GENERALIZED ACTION PRINCIPLE FOR SUPERSTRINGS AND SUPERMEMBRANES

Dmitrij V. Volkov
NSC Kharkov Institute of Physics and Technology
Kharkov, Ukraine
e-mail: kfti@rocket.kharkov.ua

Two approaches concerning the connection of the fermionic kappa – symmetry with the superstring world – sheet superdiffeomorphism transformations are discussed. The first approach is based on the twistor – like formulation of the superstring action and the second one on a reformulation of the superstring and super - p - brane actions according to the Generalized Action Principle.

1. Introduction

Superstrings (and supermembranes) are extended objects not only in the bosonic directions but also in the fermionic ones. The description of the bosonic directions of these objects can be done by the classical geometrical methods while, on the other hand, the description of the fermionic directions is up to now not satisfactory.

The historically first version of superstring theory proposed by Ramond, Neveu and Schwarz (RNS) is very complicated in exposing the target space supersymmetry. On the other hand, the celebrated Green–Schwarz (GS) formulation, being manifestly invariant in respect to the target space supersymmetry is not so in respect to the supersymmetry on the world sheet, the κ–symmetry being substituted for the latter.

Twistor–like reformulation of superparticle and superstring actions has explained the origin and the geometrical meaning of the κ–symmetry as the world sheet superdiffeomorphism. But at the same time the twistor–like approach to superstrings has its foundation on the geometrical principles which have little in common with whose used in the case of bosonic strings.

In this lecture after discussing the motivation, main ideas and shortcomings of the twistor – like approach we will consider its reformulation on the basis of the Generalized Action Principle (GAP) which was previously applied to the supergravity theories. It will be shown that GAP very conveniently formalizes the geometric procedure of minimal embedding for supersymmetric extended objects retaining at the same time all equations and constraints of the standard twistor like approach.
2 Twistor reformulation of superparticle and superstring action

If a theory has underlying local symmetries the latter exhibit themselves in the appearance of constraints. Investigation and reformulation of constraints may give new insight in the symmetry properties of the considered theory and help to find its more adequate formulation.

We begin with consideration of the simplest case of the $s = 0$ massless relativistic particle. Considering the twistor form of the constraints we will get the twistor formulation of the relativistic particle action. Then we will generalize our consideration to the cases of the spinning particle and superparticle, which are the limiting cases of the RNS and GS superstrings, and will get the twistor formulation for these cases.

And lastly we will go to superstrings and do some general conclusions which will help to understand the main part of the lecture where the Generalized Action Principle is introduced and exemplified by its application to the heterotic string.

2.1 Twistor reformulation of the massless $s = 0$ relativistic particle action.

For the massless relativistic particle with spin $s = 0$, constraints follow immediately from the particle action

$$\mathcal{L} = \frac{1}{2} e^{-1} \dot{x}^m \dot{x}_m - \frac{1}{2} e^2 p^2 \Rightarrow \text{constraints} \begin{cases} \dot{x}^2 = 0 \\ p^2 = 0 \end{cases}$$

(1)

For $D = 3, 4, 6$ and $10$ the constraints (1) are satisfied if $\dot{x}^m$ (or $p_m$) are represented in the twistor form

$$\dot{x}^m = \lambda \Gamma^m \lambda p_m = -\alpha \lambda \Gamma_m \lambda$$

(2)

Using (2), the massless particle action can also be reformulated as

$$\mathcal{L} = p_m (\dot{x}^m - \lambda \Gamma^m \lambda) \text{ or } \mathcal{L} = (\lambda \Gamma^m \lambda) \dot{x}^m$$

2.2 Spinning particle.

The spinning particle action has the well known form

$$\mathcal{L} = p_m \dot{x}^m - \frac{1}{2} e^2 p^2 - \frac{1}{2} \psi^m \dot{\psi}_m - i \xi \psi^m p_m$$

(3)

which gives the constraints

$$p^2 = 0 \text{ or } \psi^m p_m = 0$$

(4)

The first of constraints (4) is the same as (2); the second constant is its superpartner. Let us try for the both constraints the twistor representation

$$p_{\alpha \beta} = \lambda_\alpha \lambda_\beta \text{ or } \psi^{\alpha \beta} = \lambda^\alpha \theta^\beta + \theta^\alpha \lambda^\beta$$

(5)

where for simplicity we consider $D=3$ case.

After substitution (2) into (3) it can be easily seen that on the mass – shell the action (3) becomes

$$\mathcal{L} = \lambda^\alpha \lambda^\beta \{ \ddot{x}_{\alpha \beta} - \frac{i}{2} (\theta_\alpha \dot{\theta}_\beta + \theta_\beta \dot{\theta}_\alpha) \}$$

(6)
with the explicit target space supersymmetry and is equivalent to the Brink – Schwarz superparticle action.

As it follows from (8) \( \theta^a \) and \( \lambda^a \) are the superpartners. This point is the most important for further generalization and constitutes the base of twistor – like formulations (including the superspace ones) of superparticles, superstrings and supermembranes.

### 2.3 Supersymmetrization of the twistor particle action.

We will show now that the superspace formulation of the action (6) can be get by an immediate supersymmetrization of the action

\[
\mathcal{L} = p_m (\dot{x}^m - \lambda \Gamma^m \lambda) 
\]  

(7)

Using superfields

\[
P_m = p_m + i \eta \rho_m; \quad X^m = x^m + i \eta \psi^m \quad \Theta_\alpha = \theta_\alpha + \eta \lambda_\alpha
\]

we can supersymmetrize on the world – line each of two terms of the action, which procedure gives the action also as the sum of two terms

\[
S = \int d\tau d\eta P_m (\mathcal{D} X^m - i \Theta \Gamma^m \mathcal{D} \Theta) 
\]

(8)

\[
\mathcal{D} = \frac{\partial}{\partial \eta} + i \eta \frac{\partial}{\partial \tau}
\]

It is remarkable that the action (8) is target space invariant as well as local super world – sheet invariant.

It can be easily shown that (8) is equivalent to the Brink – Schwarz action for D=3 superparticle.

Let us briefly consider some points which follow from (8)

a) Since the structure of constraints is essential for understanding the main ideas of twistor – like approach let us consider how it is got from the action (8).

By variation of \( P_m \) we get the equation

\[
\mathcal{D} X^m - i \Theta \Gamma^m \mathcal{D} \Theta = 0
\]

(9)

which usually called as the ”geometrodynamical” condition.

Its integrability condition

\[
\partial_\tau X^m - i \Theta \Gamma^m \partial_\tau \Theta = i \mathcal{D} \Theta \Gamma^m \mathcal{D} \Theta
\]

(10)

gives the constraint

\[
(\partial_\tau X^m - i \Theta \Gamma^m \partial_\tau \Theta)^2 = 0
\]

(11)

We see that the constraint (11) is a superfield generalization of (2).

b) The action admits n=D-2 supersymmetrization for D=3,4,6 and 10

\[
S = \int d\tau d^n \eta P_m^a (\mathcal{D}_q X^m - i \Theta \Gamma^m \mathcal{D}_q \Theta)
\]

\[
\mathcal{D}_q = \frac{\partial}{\partial \eta^q} + i \eta^q \frac{\partial}{\partial \tau}
\]
c) It can be shown that the Lagrange multipliers in (8) give no propagating degrees of freedom.

d) In component formulation superfield \( \Theta \) is \( \Theta^\alpha = \theta^\alpha + \eta^\alpha \lambda_\alpha + \ldots \) so that twistor variables \( \lambda \)'s are the superpartners of \( \theta \)'s.

e) On the mass shell the superdiffeomorphism of (8) reproduces the \( \kappa \) – symmetry.

2.4 \( \kappa \) – symmetry.

Let us consider the last point in more details.

The local fermionic symmetry, known as the \( \kappa \) – symmetry was introduced in the papers [3] for the superparticle and in [2] for the superstring.

Introduction of the \( \kappa \) – symmetry has solved the problem of redundant fermionic degrees of freedom, but at the same time it has contained a number of undesirable features: obscure geometrical meaning, the ensuing constraints are infinitely reducible, the on mass shell formulation is only available. All these points is a handicap to covariant quantization of superstring theories.

To get the idea how the \( \kappa \) – symmetry is related to the worldsheet superdiffeomorphism we consider the \( \kappa \) – transformations

\[
\delta \theta = i(\Gamma p)\kappa \quad \delta x^m = i\theta \Gamma^m \delta \theta
\]

For the simplest case \( D = 3 \) superparticle

\[
\delta \theta_\alpha = p_{\alpha\beta} \kappa^\beta
\]

Recalling that \( p_{\alpha\beta} = \lambda_\alpha \lambda_\beta \)

\[
\delta \theta_\alpha = \lambda_\alpha \lambda_\beta \kappa^\beta = \lambda_\alpha (\lambda_\beta \kappa^\beta) = \lambda_\alpha \alpha(\kappa)
\]

we get that \( \alpha(\kappa) \) is the odd parameter of superdiffeomorphism transformations.

In general for \( D = 3,4,6,10 \), if \( p^m = \lambda \Gamma^m \lambda \), then one of \( \lambda \)'s in the \( \kappa \) – transformation together with \( \kappa \) spinor forms \( \alpha(\kappa) \) – superdiffeomorphism parameter, and the second \( \lambda \) plays the role of the superpartner of \( \theta \) in respect to these transformations.

The first papers on twistor like actions were [8], [5], [9]. Afterwards a number of authors gave their contributions [10, 11, 12, 14, 13, 15, 16].

Different but practically coinciding variants of twistor – like action for \( D = 3,4,6,10 \) superparticle and superstring were elaborated. All of them solve the problem of the \( \kappa \)– symmetry in the same way as it has been explained above.

At the same time some basic problems have not been solved satisfactory in the known versions of the approach both from the aesthetic and practical point of view. For instance, for constructing the superfield action one should use superfield Lagrange multipliers. Though some of their components can be identified (on the mass shell) with the momentum density and the tension of the super–p–brane, in general, the geometrical and physical meaning of Lagrange multipliers is obscure. Moreover, in a version suitable for the description of \( D=10 \), 11 objects [14], [15] their presence in the action gives rise to some new symmetries which turn out to be infinite reducible themselves, so that the problem which we fought in the conventional Green–Schwarz formulation reappeared in a new form in the twistor–like formulation.

Another point concerning Lagrange multipliers is that in the superfield formulation of \( D=10 \) type II superstrings [13] and a \( D=11 \), \( N=1 \) supermembrane [17] Lagrange multipliers become propagative redundant degrees of freedom which may spoil the theory at the quantum level.
Concluding this part of the lecture we note that the twistor–like approach has allowed to construct world–sheet superspace formulation of superparticle and superstring actions, which has together with nice features some mentioned above drawbacks.

The latter are connected with introduction of Lagrange multipliers into the theory, which in its turn is due to the fact that the corresponding actions are defined by means of the Beresin integral, which is not an exterior differential form and has no clear geometrical meaning.

In the next part of the lecture we will see that the application of E. Cartan’s methods of differential geometry to the twistor approach makes the theory more selfconsistent.

3 The Generalized Action Principle

Geometrical features of classical and quantum field theories as well as of the theory of (super)particles and (super)strings can be the most adequately expressed by using the exterior differential forms, firstly proposed by E. Cartan.

E. Cartan’s method has began to be widely used in the elementary particle physics in the end of the 60’s when general methods of phenomenological Lagrangians and gauge fields were elaborated.

The advantage of applying exterior differential forms to construct action for Goldstone fermions and supergravity was demonstrated as early as in 1972 – 1973 years [17] – [19].

An important step in applying E. Cartan’s method to supergravity was made in the end of the 70’s when Regge, Ne’eman, D’Auria and Fre had formulated the Generalized Action Principle together with the rheonomy principle [21], which allowed to extrapolate in some cases a component formalism of supergravity on the superspace.

Here we apply GAP together with a new principle, which we name as rheotropy principle (and which is an analog of rheonomy one) to formulate the procedure of minimal embedding of super world sheet of superstrings and supermembranes into the target superspace [10].

We formulate the GAP for these cases as follows [22]:

i) The action is a differential (p+1)–superform integrated over the (p+1)–dimensional bosonic submanifold \( \mathcal{M}_{p+1} \) : \( \{ (\xi^m, \eta); \eta = \eta(\xi) \} \) on the world supersurface

\[
S = \int_{\mathcal{M}_{p+1}} \mathcal{L}_{p+1}.
\]

The Lagrangian \( \mathcal{L}_{p+1} \) is constructed out of the vielbein differential one–forms in the target superspace and world supersurface (\textit{a priori} considered as independent) by use of the exterior product of the forms without any application of the Hodge operation.

To get the superfield equations of motion both the coefficients of the forms and the world supersurface are varied.

ii) The intrinsic geometry of the world supersurface is not \textit{a priori} restricted by any superfield constraints. All the constraints and the geometrodynamical conditions are obtained as variations of the action.

\[\text{At that time E. Cartan’s geometric ideas and his method of the exterior differential forms were not well known to the particle theorists. The most striking example is the work of S. Ferrara, D. Freedman and P. Van Nieuwenhuizen [20]. The authors, being acquainted with our articles [18], nevertheless, used the cumbersome second order formalism to rediscover } N = 1 \text{ supergravity action.}\]
iii) The field variations of the action gives two kinds of relations:
1) relations between target superspace and world supersurface vielbeins which orientate them along one another and are the standard relations of surface embedding theory; we call them “rheotropic” conditions (‘rheos’ is ‘current’ and ‘tropos’ is ‘direction, rotation’ in Greek)
2) dynamical equations causing the embedding to be minimal.
Only the latter equations put the theory on the mass shell.

iv) The theory is superdiffeomorphism invariant off the mass shell if for the action to be independent on the surface $\mathcal{M}_{p+1}$ (i.e. $dL_{p+1} = 0$) only the rheotropic relations are required, and the latter do not lead to equations of motion.

With all these points in mind we propose a super–p–brane action in the following form:

$$S_{D,p} = -\frac{(-1)^p}{p!} \int_{\mathcal{M}_{p+1}} (E^a e^a_0 \ldots e^a_p - \frac{p}{(p+1)} e^a_0 e^a_1 \ldots e^a_p) \varepsilon_{a_0 a_1 \ldots a_p}$$

$$\pm (-i)^{\frac{p(p-1)}{2}} \frac{p}{(p+1)!} \int_{\mathcal{M}_{p+1}} \sum_{k=0}^{p+1} \Pi^m_0 \ldots \Pi^m_{p+1} dX^m_0 \ldots dX^m_{p+1} d\Theta^m_0 \ldots d\Theta^m_{p+1}$$

where the exterior product of the differential forms is implied, $\varepsilon_{a_0 a_1 \ldots a_p}$ is the unit antisymmetric tensor on $\mathcal{M}_{p+1}$. $e^a(\xi, \eta)$ are the bosonic vector components of a world supersurface vielbein one–form $e^A = (e^a, e^{a\bar{p}})$. The external differential $d$

$$d = e^a D_a + e^{a\bar{p}} D_{a\bar{p}}$$

with $D_a$, $D_{a\bar{p}}$ being world–supersurface covariant derivatives.

$$\Pi^m = dX^m - id\Theta^m \Theta, \quad d\Theta^m$$

is a pullback onto world supersurface of the vielbein forms in flat target superspace.

$$E^m = \Pi^m u^a_m,$$

$u^a_m$ are the fibre coordinates of the target space vector vielbein fibre bundle, usually called in physical literature as vector Lorentz harmonics $[23]$; $u^{a}_m (a = 0, \ldots, p)$ and $u^{i}_{m} (i = p + 1, \ldots, D)$ are its subsets.

The vector Lorentz harmonics can be expressed by means of the spinor Lorentz harmonics $[11, 12]$ by the relations

$$\delta_{\bar{q}p}(\gamma_a)_{\alpha\beta} u^a_m = v_{\alpha q} \Gamma^{\bar{m}} \nu_{\beta p}, \quad \delta_{\bar{q}p}(\gamma_a)^{\alpha\beta} u^a_m = v^a_{\bar{q}} \Gamma^\bar{m} \nu^\beta_p$$

$$\delta^{a}_{\alpha} \gamma_{\bar{q}p} u^i_m = v_{\alpha q} \Gamma^m \nu^\beta_p$$

(12)

4 Generalized action principle for heterotic superstring

The action for $D = 3, 4, 6, 10$ heterotic string has the form

$$S = \int_{\mathcal{M}_2} \mathcal{L}$$
\[ \mathcal{L} = -\frac{1}{2\sqrt{\alpha'}} (E^{++}e^{--} - E^{--}e^{++} + e^{--}e^{++}) + \mathcal{L}_{WZ} \]
\[ \mathcal{L}_{WZ} = -i \frac{\Pi^m \alpha' \Theta}{\sqrt{\alpha'}} \]

where \( \alpha' \) is the Regge slope parameter (inverse string tension).

In (13) \( e^a(\xi, \eta) \equiv (e^{++}(\xi, \eta), e^{--}(\xi, \eta)) \) are bosonic vector zweinbein one-forms. The complete basis (supervielbein) contains also \((D-2)\) fermionic 1-forms \( e^{+q}(\xi, \eta) \):

\[ e^A = (e^{++}, e^{--}, e^{+q}) \]

the latter are not involved into the construction of the action. The external differential \( d \) is:

\[ d = e^{\pm\pm}D_{\pm\pm} + e^{+\nu}D_{\nu} \]

with \( D_{\pm\pm}, D_{+\nu} \) being world supersurface covariant derivatives.

\[ \Pi^m = dX^m - id\Theta \Gamma^m \Theta, \quad d\Theta^\mu \]

and

\[ E^A = (E^{++}, E^{--}, E^{+q}) \]

Moving frame vectors \( u^{\pm\pm}_m(\xi, \eta), \ u^i_m(\xi, \eta) \) are naturally composed of the spinor components (Lorentz harmonics) [12] \( v^\mu_m = (v^{\mu+}_m, v^{\mu-}_m) \) We present the corresponding expressions for the simplest \( D = 3 \) case

\[ u^{++}_m \Gamma^m_{\mu\nu} = 2v^{\mu+}_m v^{\nu+}_m, \quad u^{--}_m \Gamma^m_{\mu\nu} = 2v^{\mu-}_m v^{\nu-}_m, \quad u^{\pm\pm}_m \Gamma^m_{\mu\nu} = v^{++}_m v^{--}_m + v^{+-}_m v^{--}_m, \]

\[ v^{-\mu} v^{+\mu} \equiv v^{-\nu} v^{+\nu} \equiv v^{-\mu} \epsilon^{\mu\nu} v^{+\nu} = 1. \]

The last term in (13) is Wess-Zumino term, its coefficient being fixed by the requirement that when the action (13) is restricted to the component formulation of the superstring the resulting action has local \( \kappa \)-symmetry.

To get the equations of motion, constraints and rheotropic relations let us vary the action (13) and then project the result on the world-sheet supervielbein (14)

\[ \frac{\delta S}{\delta e^{\pm\pm}} = 0 \Rightarrow E^{++} \equiv \Pi^m u^{++}_m = e^{++} \]

\[ u^i_m \frac{\delta S}{\delta u^{\pm\pm}_m} = 0 \Rightarrow E^i e^{++} = 0 \]

which means

\[ E^i \equiv \Pi^m u^i_m = 0 \]

on the world supersurface. Eqs. (19) and (21) are part of the rheotropic relations which define tangent and outer directions of the vector target space vielbein. They can be rewritten in the following form

\[ \Pi^m = \frac{1}{2}(e^{++} u^{--} + e^{--} u^{++}) \]
Eq. (22) means that the embedding of the world supersurface satisfies the geometrodynamical condition

$$\Pi^m_{+q} = D_{+q}X^m - iD_{+q}\Theta\Gamma^m\Theta = 0$$

(23)
as well as the equations

$$\Pi_{\pm m} = D_{\pm}X^m - iD_{\pm}\Theta\Gamma^m\Theta = u^m_{\pm}$$

(24)

which are "the square roots" of the Virasoro constraints $\frac{1}{4}(\Pi_{++m})^2 = 0$, $(\Pi_{--m})^2 = 0$.

The other equations of motion are got by varying $\delta X^m$ and $\delta \Theta^\mu$

$$\frac{\delta S}{\delta X^m} = 0 \Rightarrow d(u^{++}e^{-} - u^{-}e^{++}) = 2id\Theta\Gamma_md\Theta = 0,$$

(25)

$$\frac{\delta S}{\delta \Theta^\mu} = 0 \Rightarrow d\Theta^\mu\Gamma^m_{\mu\nu}(u^{--}e^{++} - u^{++}e^{--} + 2\Pi_m) = 0$$

(26)

Eq.(25) can be reduced to straightforward superfield generalization of the Green–Schwarz equation when (24) is taken into account. It can be proved that this equations are satisfied identically due to 'rheotropic relations' and Eq.(26). Eq.(26) contains the following equation for $\Theta$

$$d_{-}\Theta^m u^{-}_{m\bar{q}} = 0$$

(27)

together with the rheotropic relation

$$d_{+}\Theta^m u^{+}_{m\bar{q}} = 0$$

(28)

for the spinor target space vielbein.

As the Lagrangian of the generalized action coincides with that of the component formalism the leading terms in the superfield expansion in $\eta$’s coincide with those of component formalism.

Equations with $D_{+q}$ allow to spread the solution to the whole superworld surface.

Now we make the last essential remark.

As it can be easily verified the requirement iv) in the definition of GAP is satisfied if the rheotropic relations (19), (21) and (28) are taken into account. If one changes the ratio of the coefficients before the first and second terms in (13) the requirement iv) will not be satisfied. This fact expresses the connection of the $\kappa$ – symmetry with superdiffeomorphism symmetry on the super world – sheet.

5 Resumé.

The twistor – like superfield approach to superstrings and supermembranes is revised, with emphasis upon its drawbacks. It is shown that the newly proposed generalized action principle which is akin to that used in the group manifold approach to supergravity [21] reproduces all the "good results" of the twistor approach and, because there are no Lagrange multipliers in the theory, it is free of its difficulties which are due to their presence in previous formulations.

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Due to the presented below identification of twistor $D_{+q}\Theta^m$ and Lorentz harmonic $v^{-}_{m}$ superfields, one of this relations can be identified with the so-called "twistor constraint" [5, 14, 13, 14, 14].
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