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PAUL DEDECKER

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1. In the classical problems involving a simple integral

$$I_1=\int L(t,\, q^i,\, \dot{q}^i)\, dt\,, \qquad i=1, \cdots, n\,, \tag{1}$$

one is led to the consideration of the Pfaffian form

$$\omega=L\, dt+\frac{\partial L}{\partial \dot{q}^i}\,\omega^i=\frac{\partial L}{\partial \dot{q}^i}\, dq^i-\left(\dot{q}^i\frac{\partial L}{\partial \dot{q}^i}-L\right)dt \tag{2}$$

where

$$\omega^i=dq^i-\dot{q}^i\, dt\,.$$

For example this form ω is the one which gives rise to the "relative integral invariant" of E. Cartan.

In a recent note [1] L. Auslander characterizes the form ω by a theorem equivalent to the following one.

THEOREM 1. *Among all semi-basic forms θ such that*

$$\theta\equiv L\, dt \bmod \omega^i \tag{3}$$

the form ω of (2) *is the only one satisfying the condition*

$$d\theta\equiv 0 \bmod \omega^i\,. \tag{4}$$

In this, a *semi-basic form* is a form for which the local expression contains only the differentials of t, q^i(not of $\dot{q}^i$). The integral I is defined over an arc $\bar{c}$ of a space $\mathscr{W}$ with local coordinates t, q^i, $\dot{q}^i$ satisfying the equations $\omega^i=0$: Therefore in (1) the form $L\,dt$ may be replaced by any θ satisfying (3).

Condition (4) is a special case of a congruence discovered by Lepage [5]. *The purpose of the present note is to give a natural reason for this congruence which goes beyond its nice algebraic expression.*

Let us observe that the space $\mathscr{W}$ is the manifold of 1-dimensional contact elements of a manifold $\mathscr{V}$ with local coordinates t, q^i. The map

$$(t,\, q^i,\, \dot{q}^i)\rightarrow(t,\, q^i)$$

is then the local expression of the natural projection π: $\mathscr{W}\rightarrow\mathscr{V}$. We

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remark that we do not integrate (1) on any arc $\bar{c}$ in $\mathscr{W}$ satisfying $\omega^i=0$ but on such an arc the projection c of which in $\mathscr{V}$ is regular.

2. **Let** U **be the domain** in $\mathscr{V}$ of the coordinates t, q^i; then the $t, q^i, \dot{q}^i$ are defined in an open subset $W \subset \mathscr{W}$ of projection $\pi(W)=U$. If we denote by L_i n real undeterminates, we have coordinates $t, q^i, \dot{q}^i, L_i$ in $W \times R^n$; we then define in this product the Pfaffian form

$$\Omega_W = L\, dt + L_i \omega^i \ . \tag{5}$$

Now, let us cover $\mathscr{W}$ with open sets $W, W', \cdots$; this way we get a family of products $W \times R^n$, $W' \times R^n$, $\cdots$ with forms $\Omega_W, \Omega_{W'}, \cdots$. Using fibre bundle techniques, one proves that over a non-empty intersection $W \cap W'$ the products $W \times R^n$ and $W' \times R^n$ can be glued together in such a way that the forms induced on $W \cap W' \times R^n$ coincide. This yields a fibre bundle $E(\mathscr{W}, R^n)$ over $\mathscr{W}$ as base, with fibre R^n. This bundle is covered by open subsets isomorphic with the products $W \times R^n$ and in which the $t, q^i, \dot{q}^i, L_i$ are local coordinates; there is also on E a global Pfaffian form Ω of local expression (5). Combining the projections $E \to \mathscr{W}$ and $\mathscr{W} \to \mathscr{V}$ we obtain a map $E \to \mathscr{V}$ locally defined by

$$(t, q^i, \dot{q}^i, L_i) \to (t, q^i) \ .$$

We want to characterize in E the extremal arcs c^* of $\int \Omega$ *which have a regular projection in* $\mathscr{V}$.

An extremal arc c^* of $\int \Omega$ has to satisfy the local equations

$$\frac{\partial(d\Omega)}{\partial(dt)} = \frac{\partial(d\Omega)}{\partial(\omega^i)} = \frac{\partial(d\Omega)}{\partial(d\dot{q}^i)} = \frac{\partial(d\Omega)}{\partial(dL_i)} = 0 \ .$$

We have

$$d\Omega = \frac{\partial L}{\partial \dot{q}^i} \omega^i \wedge dt + \left(\frac{\partial L}{\partial \dot{q}^i} - L_i\right) d\dot{q}^i \wedge dt + dL_i \wedge \omega^i \ .$$

These equations are therefore

$$\omega^i = 0 \ , \qquad \left(\frac{\partial L}{\partial \dot{q}^i} - L_i\right) dt = 0 \ , \qquad \frac{\partial L}{\partial \dot{q}^i} dt - dL_i = 0 \ .$$

Since an arc c^* of regular projection in $\mathscr{V}$ cannot satisfy simultaneously $\omega^i=0$ and $dt=0$ it has to lie in the submanifold F of E locally characterized by

$$\frac{\partial L}{\partial \dot{q}^i} = L_i$$

or equivalently by condition (4).

THEOREM 2. *Every arc c^* in E for which $\int\Omega$ is stationary and the projection of which in $\mathscr{V}$ is regular necessarily lies in the submanifold F of E locally defined by the congruence* (4). *Furthermore the projection c of c^* in $\mathscr{V}$ extremizes in the classical sense the integral* (1). *Finally if c is a regular extremal are of* (1) *in $\mathscr{V}$ let c^* be the arc of F the projection $\bar{c}$ of which in $\mathscr{W}$ is the arc of tangent directions to c; then c^* extremizes $\int\Omega$.*

3. **The submanifold** F can be identified with $\mathscr{W}$ in an obvious way so that $\mathscr{W}$ can be considered as a submanifold of E. Then clearly Ω induces ω on $\mathscr{W}$.

THEOREM 3. *If the integral* (1) *is regular there exists a (one-to-one) correspondence between the regular extremal arcs c in $\mathscr{V}$ of* (1) *and the extremal arcs $\bar{c}$ of $\int\omega$ in $\mathscr{W}$ which have a regular projection in $\mathscr{V}$. Starting from an extremal c, the corresponding $\bar{c}$ is the arc the points of which are the tangent directions to c; starting from $\bar{c}$ the corresponding c is its projection in $\mathscr{V}$.*

In this statement, regularity of (1) means that the matrix $(\partial^2 L/\partial\dot{q}^i\partial\dot{q}^j)$ is everywhere non singular.

Theorem 2 and 3 give a complete justification of condition (4). Theorem 3 was actually proved by E. Cartan [2]. These theorems are special cases of similar theorems involving multiple integrals and even those in which the function L depends on higher order contact elements. Theorem 2 was first proved by the author [3], as well as the alluded generalizations.

Combining Theorems 2 and 3 yields the following.

THEOREM 4. *In the regular case, every arc $\bar{c}$ in $\mathscr{W}$ of regular projection in $\mathscr{V}$ which extremizes $\int\omega$ with respect to variations confined to $\mathscr{W}$ does also extremize $\int\Omega$ with respect to variations in the larger space E.*

4. **There is a last question** to be answered: why in Theorem 1 restrict oneself to semi-basic forms?

We can only add to $L.dt$ a linear combination of Pfaffian forms vanishing with ω^i; every such form is a linear combination of the ω^i

and is therefore semi-basic. Hence the restriction to semi-basic forms in Theorem 1 was actually redundant.

However, as mentioned above and as I have proved in various papers (e.g. [3, 4]), the above properties generalize to a multiple integral

$$I_p=\int L(t^\alpha, q^i, q^i_\alpha)\, dt \;, \tag{6}$$

$$dt=dt^1\wedge\cdots\wedge dt^p, \qquad \alpha=1, 2, \cdots, p; \qquad i=1, 2, \cdots, n \;,$$

to be integrated over a p-surface c defined by $q^i=q^i(t^\alpha)$ and where q^i_α stands for $\partial q^i/\partial t^\alpha$. Then $\mathscr{V}$ is of dimension $n+p$ and $\mathscr{W}$ (which is geometrically the manifold of p-dimensional contact elements of $\mathscr{V}$) is of dimension $n+p+np$. We can consider that we integrate (6) in $\mathscr{W}$ over a p-surface $\bar{c}$ of regular projection in $\mathscr{V}$ and solution of the Pfaffian equations

$$\omega^i=dq^i-\sum q^i_\alpha\, dt^\alpha=0 \;.$$

Such a p-surface $\bar{c}$ is formed of the contact elements of dimension p to a regular p-surface in $\mathscr{V}$ and will be called a *p-multiplicity*.

Now in (6) we can add to $L.dt$ any p-form vanishing on all p-multiplicities and all such forms are no longer semi-basic if $p>1$: for example $d\omega^i\wedge dt^3\wedge\cdots\wedge dt^p$ is such one. Nevertheless, the semi-basic forms satisfying the Lepage congrences [5]:

$$\theta\equiv L\, dt \qquad \mathrm{mod}\ \omega^i \;, \tag{7}$$

$$d\theta\equiv 0 \qquad \mathrm{mod}\ \omega^i \;. \tag{8}$$

play an important role for a deeper reason which is actually a *transversality condition*. We briefly discuss this below referring the reader to my memoir [4] for further details.

5. Let $\mathscr{K}$ be a p-dimensional manifold and K a domain of $\mathscr{K}$ with regular boundary K. A map

$$c:\ K\to\mathscr{V}$$

is a domain of integration of (6); it gives rise canonically to a map

$$\bar{c}:\ K\to\mathscr{W}$$

such that for $k\in K$, $\bar{c}(k)$ is the contact element of dimension p to c at k. *A variation* (or *homotopy*) of c is a family of maps

$$c_t:\ K\to\mathscr{V}, \qquad t\in R\;, \qquad c_0=c\;;$$

this yields a variation of $\bar{c}$:

$$\bar{c}_t : K \to \mathscr{W} .$$

We also define $C: K \times R \to \mathscr{V}$, $\overline{C}: K \times R \to \mathscr{W}$ by

$$C(k, t) = c_t(k) , \qquad \overline{C}(k, t) = \bar{c}_t(k) .$$

The corresponding variation of $\int \theta$ is then

$$\Delta = \int_{\bar{c}_t} \theta - \int_{\bar{c}_0} \theta$$

which may be expressed as a sum of two terms:

$$\Delta = \int_{\overline{C}_{0t}} d\theta + \int_{\lambda_{0t}\overline{C}} \theta . \tag{9}$$

The domains of integration $\overline{C}_{0t}$ and $\lambda_{0t}\overline{C}$ are the restrictions of $\overline{C}$ to $K \times I_{0t}$ and $\dot{K} \times I_{0t}$ respectively (where $I_{0t} = [0, t] \subset R$). We say that the variation $\overline{C}$ is *transversal* to θ if this form vanishes on $\lambda\overline{C}$ (restriction of $\overline{C}$ to $\dot{K} \times R$). This being the case, the last integral (or boundary term) in (9) is zero.

Now the variations usually considered are those for which the restriction of C to $\dot{K}$ is constant (fixed boundary variations): for those, $\lambda\overline{C}$ has an everywhere non-regular projection in $\mathscr{V}$, so that every semi-basic form vanishes on $\lambda\overline{C}$. Therefore if we replace in (6) $L.dt$ by a semi-basic p-form θ satisfying (7), all variations with fixed boundary are transversal to it. This would of course not be the case, should we add to $L.dt$ a non-semi-basic p-form vanishing on all p-multiplicities.

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UNIVERSITÉ DE LIÈGE,
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