NON-LINEAR PARENT ACTION AND DUAL $N = 1$ $D = 4$ SUPERGRAVITY

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We give an $N = 1$ supersymmetric extension of $D = 4$ dual gravity non-linear action proposed in [1]. The dual supergravity action and symmetries of the model, but supersymmetry, are realized in a local way.

1. Introduction

Recently in [1], a new type of the dual gravity non-linear action was proposed. An apparent advantage of the approach is the locality of the action as well as of gauge symmetries of the theory. We recall that the previously proposed dual gravity non-linear actions were realized within a non-local approach, when the action and gauge symmetries of the model contain non-local parts [2, 3] (see also [4]). At the same time, it is worth mentioning that the dynamics of the field dual to the graviton one is described, after a transition to new variables [3], by a local equation of motion.

The non-locality of the approach of [2, 3] is a direct consequence of the non-locality in duality relations between the graviton field and its dual partner. The duality relation is of the first order in space-time derivatives and contains the dynamics of both fields. Depending on the basic field choice, the duality relation results either in the graviton dynamical equation or in the equation of motion of its dual partner. The action, from which the duality relation comes, was realized in [2, 3] in a duality-symmetric manner. That is, it includes, in its final form[1], the kinetic terms (and terms of interactions) of the original fields and the dual ones. A most fascinating example is given by the action of the bosonic subsector of the completely duality-symmetric $D = 11$ supergravity [2], which extends the construction of [5]. The duality-symmetric content of fields entering the action reproduces the corresponding structure of low-level generators (up to the level equal to three) in the proposed infinite-dimensional hidden symmetry algebra of the M-theory [6]. This algebra predicts a field dual to the graviton one which should be incorporated into the effective dynamics of the M-theory. It gives another reason to invoke non-locality in view of numerous no-go theorems [7] which claim on the impossibility to construct a dual non-linear spin-2 field theory action by local deformations of free theory.

The construction of [2,3] is realized within the second-order formalism, when the basic (and unique) variables of the problem are vielbeins, while the spin-connection is expressed through the vielbeins and their derivatives. In contrast to [2, 3], the formulation of [1] is based on the first-order reformulation of gravitational action that results in a number of important changes. The basic change consists in the dualization of the spin-connection rather than that of the vielbein, as it was done in [2,3]. Dualizing the spin-connection can be easily realized in the linearized limit [8] (see also [9, 10] for early papers), which turns out to be generalized to the non-linear case [1]. The non-linear first-order action of [1] is constructed out the dual spin-connection extended, in a specific way, with the "field strength" dual to the vielbein one. It also contains the original vielbeins entering the action through a Chern–Simons combination with the dual connection. Another distinctive property of the construction is its straightforward generalization to the case of the interaction with matter fields. The formulation of [1] still remains local in the case. We recall that the second-order for-

[1] This form of the action is equivalent to that of [2].

malism is "sensitive" to the presence of matter fields, when the dualization requires, even in the linearized limit, to introduce the non-locality in the duality relations [11, 12].

We have noticed the relation between the hidden symmetry algebra of M-theory [6] and the structure of the duality-symmetric action [2, 3]. It is also worth mentioning the role of supersymmetry in this respect, because the starting point in searching for the M-theory hidden symmetry structure was $D = 11$ supergravity and the structure of its hidden symmetries arising upon the toroidal dimensional reduction [6]. The low-level generators of the proposed hidden symmetry algebra, known now as E_{11}, are in the one-to-one correspondence with fields which cast an $N = 1$ supersymmetric spin-2 multiplet in eleven space-time dimensions, including the field dual to the graviton one and to a third-rank antisymmetric tensor field[2]. Therefore, we have to get the supersymmetric formulation of the theory dual to the graviton field theory at the end. Searching for a realization of this task is the main motivation of the paper.

The paper is organized as follows. In the next section, we make preliminary steps to obtain an $N = 1$ supersymmetric extension of the non-linear parent action of $D = 4$ dual gravity [1]. Doing that, we make a special accent on the supersymmetry transformations of a spin-connection. Usually, these transformations are ignored, since their explicit form is not needed to prove the invariance of the supergravity action under local supersymmetry transformations (in the so-called 1.5-formalism[3]). However, the explicit form of the spin-connection supersymmetry transformation essentially simplifies extracting the corresponding transformation of the field dual to the vierbein. The supersymmetric extension of the dual gravity parent action is given, in its final form, in Section 3. The summary of the results is contained in Conclusions. Our notation and conventions are listed in Appendix.

2. Prerequisites of the Construction

We begin with the standard action for $D = 4$ $N = 1$ supergravity [15–17]

$$S_{\rm EH+RS} = -\frac{1}{4k^2}\int d^4x\, eR(\omega)-$$

$$-\frac{i}{2}\int d^4x\, e\bar{\psi}_m\gamma^{mnk}D_n(\omega)\psi_k, \tag{1}$$

where $e = \det e_m^a$ is the determinant of the vierbein, the curvature tensor is defined by

$$R_{mn}{}^{ab}(\omega) = \partial_m\omega_n{}^{ab} + \omega_m{}^{ac}\omega_{nc}{}^{b} - (m \leftrightarrow n), \tag{2}$$

and $R(\omega) = e_a^m e_b^n R_{mn}{}^{ab}(\omega)$. The spin-connection $\omega_m{}^{ab} = -\omega_m{}^{ba}$ and the vierbein are independent fields, which corresponds to the first-order formulation.

Action (1) is invariant under space-time diffeomorphisms, local Lorentz transformations which act on the flat-type indices, and local supersymmetry transformations

$$\delta_\epsilon e_m^a = -ik\bar{\epsilon}\gamma^a\psi_m, \qquad \delta_\epsilon\psi_m = \frac{1}{k}D_m(\omega)\epsilon, \tag{3}$$

with a parameter $\epsilon(x)$. The supersymmetry transformation of the connection [17] will also be important for our aims. In our notation, it reads

$$\delta_\epsilon\omega_a{}^{bc} = \frac{1}{4}k\varepsilon^{bcde}\bar{\epsilon}\gamma_5\,\times$$

$$\times\,\left[\gamma_e\Psi_{da}(\omega) - \gamma_a\Psi_{ed}(\omega) + \gamma_d\Psi_{ae}(\omega)\right], \tag{4}$$

where we have introduced $\Psi_{ab} = e_a^m e_b^n(D_m(\omega)\psi_n - D_n(\omega)\psi_m)$.

Our next step is to transform the action into a form which would be convenient for dualization. We note to this end that (1), up to irrelevant boundary terms, may be rewritten as

$$S = -\frac{1}{4k^2}\int d^4xe\left[\omega_a{}^{ab}\omega_{cb}{}^{c} - \omega_{abc}\omega^{bca} + 2C_{ab,}{}^{a}\omega_c{}^{bc}+\right.$$

$$\left.+C_{ab,c}\omega^{cab}\right] - \frac{i}{2}\int d^4x\, e\bar{\psi}_m\gamma^{mnk}D_n(\omega)\psi_k, \tag{5}$$

with $C_{ab,}{}^{c} = 2\partial_{[a}e_{b]}^c$. This action or, more precisely, the action which apparently is related to (5)

$$S = -\frac{1}{4k^2}\int d^4xe[e_a^m e_c^n\omega_m{}^{ab}\omega_{nb}{}^{c} - e_a^m e_b^n\omega_{mbc}\omega^{nca}+$$

$$+2e_a^m e_b^n C_{mn,}{}^{a}\omega_c{}^{bc} + e_a^m e_b^n e_k^c C_{mn,c}\omega^{kab}]-$$

$$-\frac{i}{2}\int d^4x\, e\bar{\psi}_m\gamma^{mnk}D_n(\omega)\psi_k, \tag{6}$$

$C_{mn,}{}^{a} = 2\partial_{[m}e_{n]}^a$, is invariant under the local supersymmetry transformations (3), (4).

[2] The structure of the first order parent action within the E_{11} perspective was discussed in [1].

[3] See, e.g., [13] for details and [14] for discussing the relation of the 1.5-formalism to the first-order supergravity formulation.

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Next, we change the connection to the following variables [8]

$$\omega_{abc} = Y_{bc,a} + \eta_{a[b}Y_{c]d,}{}^{d}, \qquad Y_{ab,c} = -Y_{ba,c}. \quad (7)$$

This results in

$$S = -\frac{1}{4k^2}\int d^4xe\left[e^m_a e^n_b C_{mn,c}Y^{ab,c} + Y_{ab,c}Y^{ac,b} - \right.$$

$$\left. -\frac{1}{2}Y_{ab,}{}^{b}Y^{ac,}{}_{c}\right] - \frac{i}{2}\int d^4x\, e\bar{\psi}_m\gamma^{mnk}D_n(Y)\psi_k, \quad (8)$$

where

$$D_m(Y)\psi_n = \left(\partial_m + \frac{1}{4}Y^{ab,}{}_{m}\gamma_{ab} + \frac{1}{4}e^a_m Y^{bc,}{}_{c}\gamma_{ab}\right)\psi_n. \quad (9)$$

The supersymmetry transformations which leave (8) invariant are

$$\delta_\epsilon e^a_m = -ik\bar{\epsilon}\gamma^a\psi_m, \qquad \delta_\epsilon\psi_m = \frac{1}{k}D_m(Y)\epsilon, \quad (10)$$

$$\delta_\epsilon Y_{ab,c} = \frac{1}{4}k\varepsilon_{ab}{}^{fd}\bar{\epsilon}\gamma_5\left[\gamma_d\Psi_{fc}(Y) - \gamma_c\Psi_{df}(Y) + \right.$$

$$\left. +\gamma_f\Psi_{cd}(Y)\right] + \frac{3}{2}k\eta_{c[a}\varepsilon^{e}{}_{b]fd}\bar{\epsilon}\gamma_5\gamma^d\Psi^f{}_e(Y). \quad (11)$$

Finally, we write down action (8) in terms of the dual variables

$$Y^{ab,c} = \frac{1}{2}\varepsilon^{abdf}\mathcal{Y}_{df,}{}^{c}; \quad (12)$$

after that, it becomes

$$S = -\frac{1}{4k^2}\int d^4xe\left[\frac{1}{2}e^m_a e^n_b C_{mn,c}\varepsilon^{abdf}\mathcal{Y}_{df,}{}^{c} - \right.$$

$$\left. -\frac{1}{4}\mathcal{Y}_{ab,c}\mathcal{Y}^{ab,c} - \frac{1}{2}\mathcal{Y}_{ab,c}\mathcal{Y}^{ac,b} + \mathcal{Y}_{ab,}{}^{b}\mathcal{Y}^{ac,}{}_{c}\right] -$$

$$-\frac{i}{2}\int d^4x\, e\bar{\psi}_m\gamma^{mnk}D_n(\mathcal{Y})\psi_k. \quad (13)$$

The covariant derivative acting on the gravitino is

$$D_m(\mathcal{Y})\psi_n = \left(\partial_m + \frac{1}{8}\varepsilon^{abcd}e^e_m\gamma_{ab}\mathcal{Y}_{cd,e} + \right.$$

$$\left. +\frac{1}{8}e^a_m\varepsilon^{bcde}\gamma_{ab}\mathcal{Y}_{de,c}\right)\psi_n, \quad (14)$$

and (13) is invariant under the local supersymmetry transformations

$$\delta_\epsilon e^a_m = -ik\bar{\epsilon}\gamma^a\psi_m, \quad \delta_\epsilon\psi_m = \frac{1}{k}D_m(\mathcal{Y})\epsilon,$$

$$\delta_\epsilon\mathcal{Y}_{ab,c} = k\bar{\epsilon}\gamma_5\left(\gamma_c\Psi_{ba}(\mathcal{Y}) + 2\gamma_b\Psi_{ac}(\mathcal{Y}) + 2\gamma_a\Psi_{cb}(\mathcal{Y})\right), \quad (15)$$

with the covariant gravitino curl

$$\Psi_{ba}(\mathcal{Y}) = \partial_b\psi_a + \frac{i}{8}\gamma_5\gamma^{fg}\mathcal{Y}_{fg,b}\psi_a + \frac{1}{4}\varepsilon_{fgeb}\mathcal{Y}^{fg,e}\psi_a -$$

$$-\frac{3i}{4}\gamma_5\gamma^{eg}\mathcal{Y}_{bg,e}\psi_a - (a\leftrightarrow b). \quad (16)$$

3. The Parent Action

After these preparations, we are now ready to construct the non-linear parent action of dual $N = 1$ $D = 4$ supergravity. Following [1], we extend the dual connection $\mathcal{Y}_{ab,c}$ with the curl of a new field. The dual spin-connection becomes

$$\mathcal{F}_{ab,c} = \mathcal{Y}_{ab,c} + F_{ab,c}, \quad (17)$$

where

$$F_{ab}{}^{,c} = 2\partial_{[a}\mathcal{C}_{b]}{}^{,c}. \quad (18)$$

The field $\mathcal{C}_{a,b}$ is the dual to the graviton field.

Substituting the dual spin-connection (17) into (13), we arrive at

$$S = -\frac{1}{4k^2}\int d^4xe\left[\frac{1}{2}e^m_a e^n_b C_{mn,c}\varepsilon^{abdf}\mathcal{Y}_{df,}{}^{c} - \right.$$

$$\left. -\frac{1}{4}\mathcal{F}_{ab,c}\mathcal{F}^{ab,c} - \frac{1}{2}\mathcal{F}_{ab,c}\mathcal{F}^{ac,b} + \mathcal{F}_{ab,}{}^{b}\mathcal{F}^{ac,}{}_{c}\right] -$$

$$-\frac{i}{2}\int d^4x\, e\bar{\psi}_m\gamma^{mnk}D_n(\mathcal{F})\psi_k. \quad (19)$$

This is a supersymmetric extension of the action constructed in [1]. The covariant derivative acting on the gravitino is

$$D_m(\mathcal{F})\psi_n = \left(\partial_m + \frac{1}{8}\varepsilon^{abcd}e^e_m\gamma_{ab}\mathcal{F}_{cd,e} + \right.$$

$$+\frac{1}{8}e^a_m\varepsilon^{bcde}\gamma_{ab}\mathcal{F}_{de,c}\Big)\psi_n, \quad (20)$$

and we have omitted the total derivative term $de^a \wedge d\mathcal{C}^b\eta_{ab}$ in (19).

The action we get possesses the same symmetries as its non-supersymmetric predecessor. It is invariant under the local diffeomorphisms, local Lorentz transformations, and a special shift symmetry

$$\delta\mathcal{Y}_{ab}{}^{,c} = 2\partial_{[a}\Sigma_{b]}{}^{,c}, \qquad \delta\mathcal{C}_a{}^{,b} = -\Sigma_a{}^{,b}, \quad (21)$$

which leaves $\mathcal{F}_{ab,c}$ invariant. The analysis of these symmetries is the same, as it has been done in [1], so we refer the reader to this reference for details.

The rest of the symmetries of (19) is the local supersymmetry, to the consideration of which we now turn. The supersymmetry transformations which leave the action invariant are

$$\delta_\epsilon e^a_m = -ik\bar{\epsilon}\gamma^a\psi_m, \quad \delta_\epsilon\psi_m = \frac{1}{k}D_m(\mathcal{F})\epsilon,$$

$$\delta_\epsilon\mathcal{F}_{ab,c} = k\bar{\epsilon}\gamma_5\left(\gamma_c\Psi_{ba}(\mathcal{F}) + 2\gamma_b\Psi_{ac}(\mathcal{F}) + 2\gamma_a\Psi_{cb}(\mathcal{F})\right). \quad (22)$$

Since we have known the transformation law of $\mathcal{Y}_{ab,c}$, Eq. (15), the local supersymmetry transformation of the dual "field strength" is read off (22). This results in

$$\delta_\epsilon\partial_{[a}\mathcal{C}_{b,]c} = \frac{1}{2}k\bar{\epsilon}\gamma_5\ \times$$

$$\times\ \left[\gamma_c\Phi_{ba}(\partial\mathcal{C}) + 2\gamma_b\Phi_{ac}(\partial\mathcal{C}) + 2\gamma_a\Phi_{cb}(\partial\mathcal{C})\right], \quad (23)$$

where

$$\Phi_{ba}(\partial\mathcal{C}) = \frac{i}{8}\gamma_5\gamma^{fg}\partial_f\mathcal{C}_{g,b}\psi_a + \frac{1}{4}\varepsilon_{fgeb}\partial^f\mathcal{C}^{g,e}\psi_a -$$

$$-\frac{3i}{4}\gamma^{eg}\partial_b\mathcal{C}_{g,e}\psi_a - (a\leftrightarrow b). \quad (24)$$

Let us turn to the discussion of (23). Note first that (22) is similar to a standard form of the spin-connection supersymmetry transformation: the variation of the connection is expressed through a function depending on the connection (see (4), (11), (15)). The field dual to the graviton one enters the generalized connection $\mathcal{F}_{ab,c}$ through the "field strength" $F^a = dC^a$. Its transformation law is a part of the supersymmetry transformations (22); hence, (23) has the standard, if we treat it as a spin-connection, form. On the other hand, one may notice that $C_m{}^{,a}$ is the field dual to e^a_m. The vierbein possesses its own transformation under the local supersymmetry, Eq. (3). The same may be expected for $C_m{}^{,a}$, so the problem is how to read off the supersymmetry transformation of 'bare' $C_m{}^{,a}$ from (23).

We have not a good recipe to solve this problem in a local way. The point is that the dual field is transformed under the local Lorentz transformations as [1]

$$\delta\mathcal{C}_a{}^{,b} = \tilde{\Lambda}_a{}^b + \ldots, \quad (25)$$

with the dual parameter $\tilde{\Lambda}_a{}^b = -\tilde{\Lambda}^b{}_a$. We can fix $\tilde{\Lambda}_a{}^b$ to remove the antisymmetric part of $\mathcal{C}_a{}^{,b}$, i.e. $\mathcal{C}_{[a}{}^{,b]} = 0$. Then, Eqs. (23), (24) get transformed into

$$\delta_\epsilon\partial_{[a}\mathcal{C}_{b],c}|_{\text{gauge fixed}} = -\frac{i}{8}k\bar{\epsilon}\mathcal{M}^{efg}_{cba}\gamma_e(\gamma^{ij}\partial_i\mathcal{C}_{j,f})\psi_g, \quad (26)$$

where we have introduced

$$\mathcal{M}^{efg}_{cba} = \delta^e_c\delta^{fg}_{ba} + 2\delta^e_b\delta^{fg}_{ac} + 2\delta^e_a\delta^{fg}_{cb}, \qquad \delta^{fg}_{ba} \equiv \delta^f_{[b}\delta^g_{a]}.$$

It becomes clear that the structure of Eq. (26) does not allow one to extract the supersymmetry transformation of $C_m{}^{,a}$ in a straightforward and local way.

4. Conclusions

To summarize, we have constructed a supersymmetric extension of the parent action of dual $D = 4$ gravity proposed in [1]. This procedure does not break the locality of the action, its symmetries (excluding supersymmetry, cf. (23), (26), and see the discussion below), and equations of motion. Constructing the action, we followed the same routine of field transformations which was realized in [1, 8], getting started with the classical action of $D = 4$ simple supergravity. Using the explicit form of the spin-connection supersymmetry transformations, usually ignored, essentially simplified the derivation of supersymmetry rules after the dualization.

Before introducing a field dual to the graviton one, all the supersymmetry transformations are local. Once the dual field is taken into account, a non-locality appears through the dual field strength supersymmetry transformation. We have found in [3] that a by-product of the dualization is the non-locality of gauge transformations of dual fields. To be precise, the field dual to the graviton one possesses a non-local symmetry when it is transformed under the Lorentz transformations in the tangent space. Here, we have found another example of non-locality in gauge transformations which appears after dualization+supersymmetrization of the problem.

On the other hand, it is not so surprising that we get non-local supersymmetry transformations at the end. A reason for that follows from the previous experience in the construction of a hidden symmetry algebra upon the toroidal dimensional reduction of $N = 1$ $D = 4$ supergravity to one dimension [18]. We recall that fermions are needed to enlarge the hidden symmetry algebra in one dimension to a hyperbolic Kac–Moody algebra. The enlargement is realized due to an interplay between two types of transformations, the Ehlers transformations and the Matzner–Misner transformations (see [18] for details). These transformations are non-local when they act on the dual bosonic fields. Supersymmetry has to be a part of the hidden symmetry structure which also acts nonlocally on the field dual to the graviton one.

An interesting problem for the further study is to obtain a modification of the supersymmetry transformations of parent actions in the case of extended or higher-dimensional supergravities, when the antisymmetric gauge fields are taken into account. It would also be interesting to realize, in such a perspective, the applicability of the approach of [1] to duality-symmetric theories, in particular, to the description of the self-dual part of the D=10 type IIB supergravity action in a manifestly covariant way.

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APPENDIX A. Notation and conventions

Our notation is as follows: indices from the beginning of the Latin alphabet are vector flat indices, and those of the middle of the Latin alphabet are curve ones. Spinor indices are hidden.

The Levi-Civita tensor is chosen to be

$$\varepsilon_{abcd}\varepsilon^{abcd} = -4!,$$

we use the mostly minus signature with $\eta_{ab} = \mathrm{diag}(+,-,-,-)$.

The torsion and curvature tensors are defined by

$$T^a = de^a + \omega^a{}_b \wedge e^b,$$

$$R^{ab} = d\omega^{ab} + \omega^{ac} \wedge \omega_c{}^b,$$

that corresponds in the coordinate basis to

$$T_{mn}{}^a = \partial_m e^a_n + \omega_m{}^{ab} e_{nb} - (m \leftrightarrow n)$$

and to Eq. (2). The external derivative d acts from the left.

For the γ-matrices, we use

$$\gamma^{ab} = \frac{1}{2}[\gamma^a, \gamma^b], \qquad \gamma^{abc} = \frac{1}{2}\{\gamma^a, \gamma^{bc}\}.$$

We define

$$\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3,$$

then

$$\gamma^{abcd} = -i\gamma_5\varepsilon^{abcd}, \qquad \gamma^{abc} = -i\varepsilon^{abcd}\gamma_5\gamma_d.$$

Spinors are Majorana ones, the covariant derivative is defined by

$$D_m\psi_n = \left(\partial_m + \frac{1}{4}\omega_{mab}\gamma^{ab}\right)\psi_n.$$

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НЕЛІНІЙНА МАЙСТЕР-ДІЯ І ДУАЛЬНА $N = 1$ $D = 4$ СУПЕРГРАВІТАЦІЯ

О.Ю. Нурмагамбетов

Р е з ю м е

Запропоновано $N = 1$ узагальнення суперсиметричної нелінійної дії $D = 4$ дуальної гравітації праці [1]. Дія дуальної супергравітації і всі симетрії моделі, крім суперсиметрії, реалізовано локальним чином.