SUPEREMBEDDING APPROACH
AND GENERALIZED ACTION IN STRING/M-THEORY

Igor Bandos
Institute for Theoretical Physics, NSC Kharkov Institute of Physics and Technology,
310108 Kharkiv, Ukraine
and
The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy.

Abstract

A brief introduction to the superembedding approach (SEA) in its variant based on the
generalized action principle (GAP) for super-p-branes is given. A role of harmonic variables
for the Lorentz group is stressed. A relation of the GAP with complete superfield actions is
noted. Recent applications in the study of Dirichlet branes (super-Dp-branes) and M-branes
are discussed.

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2Regular Associate of the Abdus Salam ICTP.
1996 was a hard year for our Science. In January of this year we lost our teacher Dmitrij V. Volkov and, in March, Victor I. Ogievetsky left us.

In this contribution I present a brief description of the generalized action principle (GAP) and the superembedding approach (SEA) for supersymmetric extended objects. We have proposed and elaborated them for $D = 10$ superstrings (now called fundamental strings) and $D = 11$ supermembrane (now called M2-brane) in collaboration with D.V. Volkov [?, ?, ?]. They are based on the works of D.V. Volkov [?] on the doubly supersymmetric twistor-like approach, unify the latter with the Lorentz harmonic approach [?] and, thus, use essentially the concept of harmonic variables, developed by V.I. Ogievetsky and collaborators [?]. So the subject of my talk originates from the work of both these great scientists.

Recently the superembedding approach has been applied for the investigation of super-D-branes [?, ?, ?], super-M5-brane [?, ?] as well as intersecting branes [?] and brane models of gauge theories [?]. A derivation of brane action from superembedding equations, which can be regarded as an inversion of the line of the GAP approach, has been proposed in [?]. The GAP for $D = 11$ supermembrane [?] in $AdS_4 \times M_7$ background has been used to obtain the supersymmetric $Osp(8|4)$ singleton action [?].

In this talk I review the main ingredients of the SEA and the GAP using a relatively simple example of $D = 10$ heterotic string and briefly describe the achievements and problems of the SEA in studying String/M-theory.

1 Generalized action for $D = 10$ heterotic string

1.1. One of the main ingredients of the generalized action (GAP) is the Lagrangian form defined on the world volume superspace

$$\Sigma^{(p+1|\alpha)} = \{(\zeta^M) = \{(\xi^m, \eta^q)\}$$

of the super-p-brane. For $D = 10$ heterotic string ($m = 0, \ldots, 9; p = 1; m = 0, 1; q = 1, \ldots 8$) the Lagrangian two-form \textsuperscript{3}

$$L_2 = \frac{1}{2} E_+^+ \wedge E_-^- - i \Pi^m \wedge d \Theta^m \Theta + \frac{1}{2} E_-^- \wedge \Psi^I d \Psi^I, \quad I = 1, \ldots, 32$$

is constructed from the pull-backs of the basic one forms of target superspace

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

onto the world sheet superspace $\Sigma^{(1+1|\alpha)} = \{(\zeta^M) = \{(\xi^{(\pm)}, \eta^q)\}$

\textsuperscript{3}For simplicity we restrict ourselves to the case of flat target superspace. The generalization for supergravity background is straightforward [?].
\[ \Pi^m = d\zeta^M \Pi^m_M = d\zeta^M (\partial_M X^m (\zeta^{(\pm \pm)}, \eta^\mu) - i \partial_M \Theta \Gamma^m \Theta), \]
\[ d\Theta^\mu = d\zeta^M (\partial_M \Theta \gamma^L (\zeta^{(\pm \pm)}, \eta^\mu) ) \]

and heterotic fermion 1-form
\[ \Psi^I d\Psi^I_- = -d\zeta^M (\partial_M \Psi^I_-) \Psi^I_- (\zeta^{(\pm \pm)}, \eta^\mu) \]

by the use of the external product of the superforms only.

Supervielbein of flat target superspace \( E^\alpha = (E^a, E^\alpha) \)
\[ E^\alpha = (E^{\pm \pm}, E^i) = (\Pi^m a_m^a, \Pi^m u_m^i) \]
\[ E^\alpha = (E^{+q}, E^{-q}) = (d\Theta^\mu v^\mu_{-q}, d\Theta^\mu v^\mu_{+q}) \]

is distinct from the standard one \( (\Pi^m, d\Theta^\mu) \) by a Lorentz rotation. The vector and spinor representations of this \( SO(1, D - 1) \) transformation are given by the matrices

\[ u_m^a = (u_{m^a}^{\pm \pm}, u_m^i) \in SO(1,9) \quad v_\mu^a = (v_{\mu}^{-q}, v_{\mu}^{+q}) \in Spin(1,9) \]
\[ \Leftrightarrow \quad u_m^a \eta_{mn} u_n^b = \eta^{ab} \quad \Leftrightarrow \quad \begin{cases} u_{m}^{++} u_{m}^{++} = 0, & u_{m}^{-} u_{m}^{-} = 0, \\ u_{m}^{--} u_{m}^{++} = 2, & u_{m}^{+-} u_{m}^{--} = -\delta^{ij}, \\ u_{m}^{++} u_{m}^{-} = 0, & u_{m}^{+-} u_{m}^{--} = 0, \end{cases} \]

(vector and spinor \( SO(1,9) \) Lorentz harmonics, see \cite{[7]} and refs. therein). They are related by
\[ u_m^a \Gamma^\mu_{\alpha} = v_\mu^a \Gamma_{\alpha}^\mu \]
\[ u_m^a \Gamma^\delta_{\beta} = v_{\mu}^a \Gamma^\mu_{\beta} \]
\[ \Leftrightarrow \quad \delta_{qp} u_{m}^{++} = v_{q}^{-} \Gamma_{\mu}^{m} v_{p}^{-}, \quad \delta_{qp} u_{m}^{-} = v_{q}^{+} \Gamma_{\mu}^{m} v_{p}^{+}, \quad \gamma_{qp}^i u_m^i = v_q^+ \Gamma_m^i v_p^-, \quad \gamma_{qp}^i u_{m}^{-} = v_q^- \Gamma_m^i v_p^+ , \]

(\text{where} \( \Gamma_m \) \text{and} \( \gamma_{qp}^i \) \text{are the} \( SO(1,9) \) \text{and} \( SO(8) \) \text{\( \gamma \)-matrices}). Their differentials
\[ du_m^a = u_m^b \Omega_{b}^a (d) \quad \Leftrightarrow \quad \begin{cases} du_m^{++} = \pm u_m^{++} \Omega^{(0)} (d) + u_m^{ii} \Omega^{i+j}(d), \\ du_m^{-} = -u_m^{ii} \Omega^{i+j} + \frac{1}{2} v_{m}^{++} \Omega^{(1)} (d), \end{cases} \]
\[ dv_\mu^a = 1/4 v_{\mu}^b (\Gamma_{ab})^b_{\alpha} \Omega^{ab} (d) \]

are expressed in terms of the \( so(1, D - 1) \) valued Cartan 1-forms
\[ \Omega^{ab} = -\Omega^{ba} = \left( \begin{array}{cc} \Omega^{ab} & \Omega^{ij} \\ -\Omega^{ij} & \Omega^{ab} \end{array} \right) = u_m^a du_m^b = \frac{1}{16} dv_\mu^a (\Gamma_{ab})^b_{\alpha} \Omega^{ab} (d) \]

Integrating the Lagrangian form \( \mathcal{L}_2 \) over pure bosonic world sheet
\[ S_0 = \int_{M^{1+1}} \mathcal{L}_2 \equiv \int d^2 \zeta \ e^{mn} (\mathcal{L}_2)_{mn|\eta^\mu = 0} \]
gives the usual (component) superstring action in the first order form \([?, ?]\)). The equations of motion following from the functional \([??]\)

\[
E_i^\alpha \equiv \Pi_{\mu\nu} u^i_{\mu\nu} = 0.
\]

\[
E_{--} \wedge \mathcal{D}\Psi_-^I = 0 \quad \Rightarrow \quad \mathcal{D}\Psi_-^I = E_{--} \mathcal{D} \Psi_-^I \tag{9}
\]

\[
E_q^- = (E^{++} - \frac{1}{2} \Psi_-^I d\Psi_-^I)_{\psi_{++}^{-}} = (E^{++} - E_{-}^{--}) \mathcal{D} \Psi_-^I \tag{10}
\]

\[
E_{--} \wedge \Omega^{++} - (E^{++} - \Psi_-^I d\Psi_-^I) \wedge \Omega^{++} + 4iE_q^+ \wedge E_{qq}^{-} = 0 \tag{11}
\]

\[
E_{--} \wedge \mathcal{D} \Psi_-^I = 0 \tag{12}
\]

can be reduced to the standard superstring equations upon eliminating the auxiliary fields (harmonics). A part of the variations does not produce independent equations. They, hence, can be identified with the parameters of the gauge symmetries:

\[
i_\delta \Omega^{(0)} = \frac{1}{2} u_{--} \delta u^{++} \quad \rightarrow \quad SO(1, 1),
\]

\[
i_\delta \Omega^{ij} = u^i \delta u^j \quad \rightarrow \quad SO(8),
\]

\[
i_\delta E_a \rightarrow \quad \text{'b - symmetry' or reparametrization,}
\]

\[
i_\delta E_q^+ \rightarrow \quad \kappa - symmetry.
\]

The generalized action for \(D = 10\) heterotic string

\[
S = \int_{\mathcal{M}^{1+1}} \mathcal{L}_2 \equiv \int_{\mathcal{M}^{1+1}} \mathcal{L}_2 \left[ \eta^q = \eta^q(\xi) \right] \tag{13}
\]

[?] (see [?] for supergravity) is given by the integral of the Lagrangian 2-form \([??]\) over arbitrary 2 - dimensional bosonic surface

\[
\mathcal{M}^{1+1} = \{ (\xi^{(\pm)}), \eta^{(+)q} : \eta^{(+)q} = \eta^{(+)q}(\xi) \} \quad \in \quad \Sigma^{(1+1|n)}
\]

in the world volume superspace \(\Sigma^{(1+1|n)} = \{ (\xi^{(\pm)}), \eta^{(+)q}) \}. Hence, in the functional \([??]\) all the variables shall be considered as world volume superfields but, taken on the surface \(\mathcal{M}^{1+1}\) (i.e. with \(\eta^q = \eta^q(\xi)\)):

\[
X^m = X^m(\xi, \eta(\xi)), \quad \Theta^\alpha = \Theta^\alpha(\xi, \eta(\xi)), \quad u^a_{m} = u^a_{m}(\xi, \eta(\xi)), \quad \Psi_-^I = \Psi_-^I(\xi, \eta(\xi)).
\]

The variation of the GAP \([??]\) should vanish for arbitrary variations of the (super)fields involved as well as for arbitrary variations of the surface \(\mathcal{M}^{1+1}\) (i.e. \(\delta S/\delta \eta(\xi) = 0\)). For the Lagrangian form under consideration it can be proved that the latter variation does not lead to new equations of motion. Instead, the arbitrariness of the surface \(\mathcal{M}^{(p+1)}\) provides the possibility to regard the 'field' equations \([??], \(??), \(??), \(??), \(??), \(??), \(??), \(??), \(??), \(??), \(??), \(??)\), as equations for forms and superfields defined on the whole world volume superspace \(\Sigma^{(1+1|8)}\).

\[\text{These nontrivial equations are produced by variations of Lorentz harmonic variables } \delta S/i_\delta \Omega^{\pm|++} \equiv \eta^m \delta S/\delta u^m_{\pm|++} = 0 \quad (??), \text{ heterotic fermions } \delta S/\delta \psi_-^I = 0 \quad (??), \text{ and superspace coordinate fields } \delta S/i_\delta E_q^+ \equiv \eta^m \delta S/\delta X^m = 0 \quad (??), \delta S/i_\delta E_q^- \equiv \eta^m \delta S/\delta \Theta^\alpha = 0 \quad (??) \text{ respectively.}\]
2 Superembedding equations of heterotic string and complete superfield action

Thus the GAP produces formally the same equations (??), (??), (??), (??). However, now they can be considered as equations for superfields and differential forms on the world volume superspace \( \Sigma^{(1+1|8)} \).

A pragmatic way to find that a Lagrangian form \( \mathcal{L} \) is proper for constructing the GAP is to prove that corresponding equations are selfconsistent as equations on the world volume superspace \( \Sigma^{(p+1|n)} \) of the super-p-brane, i.e. form the free differential algebra on this superspace [?]).

Eqs. (??), (??), (??), (??) are selfconsistent on \( \Sigma^{(1+1|8)} \) and describe the minimal (on-shell) embedding of the heterotic string world volume superspace \( \Sigma^{(1+1|8)} \) into the flat \( D = 10, N = 1 \) superspace. Not all of them are independent. Eqs. (??), and the bosonic component of (??) \( D_{+} \psi_{+} = 0 \) are independent dynamical superfield equations while Eq. (??) and Grassmann component of (??) \( D_{++} \psi_{+} = 0 \) appear as their consequences.

The off—shell superembedding \( \Sigma^{(1+1|8)} \) is specified by equation (??) only. Eq. (??) can be recognized as the geometrodynamic equation [?, ?, ?] (and refs. therein) or superembedding condition [?, ?, ?]. To justify the equivalence of (??) with the standard form of superembedding equations

\[
E_{i} = \Pi_{m} u_{m}^{i} - 0 \quad \Leftrightarrow \quad \Pi_{m} u_{m}^{i} = \mathcal{D}_{+ q} X^{m} - i \mathcal{D}_{+ q} \Theta \Gamma^{m} \Theta,
\]

(14)

we have to take into account the freedom in choice of the intrinsic supervielbein of the world volume superspace

\[
e^{A} = (e^{\pm \pm}, e^{+ q}) = d \xi^{(\pm \pm)} e^{A^{\pm \pm}} + d\eta^{(+ q)} e^{A^{+ q}},
\]

\[
(d = e^{A} \mathcal{D}_{A} = e^{+ q} \mathcal{D}_{+ q} + e^{\pm \pm} \mathcal{D}_{\pm \pm}),
\]

as well as a freedom to adapt the moving frame (Lorentz harmonics) to the world volume (see [?, ?]) 5.

As it is known [?], for heterotic string the geometrodynamic condition (??) does not contain equations of motion among its consequences. Indeed, from the integrability condition for Eq. (??) one obtains

\[
E_{- q}^{-} = E_{+ q}^{-} + E_{- q}^{+} \quad \text{(15)}
\]

while the superfield equations of motion (??) specifies

\[
\psi_{- q}^{-} = - \frac{1}{2} \psi_{+}^{l} \mathcal{D}_{-} \psi_{+ q}^{l} \psi_{- q}^{-}.
\]

---

5In the presence of heterotic fermions the most convenient choice of the world volume supervielbein is

\[
e_{\pm \pm} = E_{\pm \pm} \equiv \Pi_{m} u_{m}^{\pm \pm}, \quad e_{+ q} = E_{+ q} = 0 \psi_{+}^{l} d \psi_{- q}^{l}, \quad e_{+ q} = E^{+ q} \equiv d \Theta \omega_{q+}^{+}
\]

with \( a = 1/2 \). The harmonic frame can be chosen in such a way that \( \Pi_{m} u_{m}^{i} = 0 \) holds.
In the absence of heterotic fermions the external derivative of the Lagrangian form (??)
\[ dL |_{\Psi_I = 0} = -2iE_i^- \wedge E_i^- \wedge E^{++} + \frac{1}{2} E_i^+ \wedge (E^{++} \wedge \Omega^{\pm \pm I} - 4iE^-_q \wedge E^-_{q\pm} - E^+_{q\pm}) \] (16)
evidently vanishes as a consequence of the geometrodynamic condition (??) only. As the latter has no dynamical content, this statement means the off-shell superdiffeomorphism invariance of the GAP (in the rheonomic sense).

This provides the possibility to construct the complete superfield action using the GAP Lagrangian form \( L_2 \equiv \frac{1}{2} d\zeta^M \wedge d\zeta^N L_{NM} \)
\[ S_{superfield} = \int d^2 \xi d^8 \eta \left( P_{m^+q}^{+q} \Pi^{m+q} + P^{MN} (L_2 - dY)^{NM} \right). \] (17)
Here \( P_{m^+q}^{+q}, P^{MN} \) are Lagrangian multipliers and \( Y = d\zeta^M Y_M \) is an auxiliary 1–form superfield. The functional (??) is just the superfield action for heterotic string discovered in [?], where the GAP Lagrangian form \( L_2 \) was called the ‘Wess–Zumino 2–form’. It is worth mentioning that in all the superfield functionals for superbranes (see [?] and refs. in [?]) the so-called ‘Wess–Zumino form’ is nothing else than the GAP Lagrangian form for the corresponding brane.

When the heterotic fermions are present, the derivative of the Lagrangian form is
\[ dL_2 = dL_2 |_{\Psi_I = 0} + iE_i^- \wedge E_i^- \wedge \Psi^I d\Psi^I + \frac{1}{2} E^{--} \wedge D\Psi^I \wedge D\Psi^I \]
To write the complete superfield action, the inputs from heterotic fermions has to be separated and considered with some care [?, ?, ?, ?].

Thus the GAP produces superembedding equations together with their consequences (including proper equations of motion). This can simplify essentially the study of brane superembeddings. On the other hand, when the Lagrangian form is closed on the surface of nondynamical equations, the GAP can be used for the construction of the complete superfield action.

3 Generalized action and superembedding approach to D-branes and M-branes

The superembedding approach (SEA) demonstrated its strength in studying the new objects of String/M-theory: \( D = 10 \) Dirichlet superbranes (super-Dp-branes) and M5-brane. The equations of motion for these objects had been obtained in the frame of the superembedding approach [?, ?] before the covariant action functionals were constructed [?, ?, ?, ?, ?].

The complete bridge between the covariant actions and the SEA description can be built by constructing the GAP.

The GAP Lagrangian form in all cases includes the same Wess–Zumino term \( L_{p+1}^{WZ} \) as the ‘standard’ (component) action does. So the only problem is to write down the ‘kinetic’ part (in terms of differential forms, without any use of the Hodge operation). This goal is achieved using
Lorentz harmonics $u^m_{\alpha} = (u^m_{\alpha}, u^{\dot{m}}_{\dot{\alpha}}) \in SO(1, D - 1)$ ($a = 0, \ldots p$, $i = 1, \ldots (D - p - 1)$) providing the possibility to adapt the bosonic component of target superspace supervielbein $E^a$ to the superembedding of the world volume superspace

$$E^a = (E^a, E^i), \quad E^a \equiv \Pi^m u^a_m, \quad E^i \equiv \Pi^m u^i_m$$

The GAP for M2-brane (supermembrane) is known since 1995 [?] and is based on the Lagrangian form

$$\mathcal{L}^M_2 = E^\Lambda_3 + \mathcal{L}^{WZ}_2$$

It produces the superembedding equation

$$E^i = 0,$$

its consequence

$$E^a_q \equiv d\Theta^q u^a_{\underline{\alpha} q} = E^a\psi^\alpha_{\underline{\alpha} q}$$

as well as the superfield equations of motion

$$\psi^\alpha_{\underline{\alpha} q} \epsilon^a_{\underline{\alpha} \beta} = 0.$$

The Lagrangian form for $D = 10$ super-Dp-branes

$$\mathcal{L}^{Dp}_{p+1} = E^{\Lambda(p+1)} \sqrt{\det(\eta_{ab} + F_{ab})} + Q_{p-1} \wedge (dA - B_2 - \frac{1}{2} E^b \wedge E^c F_{cb}) + \mathcal{L}^{WZ Dp}_{p+1}$$

[?] includes the auxiliary tensor field $F_{ab} = - F_{ba}$ as well as $(p - 1)$-form Lagrange multiplier $Q_{p-1}$. It produces the generalized gauge field constraints

$$dA - B_2 = \frac{1}{2} E^b \wedge E^c F_{cb},$$

which complete the geometrodynamical condition

$$E^i = 0$$

up to the complete set of superfield equations for any Dp-brane (cf. with [?, ?]). The geometrodynamical equation $E^i = 0$ as well as its consequence (fermionic superembedding condition)

$$E^a_q = E^a \eta_{\beta}^\alpha + E^a \psi^\alpha_{\underline{\alpha} q}$$

and equations of motion

$$\psi^\alpha_{\underline{\alpha} q} (\eta + F)^{-1} ab (\gamma_b)_{\underline{\alpha} \beta} = 0$$

follow from the GAP (??) as well.
It is worth mentioning that the spin–tensor field $h_\beta^\alpha$ involved into the fermionic superembedding conditions $E'^{\alpha2} = E'^{\beta1}_q h_\beta^\alpha + E'^{\alpha}_q \psi_{aq}$ [?], (1997)) is Lorentz group valued

$$h_\beta^\alpha \in \text{Spin}(1,p)$$

and provides the spinor representation for the Cayley image

$$k_b^\alpha \equiv (\eta - F)_{bc}(\eta + F)^{-1} c^a \in \text{SO}(1,p)$$

of the gauge field strength $F_{ab}$ [?]

$$h_{\beta'}^\gamma \gamma_{\beta'\alpha'} h_{\alpha'}^\gamma = h_{\beta\alpha}^b.$$

Returning to M-branes, note that the GAP for $D = 11$ massless superparticle or M0-brane [?] can be constructed on the basis of Lagrangian 1-form

$$\mathcal{L}_1 = P_{-\mu} v_{-\mu A}^a \Gamma_{\mu}^\alpha_\beta \Pi^a, \quad (A = 1, ..., 16)$$

[?] where (cf. [?]) $P_{-\mu}$ is a Lagrange multiplier, and

$$v_{-\mu A}^a = (v_{-\mu A}^-, v_{-\mu A}^+) \in \text{Spin}(1,10)$$

are spinor Lorentz harmonics parametrizing the coset

$$\frac{SO(1,10)}{SO(1,1) \otimes SO(9)} \cong K_9$$

One of the open problems is the construction of the GAP for M5-brane. The superembedding equations for the M5-brane are known [?], producing the same field equations as the covariant action [?, ?] and found many physical applications [?].

However, the natural candidate for the GAP Lagrangian form $\mathcal{L}_0^{M5}$ (see [?]), whose integration over the bosonic world volume provides the first order form for the action [?], produces (in addition to the superembedding equations

$$E^i = 0, \quad E_{aq} = E'^{\beta}_q h_{\beta\alpha} + E^a \psi_{aq}$$

[?]) the equation

$$da = E^a u_a,$$

whose superspace extension has only trivial solutions. As the presence of the closed form $da$ is characteristic for the PST approach, developed for covariant Lagrangian description of self-dual (chiral) fields [?] and used in [?], the problem can be formulated in a more general way as looking for a consistent unification of the GAP with the PST approach. Another possible way consists in searching for reformulation of the M5–brane action in terms of the spin–tensor field

$$h_{\alpha\beta} = h^{abc} x_{\alpha\beta}^{abc}$$
(involved into the fermionic superembedding condition $E_{\alpha q} = E_{\beta q}^{\lambda} \delta_{\alpha \lambda} + F^a \psi_{\alpha a q}$) instead of $H_3 = dB_2 - A_3$ and the PST scalar $a$. A similar reformulation of D3-brane action was found recently [?].

Another relevant problem for further study consists in searching for SEA and GAP description for $D = 11$ KK monopole [?] and M–brane [?].

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