagonal matrices are equal, that is,

$$W_2^{-1}\left(R_{\mu}^{\nu}\right)W_2=W_1^{-1}\left(F_{\mu\nu}\right)W_1\tag{19}$$

This is because two similar matrices have the same diagonal matrix and the same eigenvalues. Now we know that according to the theory of matrix algebra, in Lorentz coordinates, the eigenvalues of antisymmetric matrices are complex numbers, which is determined by their specific mathematical and physical structure. Or in an orthogonal coordinate system, the eigenvalues of antisymmetric matrices are imaginary numbers or 0, but the trace is 0, but this does not affect the eigenvalues being complex or non-zero. However, no matter what this complex number is, in theory we can adjust the electromagnetic field so that this complex number is exactly equal to the eigenvalue of the curvature geometry field on the left, so that the diagonal matrices on both sides are equal. Then we use the anti-diagonal transformation of W_2 on the left to transform the diagonal matrix of the electromagnetic field into $\left(R_{\mu}^{\nu}\right)$, that is, for $W_1\in U(1)$, $W_2\in SO(1,3)$ or $\in O(4)$, we can get

$$\left(R_{\mu}^{\nu}\right)=W_2W_1^{-1}\left(F_{\mu\nu}\right)W_1W_2^{-1}=W^{-1}\left(F_{\mu\nu}\right)W, \tag{20}$$

where

$$W=W_1W_2^{-1} \tag{21}$$

It corresponds exactly to the conversion function of the generalized gauge transformation $g_{UV}(x)=S_U(p)S_V(p)^{-1}$, $\forall x\in U\cap V\neq\varnothing$, $\pi(p)=x$, where $S_U(p)$ and $S_V(p)$ belong to two different subgroups respectively. For example, in the above gauge transformation from electromagnetic force to gravitational force, $S_U(p)\to W_1$ belong to the group $U(1)$ corresponding to the electromagnetic field and $S_V(p)^{-1}\to W_2^{-1}$ belong to the group $SO(1,3)$ or $\in O(4)$ corresponding to the gravitational field.

The proof is as follows:

From the definition of the transition function, that is, let $T_U:\pi^{-1}[U]\to U\times G$ and $T_V:\pi^{-1}[V]\to V\times G$ be two local trivials of the principal bundle $P(M,G)$, with $U\cap V\neq\varnothing$, the mapping $g_{UV}:U\cap V\to G$ is called the transition function from T_U to T_V, that is, $g_{UV}(x)=S_U(p)S_V(p)^{-1}$, $\forall x\in U\cap V\neq\varnothing$, $\pi(p)=x$, it can be immediately seen that when $S_U(p)=g_U\in U(1)\in GL(4)$, and $S_V(p)=g_V\in SO(1,3)$ or $\in O(4)\in GL(4)$, therefore we still have

$$g_{UV}=g_Ug_V^{-1}=S_US_V^{-1}\Rightarrow W=W_1W_2^{-1} \tag{22}$$

namely

$$S_U\Rightarrow W_1, S_V^{-1}\Rightarrow W_2^{-1} \tag{23}$$

q.e.d.

Therefore, from this, the following definition of the gauge transformation cross basic interactions can be derived: Let $T_U:\pi^{-1}[U]\to U\times G$ and $T_V:\pi^{-1}[V]\to V\times G$ be the two local ordinariness of the principal bundle $P(M,G)$, where $U\cap V\neq\varnothing$. The mapping $g_{UV}:U\cap V\to G$ is called the transition function from T_U to T_V. If there are

$$g_{UV}(x)=S_U(p)S_V(p)^{-1}, \forall x\in U\cap V, \pi(p)=x? \tag{24}$$

where, the images of $p\in P$ under the mappings of T_U and T_V are $(x,g_U)\in U\times G_U$ and $(x,g_V)\in V\times G_V$, respectively. Here, $g_U\in G_U$, $g_V\in G_V$, G_U and G_V are the subgroups corresponding to the basic interactions described in $G=GL(m,C)$: for example, $G_U=U(1)$ or $SU(2)$ for electromagnetic interactions, $G_V=SO(1,3)$ or $O(4)$ for gravitational interactions, then g_{UV} defines a gauge transformation from electromagnetic interactions to gravitational interactions. If G_U and G_V only belong to a subgroup that describes the same fundamental interaction, then g_{UV} only defines the gauge transformation within the same fundamental interaction. This can be referred to as two types of gauge transformations, namely the gauge transformation across fundamental interactions and the traditional gauge transformation. We can refer to them as the cross basic gauge transformation and the basic gauge transformation [21]-[25].

The conversion function $g_{UV}(x)$ defined above [26] can still be proven that the following theorem is satisfied:

$$g_{UU}(x) = g_U g_U^{-1} = e, \forall x \in U \text{ ;}$$

$$g_{VU}(x) = g_V g_U^{-1} = \left(g_U g_V^{-1}\right)^{-1} = \left(g_{UV}(x)\right)^{-1}, \forall x \in U \cap V \text{ ;}$$

$$g_{UV}(x) g_{VW}(x) g_{WU}(x) = g_U g_V^{-1} g_V g_W^{-1} g_W g_U^{-1} = e, \forall x \in U \cap V \cap W \text{ .} \tag{25}$$

Therefore, the actual similarity transformation matrix constructed above is completely consistent with the theoretical formula, which once again shows that the generalized gauge transformation can cross the fundamental interactions. Specifically, gravity and electromagnetic force can be transformed into each other through the generalized gauge transformation. Let's take a more general example.

4. Deep Connection between Electromagnetic Field and Weyl Tensor

In general relativity, some free components of the Weyl tensor may have a mathematical structure similar to that of the electromagnetic field. In particular:

- The electromagnetic field tensor $F_{\mu\nu}$ is antisymmetric and its dynamics are determined by Maxwell's equations, namely, from Equation (11)

$$\left(F_{\mu\nu}\right) = \begin{pmatrix} 0 & -E_1 & -E_2 & -E_3 \\ E_1 & 0 & B_3 & -B_2 \\ E_2 & -B_3 & 0 & B_1 \\ E_3 & B_2 & -B_1 & 0 \end{pmatrix}$$

Its Maxwell equation is expressed as

$$\partial^a F_{ab} = -4\pi J_b \tag{26}$$

$$\partial_{[a} F_{bc]} = 0 \tag{27}$$

where J_b is the 4 current density.

- The components of the Weyl tensor can also be expressed as a set of antisymmetric tensor components (but they describe the degrees of freedom of gravitational waves or curvature), that is, for a generalized Riemann space with dimension $n \geq 3$, the Weyl tensor C_{abcd} can be defined as:

$$C_{abcd} := R_{abcd} - \frac{2}{n-2}\left(g_{a[c} R_{d]b} - g_{b[c} R_{d]a}\right) + \frac{2}{(n-1)(n-2)} R g_{a[c} g_{d]b} \tag{28}$$

The Weyl tensor is basically antisymmetric [26] [27], so the Weyl tensor is the traceless part of the curvature tensor, that is

$$C_{abcd} = -C_{bacd} = -C_{abdc} = C_{cdab}\text{ , } C_{[abc]d} = 0 \tag{29}$$

$$C_{abcd} \text{ all traces of are 0.} \tag{30}$$

Furthermore, here we can introduce 2-form Weyl tensor $C_{ab\mu\nu}$ corresponding to 2-form $R_{ab\mu\nu}$, where a and b are abstract indices, μ and ν are component indices. If we put certain components of the Weyl tensor $C_{ab\mu\nu}$ into one-to-one correspondence with the electromagnetic field tensor and force their eigenvalues of the matrix to be equal, then we can actually physically propose a possibility of transforming the two into each other using the generalized gauge similarity transformation as in Equation (7) or Equation (19):

- The dynamic behavior of the electromagnetic field may be the dynamic behavior of some kind of curvature tensor (geometrization).
- From the perspective of eigenvalues, this curvature can in some sense "encode" the properties of the electromagnetic field.

Then, if we de-diagonalize the eigenvalues back into the curvature tensor matrix, we are actually trying to reconstruct the complete tensor structure from the "geometric features". In this case, it can be understood as:

- All information about the electromagnetic field is fully embedded in the tensor representation of spacetime curvature.
- This regression operation shows that the electromagnetic field is no longer an independent field, but a specific manifestation in spacetime geometry.

Mathematical physics processes can still be expressed in similar expressions as above. For example, by diagonalizing both sides and adjusting the electromagnetic field to make their eigenvalues of the matrix equal, we can get

$$W_2^{-1}\left(C_{\mu\nu cd}\right)W_2 = W_1^{-1}\left(F_{\mu\nu}\right)W_1 \tag{31}$$

We then de-diagonalize the eigenvalues back into the curvature tensor matrix, in effect trying to reconstruct the complete tensor structure from the "geometric features", then we get

$$\left(C_{\mu\nu cd}\right) = W_2 W_1^{-1}\left(F_{\mu\nu}\right)W_1 W_2^{-1} = W^{-1}\left(F_{\mu\nu}\right)W \tag{32}$$

where $W = W_2 W_1^{-1}$, $W_1 \in U(1)$, $W_2 \in SO(1,3)$ or $O(4)$, which is consistent with the definition of the conversion function formula (22) of the generalized gauge transformation above. The electromagnetic field is converted into the gravitational field through the generalized gauge transformation.

This is an important consequence of geometrization thinking and may mean:

- The electromagnetic field and the gravitational field are no longer independent, but are linked to the space-time geometry itself through the generalized gauge transformations.
- Therefore, electromagnetic waves may have a deep mutual conversion with gravitational waves, indicating that they are both specific projection forms of the principal bundle curvature (or connection) in our universe.

The further significance of the above formula is that the unified field theory [21]-[25] we proposed is physically based and correct. The potential significance of this method for the unified field theory is

- The complex eigenvalues of the electromagnetic field are equivalent to the complex eigenvalues of the Weyl curvature, indicating that the two may share some common geometric basis.
- The gravitational field described by general relativity can be completely described by a geometric tensor, and if the electromagnetic field can be geome-

trized, then the electromagnetic phenomenon is actually part of a higher-dimensional geometric structure.

This is consistent with some modern theories, such as:

- Kaluza-Klein theory, which holds that the electromagnetic field originates from the compactification of high-dimensional geometry [28] [29].
- Spin-geometry theory, which holds that the electromagnetic field and the gravitational field are directly related at the spin geometry level [30]-[33].

In short, if the complex eigenvalues of the Weyl tensor can be adjusted to be consistent with the electromagnetic field, it can indeed be considered that the electromagnetic field is geometrically reinterpreted. This "geometric" approach shows that:

- The electromagnetic field can be regarded as a manifestation of the curvature of space-time.
- Electromagnetic phenomena can be transformed into a gravitational geometric framework by generalized gauge transformation.

5. Application of Warp Drive Spacecraft

The above formulation of converting electromagnetic force into gravitational force can be applied to the problem of negative curvature generated by curvature drive spacecraft, thereby eliminating the requirement for exotic matter, which may be of great help in the manufacture of curvature drive spacecraft.

The concept of superluminal travel mentioned here involves the control of spacetime structure, similar to the theoretical Alcubierre Drive. This theoretical concept is based on manipulating the local curvature of spacetime, creating a contracted spacetime region in front of the spacecraft and an expanding spacetime region behind it, allowing the spacecraft to achieve effective superluminal travel without violating the speed of light limit [34].

In the Alcubierre Drive scenario, the spacecraft does not move at superluminal speeds within the local spacetime. Instead, the spacecraft remains stationary or subluminal within its surrounding "warp bubble" and achieves superluminal relative motion by manipulating the geometric structure of spacetime. In other words, the spacecraft "glides" by bending spacetime, rather than directly moving at high speeds within spacetime.

The idea of creating differing curvature effects in front and behind the spacecraft is theoretically similar to the Alcubierre Drive: by manipulating the geometry of local spacetime, different curvature effects (compression in front, expansion behind) can be created, thus "propelling" the spacecraft to move at superluminal speeds relative to distant observers.

Although theoretically similar to the framework of the Alcubierre Drive, several significant challenges exist:

1) Massive Energy Requirements: According to the principles of the Alcubierre Drive, achieving spacetime curvature manipulation requires vast amounts of energy. The process of controlling spacetime curvature may require immense negative energy (e.g., negative energy density materials or so-called "exotic matter"), which remains an unresolved issue in current physical theory [34].

2) Precise Control of the Weyl Tensor: Adjusting the Weyl tensor is not a simple task; it involves extremely fine manipulation of spacetime geometry. Even in a vacuum, manipulating the Weyl tensor to generate significant positive and negative curvature differences would require highly complex techniques and methods. How to create stable, controllable local spacetime curvature remains a theoretical challenge [35].

3) Stability Issues: Even if local spacetime curvature manipulation can be achieved, ensuring the stability and persistence of this curvature, and preventing undesirable effects (such as the propagation of gravitational waves or spacetime rupture), is a key problem that must be solved [36] [37].

However, the above formula for converting electromagnetic force into gravity can be applied to the problem of negative curvature of curvature engine spacecraft, thereby eliminating the requirement of exotic matter, which may be of great help in manufacturing curvature engine spacecraft.

In fact, this problem involves the geometric and physical properties of curvature in general relativity, and how the Weyl tensor affects the overall space-time curvature. The detailed analysis is as follows:

How about the physical possibility? In fact, the idea of adjusting the Weyl tensor through the antisymmetric electromagnetic field tensor to produce specific curvature with positive and negative properties involves manipulating local curvature. It attempts to manipulate the Weyl tensor (and thus the structure of the curvature tensor) to create a phenomenon where there are positive and negative curvature differences in front and behind the spacecraft. This idea could be highly creative and is linked to theories about "curvature engines" or "curvature drive" concepts, such as those seen in science fiction (e.g., the "warp bubble" in *Star Trek*). We can analyze these concepts from the perspectives of general relativity and modern physics to see if it is possible to achieve this without violating the principles of relativity:

1) General Relativity and the Invariance of the Speed of Light: In general relativity, the core content of the invariance of the speed of light principle is that the speed of light (in vacuum) is the same for all observers, regardless of their motion. This principle is one of the cornerstones of relativity [38]. To maintain this principle, no object can exceed the speed of light, unless the structure of spacetime itself is altered. For example, if one could manipulate spacetime curvature to create an "effective superluminal motion", this would not violate the light-speed limit of relativity because the speed limit applies to the velocity within local spacetime, not to altering the overall geometry of spacetime itself.

2) The Relationship between the Weyl Tensor and Curvature Engines: The Weyl tensor itself describes the purely geometric part of spacetime, that is, the curvature that does not include matter or energy sources. It represents phenomena such as gravitational waves and tidal forces. Adjusting it mainly affects the local geometric structure, such as the distances and shapes between different points. The direction of Weyl tensor adjustment alters the local spacetime geometry, and this change manifests as:

- **Positive Curvature Region**: Spacetime "compresses" the distance between objects, similar to positive curvature in spherical geometry.
- **Negative Curvature Region**: Spacetime "expands" the distance between objects, similar to negative curvature in hyperbolic geometry.

If we could somehow control the distribution of the Weyl tensor so that there is different curvature in the space in front and behind the spacecraft (positive and negative differences), we could indeed influence the "effective" motion of the spacecraft in the local region. The curvature in front of the spacecraft compresses space, while the curvature behind it expands space, creating a structure that could produce an "acceleration effect", similar to pushing an object through spacetime via distortion [35]-[37].

However, the problem lies in the mechanism for realizing this concept. To achieve this, we would need to precisely control the Weyl tensor around the spacecraft, ensuring that the local spacetime geometry shows significant positive and negative curvature differences in front and behind the spacecraft.

But, if we use the generalized gauge transformation to transform electromagnetic force into gravity, and thus use the electromagnetic force (which is most familiar to humans) to change the geometric curvature of spacetime, then we can bypass the requirement of Alcubierre drive for strange matter such as negative energy, making the possibility of curvature engine spacecraft a step further. The specific formula is as follows:

In front of the curvature engine spacecraft: electromagnetic force turns into gravity, that is, $\gamma > 0$,

$$\left(C_{\mu\nu cd}\right) = \gamma\left(F_{\mu\nu}\right) = W_2 W_1^{-1}\left(F_{\mu\nu}\right) W_1 W_2^{-1} = W^{-1}\left(F_{\mu\nu}\right) W \tag{33}$$

Behind the curvature engine spacecraft: electromagnetic force turns into anti-gravity, that is, $\gamma < 0$,

$$\left(C_{\mu\nu cd}\right) = \gamma\left(F_{\mu\nu}\right) = W^{-1}\left(F_{\mu\nu}\right) W \tag{34}$$

In this way, introducing electromagnetic fields to adjust the Weyl tensor in an attempt to get rid of the "negative energy" that is difficult to achieve in current physics is a direction that is worth exploring. This method may make the curvature engine more physically feasible and provide a more practical technical route for research and experiments. The mathematical construction is followings.

6. Mathematical Construction of Weyl Tensor Control in Warp Drive

In the original model of the Alcubierre warp drive [34], the Alcubierre metric has the form:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \left(\mathrm{d}x - v_s(t) f(r_s)\mathrm{d}t\right)^2 + \mathrm{d}y^2 + \mathrm{d}z^2 \tag{35}$$

where $v_s(t)$ is the instantaneous velocity of the warp bubble, and

$$r_s(t) = \sqrt{\left(x - x_s(t)\right)^2 + y^2 + z^2} \tag{36}$$

is the distance from the center of the spacecraft $x_s(t)$ to the space point, $f(r_s)$ is the adjustment function, satisfying $f(r_s) \approx 1$ (front compression) and $f(r_s) \approx 0$ (rear stretching).

Now, based on the new physical theory of generalized gauge transformations above, we imagine that the Weyl tensor can be controlled by electromagnetic fields, so the Weyl tensor $C_{\mu\nu\rho\sigma}$ can be actively controlled, and the signs and amplitudes of its components can be set independently. The goal is to generate positive curvature (compression) in front of the spacecraft ($x > x_s$) and negative curvature (stretching) behind ($x < x_s$) by controlling $C_{\mu\nu\rho\sigma}$.

Then we can design an improved metric for the warp engine, that is, introduce the Weyl tensor control term into the Alcubierre metric and construct a modified metric:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \left(dx - v_s(t)\left[f_+(r_s) - f_-(r_s)\right]\mathrm{d}t\right)^2 + \mathrm{d}y^2 + \mathrm{d}z^2 + \delta g_{\mu\nu} \tag{37}$$

where $f_+(r_s)$ and $f_-(r_s)$ are the regulation functions of the front and rear regions respectively, $\delta g_{\mu\nu}$ is the metric correction term caused by the Weyl tensor regulation.

Furthermore, it is possible to make $\delta g_{\mu\nu} = 0$, if we assume that the variation of the shape function is controlled by the components of the external tensor:

$$f(r_s) = f_0 + \alpha \cdot \tanh\left(\frac{x - x_s}{\sigma}\right) \tag{38}$$

here, f_0 is a fundamental shape function that gives the curved bubble a basic structure; α is the strength of the influence of the Weyl tensor; $th\left(\frac{x - x_s}{\sigma}\right)$ controls the smoothness of the transition region.

Then we localize the Weyl tensor, and allow the components of the Weyl tensor in the region ahead and behind the spacecraft have opposite signs, namely, in the front region ($x > x_s$), we have

$$C_{txtx} = +k,\ C_{tyty} = C_{tztz} = -\frac{k}{2} \tag{39}$$

where $k > 0$, resulting in compression of space (positive curvature), while in the rear region ($x < x_s$), we have

$$C_{txtx} = -k,\ C_{tyty} = C_{tztz} = +\frac{k}{2} \tag{40}$$

where $k > 0$, resulting in a stretching of space (negative curvature).

In this way, by regulating the Weyl tensor, the total Riemann curvature tensor

$R_{\mu\nu\rho\sigma}$ is divided into background curvature and Weyl tensor contribution:

$$R_{\mu\nu\rho\sigma} = R_{\mu\nu\rho\sigma}^{Alcubierre} + C_{\mu\nu\rho\sigma} \tag{41}$$

In the front region (positive curvature compression), we get

$$R_{txtx} = R_{txtx}^{Alcubierre} + k, \; R_{tyty} = R_{tyty}^{Alcubierre} - \frac{k}{2} \tag{42}$$

When $\gg \left|R_{txtx}^{Alcubierre}\right|$, the total curvature $R_{txtx} > 0$ and the space is compressed, while in the rear region (negative curvature stretch), we get

$$R_{txtx} = R_{txtx}^{Alcubierre} - k, \; R_{tyty} = R_{tyty}^{Alcubierre} + \frac{k}{2} \tag{43}$$

When $\gg \left|R_{txtx}^{Alcubierre}\right|$, the total curvature $R_{txtx} < 0$, and the space is stretched.

For a smooth transition, we can choose the specific form of the regulation function, that is, we choose the hyperbolic tangent function to define the Weyl tensor regulation of the front and back regions:

$$C_{txtx} = k\,th\left(\frac{x - x_s(t)}{\sigma}\right) \tag{44}$$

$$C_{tyty} = C_{tztz} = -\frac{k}{2}th\left(\frac{x - x_s(t)}{\sigma}\right) \tag{45}$$

where σ is the transition scale, this parameter controls the steepness of the curvature change. This means:

$$f(r_s) \sim C_{txtx} \tag{46}$$

$$f(r_s) \sim -C_{tyty} \tag{47}$$

therefore, the variation of the shape function is controlled by the control of the Weyl tensor.

Formula Summary:

Region	Weyl tensor components	Curvature symbol	Spatial Effect
Front ($x > x_s$)	$C_{txtx} = +k$, $C_{tyty} = -\frac{k}{2}$	$R_{txtx} > 0$	Compress (+curvature)
Rear ($x < x_s$)	$C_{txtx} = -k$, $C_{tyty} = +\frac{k}{2}$	$R_{txtx} < 0$	Stretch (−curvature)

7. Energy Conditions and Physical Feasibility

The negative energy of the Alcubierre engine spacecraft actually comes from the constraints of the Einstein field equations. This is because according to the Einstein field equations $G_{\mu\nu} = 8\pi T_{\mu\nu}$, the spacetime curvature is determined by the energy-momentum tensor $T_{\mu\nu}$. By calculating the Einstein tensor $G_{\mu\nu}$ of the Alcubierre metric, the expression for the required energy density (T_{00}) can be obtained as

$$T_{00} = \frac{1}{8\pi}\left[-\frac{v_s^2\rho^2}{4}\left(\frac{\mathrm{d}f}{\mathrm{d}r_s}\right)^2\right] \tag{45}$$

where $\rho = \sqrt{y^2 + z^2}$.

From the above formula, we can see that in the area where the warp wall ($f(r_s)$) changes rapidly, the energy density T_{00} is negative. The negative energy is concentrated in the annular area around the spacecraft, not just at the tail end. Although the negative energy is distributed throughout the warp wall, the negative curvature (stretching space) at the tail end is the core reason for the negative energy requirement. Negative curvature means that the expansion rate of space exceeds that of flat spacetime and must be driven by negative energy (negative pressure), this is similar to the dark energy effect in the expansion of the universe. The compression in front (positive curvature) corresponds to positive energy density, but actual calculations show that all energy density in the Alcubierre metric is dominated by negative energy. This is due to the overall coordination requirements of the space-time structure: compressing the space-time in front while stretching the space-time behind, dynamic balance must be maintained through negative energy [34]-[37].

Negative curvature mean that the expansion rate of space exceeds the flat spacetime, and it must be driven by negative energy (negative pressure), similar to the dark energy effect in the expansion of the universe. Although the front compression (positive curvature) corresponds to positive energy density, actual calculations show that all energy densities in the Alcubierre metric are dominated by negative energy, because this is the overall coordination requirement of the spacetime structure, that is, compressing the spacetime in front while stretching the spacetime behind, and negative energy must be used to maintain dynamic balance.

While the classical general relativity requires that matter satisfy energy conditions, such as:

1) Weak Energy Condition (WEC): ($T_{\mu\nu}u^{\mu}u^{\nu} \geq 0$) (for all time-like vectors u^{μ}), that is, the energy density is non-negative.

2) Zero Energy Condition (NEC): ($T_{\mu\nu}k^{\mu}k^{\nu} \geq 0$) (for all light-like vectors k^{μ}).

Therefore, the negative energy density of the Alcubierre engine directly violates these conditions, leading to the following problems:

1) Existence of exotic matter: A substance with negative energy density is required, which is not met by known substances in nature (such as ordinary matter and electromagnetic fields).

2) Stability and causality: Negative energy may lead to space-time instability (such as vacuum decay) or closed timelike curves (time travel paradox) [34]-[37].

However, the negative curvature (space stretching) at the tail end of the Alcubierre engine requires negative energy drive, which is a direct result of Einstein's field equations. The solution proposed by the author here is to allow the electromagnetic field to directly regulate the Weyl tensor or curvature tensor through the generalized gauge transformation proposed above, bypassing the constraints of Einstein's equations. If the electromagnetic field can directly produce positive or negative Weyl tensor components (for example, by adjusting the direction or intensity of the electromagnetic field), then in theory, curvature of arbitrary signs can be generated (compressing or stretching space) without relying on negative energy matter. In the new theory, the contribution of the electromagnetic field to curvature may be reinterpreted as a "geometric effect" rather than the energy-momentum of traditional matter, thereby circumventing the limitations of weak energy conditions.

As for the second question, which involves whether time travel is possible, there are currently views on both sides, but the author believes that the Alcubierre superluminal motion of a warp engine does not necessarily lead to time travel, but there are conditional correlations as follows: a) Theoretical possibility, namely the combination of superluminal motion and specific spatiotemporal topology (such as closed paths or wormholes) may allow the closed time-like curve to open up time travel channels. b) Physical Limitations, namely the infeasibility of temporal protection mechanisms, violation of energy conditions, and the possibility of quantum gravity effects actually preventing time travel. c) Philosophy and logical constraints, namely even if time travel is feasible, the principle of self consistency or multi world interpretation may resolve the paradox. Therefore, the superluminal characteristics of the Alcubierre engine only provide a mathematical framework for time travel, and its practical implementation requires breaking through multiple theoretical and experimental barriers, which is far from a "certain" result.

In short, by directly controlling the sign of the components of the Weyl tensor, positive curvature (compressing space) can be generated in front of the warp drive and negative curvature (stretching space) can be generated behind. Mathematically, this is achieved through the following steps:

1) Localized Weyl tensor design: set components with opposite signs in the front and back regions.

2) Metric correction: embed the Weyl tensor into the Alcubierre metric to correct the geometric structure of the warp bubble.

3) Smooth transition: use a regulating function (such as hyperbolic tangent) to avoid sudden changes in curvature.

This model provides a theoretical framework for the physical realization of the warp drive, although further research is needed on how the new physical mechanism specifically regulates the Weyl tensor.

8. Explores Potential Feasibility and Challenges

The following is an in-depth analysis of the improvement ideas proposed above, and explores potential feasibility and challenges:

A) Theoretical possibility of regulating Weyl tensor using electromagnetic field

In a vacuum (or in regions of extremely low matter density), if there is a strong electromagnetic field distribution, then it may have a significant effect on the curvature tensor. Our idea is to adjust the Weyl tensor through electromagnetic fields and change the local space-time geometry. Here are the possible ways:

1) Changes in the Weyl Tensor Caused by the Electromagnetic Field: The electromagnetic field affects the distribution of the Ricci tensor through its energy-momentum tensor and changes the characteristics of the Weyl tensor. If the electromagnetic field has different distributions in front and behind the spacecraft, it may cause the traceless part of the curvature tensor (*i.e.*, the Weyl tensor) to form an asymmetric positive and negative distribution around the spacecraft.

2) Weyl Tensor and Tidal Force Control: The Weyl tensor is directly related to tidal force effects. The electromagnetic field can adjust the distribution of tidal forces in spacetime, creating a compressive effect in front and an expansive effect behind. Theoretically, if the electromagnetic field is sufficiently strong and appropriately distributed, such adjustments may result in different curvatures at the front and rear of a spacecraft [38]-[40].

B) Practical Mechanism of Electromagnetic Field Coupling with Spacetime Curvature

The coupling of the electromagnetic field with spacetime curvature in general relativity has been extensively studied in theoretical works. The following are several possible mechanisms that could support our hypothesis:

1) Curvature Effects of Classical Electromagnetic Fields: Under strong electromagnetic fields, such as extreme conditions with strong magnetic fields (close to the field strength of neutron stars or magnetars, approximately 10^{10} Gauss or higher), the energy-momentum tensor of the electromagnetic field can significantly influence the local curvature of spacetime. By precisely designing the distribution of the electromagnetic field, regions of positive and negative curvature in spacetime can be formed locally.

For examples:

- In front of the spacecraft, creating a high-intensity electric and magnetic field cross-distribution can induce spacetime compression.
- Behind the spacecraft, designing a symmetric magnetic field expansion region can produce a negative curvature effect (spacetime expansion) [38]-[40].

2) Nonlinear Electromagnetic Theory: Beyond the classical Maxwell electromagnetic field, some nonlinear electromagnetic theories (such as Born-Infeld electrodynamics or other modified electrodynamics theories) may provide additional tools to control curvature. Nonlinear electromagnetic theories exhibit characteristics of strong coupling with general relativity under extremely high field strengths. The nonlinear effects of these theories can enhance the electromagnetic field's ability to control the Weyl tensor, potentially offering more flexible ways to regulate spacetime curvature [40].

C) Introduction of Equivalent Spacetime Under Extreme Conditions

In extreme electromagnetic fields, there exists the concept of "equivalent spacetime", where the electromagnetic field alters the propagation path of light, similar to the gravitational effects of curved spacetime. By designing such equivalent spacetime distributions, "compression" and "expansion" regions can be indirectly created, achieving the spacetime curvature effects our envision.

D) Possible Experimental and Technical Approaches

Although our hypothesis is theoretically grounded, achieving this goal requires solving several technical challenges. Below are some potential technical pathways and challenges:

1) Generation of Ultra-Strong Electromagnetic Fields: The first step is generating sufficiently strong electromagnetic fields. To regulate the Weyl tensor through the electromagnetic field, extremely high field strengths may be required. Currently, the strongest magnetic fields humans can produce (e.g., laser-pulse-induced magnetic fields) are approaching 10^{15} Gauss but may still be insufficient to significantly bend spacetime. Therefore we may consider:

- **Technical Approach**: Utilize high-energy lasers or plasma devices to generate ultra-strong electromagnetic fields.
- **Challenge**: How to focus the electromagnetic field in the local region surrounding the spacecraft while ensuring its controllability and stability.

2) Electromagnetic Field Distribution Design: The distribution of the electromagnetic field needs to be highly asymmetric to create different curvature effects in the front and rear of the spacecraft. This requires precise calculation and design of the electromagnetic field morphology.

3) Technical Approach: Use supercomputers to simulate the coupling behavior of electromagnetic fields with spacetime curvature and design appropriate field distributions.

4) Challenge: How to maintain this field distribution during spacecraft motion.

5) Precise Control of the Weyl Tensor: Currently, the adjustment and measurement of the Weyl tensor are mainly theoretical, with a lack of experimental means. How to precisely manipulate the distribution of the Weyl tensor using the electromagnetic field remains a core issue.

6) Technical Approach: Combine gravitational wave experiments with strong-field quantum electrodynamics experiments to explore the precise control of spacetime curvature through electromagnetic fields.

E) Realistic Limitations and Future Prospects

1) Energy Requirements: Although the need for "negative energy" has been eliminated, the generation of electromagnetic fields still requires a huge amount of energy. The spacecraft engine needs to store huge amounts of energy to maintain this strong field, or an energy collection mechanism is required (such as extracting energy from the cosmic vacuum).

2) Complexity of the Weyl Tensor: The regulation of the Weyl tensor is not equivalent to a simple regulation of the field distribution. It depends on the structure of the entire spacetime geometry. To achieve the difference in positive and negative curvature around the spacecraft, it may be necessary to develop a completely new electromagnetic field-gravitational field coupling theory. In this regard, our proposed theory of generalized gauge transformation that enables the mutual conversion of gravity and electromagnetic force can serve as a certain basis.

3) Difficulty of Experimental Verification: At present, we cannot directly observe or measure the effect of the change of the Weyl tensor. The relevant theoretical verification may need to rely on gravitational wave detection or other indirect methods.

9. Conclusion and Outlook

In this paper, the author has proposed a systematic method of converting electromagnetic force into gravitational force using the theory of generalized gauge transformations. By introducing electromagnetic fields to regulate the Weyl tensor, the need for negative energy is avoided, providing a valuable improvement to the theoretical model of curvature engine-type spacecraft. Although current technology is not yet capable of realizing this concept, the following points indicate that the author's approach has significant potential for both theoretical and technological development:

1) The electromagnetic field not only influences the curvature tensor and indirectly regulates the Weyl tensor through its energy-momentum tensor but can also directly convert into gravity through the generalized gauge equations. This direct conversion may be more efficient and easier to control in its physical processes.

2) By leveraging the generalized gauge equations, it is possible to achieve a significant difference in positive and negative curvature between the front and rear of the spacecraft under strong electromagnetic fields and asymmetric distributions, potentially allowing for "superluminal" travel without violating relativistic light-speed limits.

3) This concept has sparked further research into the "electromagnetic control of spacetime curvature", which could lead to the development of new engine technologies and contribute to human interstellar flight.

In conclusion, the key to the future lies in developing more powerful electromagnetic field generation technologies, improving theoretical models of nonlinear electromagnetic fields and gravitational fields, and exploring methods for the precise control of the Weyl tensor. The proposed concept may become a new direction in the research of curvature engine-type spacecraft.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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