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<td>A set of integral elements of higher order jet spaces</td>
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<td>Author(s)</td>
<td>Shibuya, Kazuhiro</td>
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<tr>
<td>Citation</td>
<td>Hokkaido University Preprint Series in Mathematics, 925, 1-12</td>
<td></td>
</tr>
<tr>
<td>Issue Date</td>
<td>2008-09</td>
<td></td>
</tr>
<tr>
<td>DOI</td>
<td>10.14943/84074</td>
<td></td>
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<td>Doc URL</td>
<td><a href="http://hdl.handle.net/2115/69732">http://hdl.handle.net/2115/69732</a></td>
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**File Information:**
pre925.pdf

**Hokkaido University Collection of Scholarly and Academic Papers:** HUSCAP
A SET OF INTEGRAL ELEMENTS OF HIGHER ORDER JET SPACES

KAZUHIRO SHIBUYA

1. Introduction

In this paper, we will consider extension of ”Monster Goursat manifold” in [MZ] to multi independent variables case. We denote by \((R, D)\) a pair of a manifold \(R\) and a distribution \(D\) on \(R\).

Historically, the original problem is to characterize the canonical systems \((J^k(M, n), C^k)\) on jet spaces. This problem was studied by Engel, Goursat and E.Cartan and they showed that, generically, the contact systems on \(k\)-jet spaces of 1 independent and 1 dependent variable were characterized as the so-called ”Goursat flags”. But A.Giaro, A. Kumpera and C. Ruiz explicitly pointed out that a Goursat flag of length 3 has singularities in [GKR], that is, they proved the existence of the \((R, D)\) which is a Goursat flag and is not locally isomorphic to \((J^3(M, 1), C^3)\). The correct characterization of the canonical (contact) systems on jet spaces was given by R. Bryant in [B] for the first order systems and K.Yamaguchi in [Y1] and [Y2] for higher order systems for \(n\) independent and \(m\) dependent variables.

To this situation, R. Montgomery and M. Zhitomirskii constructed the ”Monster Goursat manifold” by successive applications of the ”Cartan prolongation of rank 2 distributions [BH]” to a surface and showed that Goursat flag \((R, D)\) of length \(k\) is locally isomorphic to this ”Monster Goursat manifold” in [MZ]

After that, ”Monster Goursat manifolds” are extended to multi dependent variables cases, that is, successive applications of the ”generalized Cartan prolongation” to the space of 1-jets of 1 independent and \(m\) dependent variables in [M2] or ”rank 1 prolongation” in [SY]. And the characterization of the extended Monster Goursat manifolds was given in [SY], [M1].

”Monster manifolds(multi independent variables)” should be the sets of integral elements of higher order jet spaces;

Let \((J^k(M, n), C^k)\) be the \(k\)-jet space and its canonical system(\(\dim M = m + n\)). We define \(\Sigma(J^k(M, n))\) as follows:

\[ \Sigma(J^k(M, n)) := \bigcup_{x \in J^k} \Sigma_x \]

where \(\Sigma_x = \{\text{n-dim integral elements of } (J^k(M, n), C^k)\}\).

The first obstruction to form Monster manifolds is that \(\Sigma\) may not be a manifold. This phenomenon does not appear for 1 independent variable case, due to the lack of the 2-form condition. So the main purpose of this paper is to clarify when a set of integral elements of higher order jet spaces becomes a manifold. In fact we shall prove
Theorem 4.1. $\Sigma(J^k(M^{n+n}, n))$ are not manifolds except for $\Sigma(J^2(M^{1+2}, 2))$ and trivial cases.

Here trivial cases are when $n = 1$ and when $k = m = 1$. In the first case, $\Sigma(J^k(M^{m+1}, 1))$ is a projective bundle over $J^k(M^{m+1}, 1)$ by a rank 1 prolongation. In the second case, $\Sigma(J^1(M^{1+n}, n))$ is the Lagrange-Grassmann bundle over a contact manifold $J^1(M^{1+n}, n)$. We will prove $\Sigma(J^2(M^{1+2}, 2))$ becomes a manifold in [S].

2. Geometric construction of Jet Spaces

In this section, we will briefly recall the geometric construction of jet bundles in general, following [Y1] and [Y2], which is our basis for the later considerations.

Let $M$ be a manifold of dimension $m + n$. Fixing the number $n$, we form the space of $n$-dimensional contact elements to $M$, i.e., the Grassmann bundle $J(M, n)$ over $M$ consisting of $n$-dimensional subspaces of tangent spaces to $M$. Namely, $J(M, n)$ is defined by

$$J(M, n) = \bigcup_{x \in M} J_x, \quad J_x = \text{Gr}(T_x(M), n),$$

where $\text{Gr}(T_x(M), n)$ denotes the Grassmann manifold of $n$-dimensional subspaces in $T_x(M)$. Let $\pi : J(M, n) \to M$ be the bundle projection. The canonical system $C$ on $J(M, n)$ is, by definition, the differential system of codimension $m$ on $J(M, n)$ defined by

$$C(u) = \pi^{-1}_u(u) = \{ v \in T_u(J(M, n)) \mid \pi_*(v) \in u \} \subset T_u(J(M, n)) \xrightarrow{\pi_*} T_x(M),$$

where $\pi(u) = x$ for $u \in J(M, n)$.

Let us describe $C$ in terms of a canonical coordinate system in $J(M, n)$. Let $u_o \in J(M, n)$. Let $(x_1, \ldots, x_n, z^1, \ldots, z^m)$ be a coordinate system on a neighborhood $U'$ of $x_o = \pi(u_o)$ such that $dx_1, \ldots, dx_n$ are linearly independent when restricted to $u_o \subset T_x(M)$. We put $U = \{ u \in \pi^{-1}(U') \mid dx_1|_u, \ldots, dx_n|_u \text{ are linearly independent} \}$. Then $U$ is a neighborhood of $u_o$ in $J(M, n)$. Here $dz^\alpha|_u$ is a linear combination of $dx_i|_u$'s, i.e., $dz^\alpha|_u = \sum_{i=1}^n p_i^\alpha(u) dx_i|_u$. Thus, there exist unique functions $p_i^\alpha$ on $U$ such that $C$ is defined on $U$ by the following 1-forms:

$$\omega^\alpha = dz^\alpha - \sum_{i=1}^n p_i^\alpha dx_i \quad (\alpha = 1, \ldots, m),$$

where we identify $z^\alpha$ and $x_i$ on $U'$ with their lifts on $U$. The system of functions $(x_i, z^\alpha, p_i^\alpha) \ (\alpha = 1, \ldots, m, i = 1, \ldots, n)$ on $U$ is called a canonical coordinate system of $J(M, n)$ subordinate to $(x_i, z^\alpha)$.

$(J(M, n), C)$ is the (geometric) 1-jet space and especially, in case $m = 1$, is the so-called contact manifold. Let $M, \hat{M}$ be manifolds of dimension $m+n$ and $\varphi : M \to \hat{M}$ be a diffeomorphism. Then $\varphi$ induces the isomorphism $\varphi_* : (J(M, n), C) \to (J(M, n), \hat{C})$, i.e., the differential map $\varphi_* : J(M, n) \to J(M, n)$ is a diffeomorphism sending $C$ onto $\hat{C}$. The reason why the case $m = 1$ is special is explained by the following theorem of Bäcklund.
Let \( M \) and \( \hat{M} \) be manifolds of dimension \( m + n \). Assume \( m \geq 2 \). Then, for an isomorphism \( \Phi : (J(M, n), C) \to (J(\hat{M}, n), \hat{C}) \), there exists a diffeomorphism \( \varphi : M \to \hat{M} \) such that \( \Phi = \varphi_* \).

The essential part of this theorem is to show that \( F = \text{Ker} \pi_* \) is the covariant system of \((J(M, n), C)\) for \( m \geq 2 \). Namely an isomorphism \( \Phi \) sends \( F \) onto \( \hat{F} = \text{Ker} \hat{\pi}_* \) for \( m \geq 2 \). For the proof, we refer the reader to Theorem 1.4 in [Y2].

In case \( m = 1 \), it is a well known fact that the group of isomorphisms of \((J(M, n), C)\), i.e., the group of contact transformations, is larger than the group of diffeomorphisms of \( M \). Therefore, when we consider the geometric 2-jet spaces, the situation differs according to whether the number \( m \) of dependent variables is 1 or greater.

(1) Case \( m = 1 \). We should start from a contact manifold \((J, C)\) of dimension \( 2n + 1 \), which is locally a space of 1-jet for one dependent variable by Darboux’s theorem. Then we can construct the geometric second order jet space \((L, E)\) as follows: We consider the Lagrange-Grassmann bundle \( L(J) \) over \( J \) consisting of all \( n \)-dimensional integral elements of \((J, C)\);

\[
L(J) = \bigcup_{u \in J} L_u \subset J(J, n),
\]

where \( L_u \) is the Grassmann manifolds of all Lagrangian (or Legendrian) subspaces of the symplectic vector space \((C(u), d\varpi)\). Here \( \varpi \) is a local contact form on \( J \). Namely, \( v \in J(J, n) \) is an integral element if and only if \( v \subset C(u) \) and \( d\varpi|_v = 0 \), where \( u = \pi(v) \).

Let \( \pi : L(J) \to J \) be the projection. Then the canonical system \( E \) on \( L(J) \) is defined by

\[
E(v) = \pi_*^{-1}(v) \subset T_v(L(J)) \xrightarrow{\pi_*} T_u(J),
\]

where \( \pi(v) = u \) for \( v \in L(J) \). We have \( \partial E = \pi_*^{-1}(C) \) and \( \text{Ch}(C) = \{0\} \) (cf. [Y1]). Hence we get \( \text{Ch}(\partial E) = \text{Ker} \pi_* \), which implies the Bäcklund theorem for \((L(J), E)\) (cf. [Y1]).

Now we put

\[
(J^2(M, n), C^2) = (L(J(M, n)), E),
\]

where \( M \) is a manifold of dimension \( n + 1 \).

(2) Case \( m \geq 2 \). Since \( F = \text{Ker} \pi_* \) is a covariant system of \((J(M, n), C)\), we define \( J^2(M, n) \subset J(J(M, n), n) \) by

\[
J^2(M, n) = \{n\text{-dim. integral elements of } (J(M, n), C), \text{ transversal to } F\},
\]

\( C^2 \) is defined as the restriction to \( J^2(M, n) \) of the canonical system on \( J(J(M, n), n) \).

Now the higher order (geometric) jet spaces \((J^{k+1}(M, n), C^{k+1})\) for \( k \geq 2 \) are defined (simultaneously for all \( m \)) by induction on \( k \). Namely, for \( k \geq 2 \), we define \( J^{k+1}(M, n) \subset J(J^k(M, n), n) \) and \( C^{k+1} \) inductively as follows:

\[
J^{k+1}(M, n) = \{n\text{-dim. integral elements of } (J^k(M, n), C^k), \text{ transversal to } \text{Ker} (\pi_{k-1}^{k})_* \},
\]

where \( \pi_{k-1}^{k} : J^k(M, n) \to J^{k-1}(M, n) \) is the projection. Here we have

\[
\text{Ker} (\pi_{k-1}^{k})_* = \text{Ch}(\partial C^k),
\]

and \( C^{k+1} \) is defined as the restriction to \( J^{k+1}(M, n) \) of the canonical system on \( J(J^k(M, n), n) \).
where the derived system and Cauchy characteristic system of \((R, D)\) are generally defined as follows;

The derived system \(\partial D\) of \(D\) is defined, in terms of sections, by

\[
\partial D = D + [D, D].
\]

where \(D = \Gamma(D)\) denotes the space of sections of \(D\). In general \(\partial D\) is obtained as a subsheaf of the tangent sheaf of \(R\) (for the precise argument, see e.g.\([Y1], [BCG3]\)). Moreover higher derived systems \(\partial^i D\) are defined successively by

\[
\partial^i D = \partial(\partial^{i-1} D),
\]

where we put \(\partial^0 D = D\) by convention.

the Cauchy characteristic system \(\text{Ch}(D)\) of a differential system \((R, D)\) is defined by

\[
\text{Ch}(D)(x) = \{X \in D(x) \mid X d\omega_i \equiv 0 \pmod{\omega_1, \ldots, \omega_s}\} \quad \text{for } i = 1, \ldots, s,
\]

where \(D = \{\omega_1 = \cdots = \omega_s = 0\}\) is defined locally by defining 1-forms \(\{\omega_1, \ldots, \omega_s\}\).

Here we observe that, if we drop the transversality condition in our definition of \(J^k(M, n)\) and collect all \(n\)-dimensional integral elements, we may have some singularities in \(J^k(M, n)\) in general. However, since every 2-form vanishes on 1-dimensional subspaces, in case \(n = 1\), the integrability condition for \(v \in J(J^{k-1}(M, 1), 1)\) reduces to \(v \subset C^{k-1}(u)\) for \(u = \pi_{k-1}^k(v)\). Hence, in this case, we can safely drop the transversality condition in the above construction as in the next section.

3. Rank 1 Prolongation

Let \((R, D)\) be a differential system, i.e., \(R\) is a manifold of dimension \(s + m + 1\) and \(D\) is a subbundle of \(T(R)\) of rank \(m + 1\). Starting from \((R, D)\), we define \((P(R), \hat{D})\) as follows (cf. [BH]):

\[
P(R) = \bigcup_{x \in R} P_x \subset J(R, 1),
\]

where

\[
P_x = \{1\text{-dim. integral elements of } (R, D)\} = \{u \subset D(x) \mid 1\text{-dim. subspaces} \} \cong \mathbb{P}^m.
\]

Let \(p : P(R) \to R\) be the projection. We define the canonical system \(\hat{D}\) on \(P(R)\) by

\[
\hat{D}(u) = p_*^{-1}(u) = \{v \in T_u(P(R)) \mid p_*(v) \in u \subset T_u(P(R)) \xrightarrow{p_*} T_x(R),\n\]

where \(p(u) = x\) for \(u \in P(R)\).

We call \((P(R), \hat{D})\) the prolongation of rank 1 (or Rank 1 Prolongation for short) of \((R, D)\). Then \(P(R)\) is a manifold of dimension \(2m + s + 1\) and \(\hat{D}\) is a differential system of rank \(m + 1\). In case \((R, D) = (M, T(M))\), we have \((P(M), \hat{D}) = (J(M, 1), C)\). Moreover

\[
J^2(M, 1) \subset P(J(M, 1)) \subset J(J(M, 1), 1)
\]

As for the prolongation of rank 1, we have

**Proposition** ([SY]) Let \((R, D)\) be a differential system of rank \(m + 1\) and let \((P(R), \hat{D})\) be the prolongation of rank 1 of \((R, D)\). Then \(\hat{D}\) is of rank \(m + 1\), \(\partial \hat{D} = p_*^{-1}(D)\) and


Ch (\(\hat{D}\)) is trivial. Moreover, if Ch (D) is trivial, then Ch (\(\partial\hat{D}\)) is a subbundle of \(\hat{D}\) of corank 1.

This proposition implies that, starting from any differential system \((R, D)\), we can repeat the procedure of Rank 1 Prolongation. Let \((P^{1}(R), D^{1})\) be the prolongation of rank 1 of \((R, D)\). Then \((P^{k}(R), D^{k})\) is defined inductively as the prolongation of rank 1 of \((P^{k-1}(R), D^{k-1})\), which is called \(k\)-th prolongation of rank 1 of \((R, D)\). Moreover, starting from a manifold \(M\) of dimension \(m+1\), we put

\[
(P^{k}(M), C^{k}) = (P(P^{k-1}(M)), \hat{C}^{k-1})
\]

where \((P^{1}(M), C^{1}) = (J(M, 1), C)\). When \(m = 1\), \((P^{k}(M), C^{k})\) are called “monster Goursat manifolds” in [MZ].

4. Main theorem

In this section, we extend ”Monster Goursat manifolds” to multi independent variables cases, that is, consider geometric construction of the jet spaces without transversality conditions.

Let \((J^{k}(M, n), C^{k})\) be a \(k\)-jet space and its canonical system(\(\dim M = m + n\)). We define \(\Sigma(J^{k}(M, n))\) as follows:

\[
\Sigma(J^{k}(M, n)) := \bigcup_{x \in J^{k}} \Sigma_{x},
\]

where \(\Sigma_{x} = \{n\text{-dim integral element of } (J^{k}(M, n), C^{k})\}\). By definition,

\[
J^{k+1}(M, n) \subset \Sigma(J^{k}(M, n)) \subset J(C^{k}, n) \subset J(J^{k}(M, n), n),
\]

where \(J(C^{k}, n)\) is defined by

\[
J(C^{k}, n) = \bigcup_{x \in J^{k}} C_{x}, \quad C_{x} = \text{Gr}(C^{k}(x), n),
\]

i.e. \(C_{x}\) is the Grassmann manifold consisting of \(n\)-dimensional subspaces in \(C^{k}(x)\). Note that

\[
\Sigma(J^{k}(M, 1)) = J(C^{k}, 1) = P(J^{k}(M, 1)).
\]

\(J^{k+1}(M, n)\) is an open dense subset in \(\Sigma(J^{k}(M, n))\), so the codimension of \(\Sigma(J^{k}(M, n))\) equals to the codimension of \(J^{k+1}(M, n)\) in \(J(C^{k}, n)\).

Generally \(\Sigma(J^{k}(M, n))\) is a variety and is not a submanifold in \(J(C^{k}, n)\). In fact we have

**Theorem 4.1.** \(\Sigma(J^{k}(M^{m+n}, n))\) are not manifolds except for \(\Sigma(J^{2}(M^{1+2}, 2))\) and trivial cases.

**Remark 4.2.** \(\Sigma(J^{k}(M^{m+1}, 1))\) are manifolds, because \(n = 1\) case is nothing but a rank 1 prolongation. And \(\Sigma(J^{1}(M^{1+n}, n))\) are Lagrange-Grassmann bundle \(L(J)\), by definition. Hence \(\Sigma(J^{1}(M^{1+n}, n))\) are also manifolds. we call these cases trivial cases. \(\Sigma(J^{2}(M^{1+2}, 2))\) is shown to be a manifold in [S].
Proof. We will divide the proof into several cases. 

(1) $n = 2, m = 2, k = 1$ case;

For $w \in \Sigma(J^1(M^{2+2}, 2))$, let $p(w) = v \in J^1(M^{2+2}, 2)$, where $p : \Sigma(J^1(M^{2+2}, 2)) \to J^1(M^{2+2}, 2)$ is the projection. And let $\{(U, (x_1, x_2, y_1, y_2, p_1^1, p_1^2, p_2^1, p_2^2))\}$ be a canonical coordinate in $J^1(M^{2+2}, 2)$ around $v$. Then the canonical system $C^1$ is expressed by $\{\varpi_1 = \varpi_2 = 0\}$, where $\varpi_1 = dy_1 - p_1^1 dx_1 - p_2^1 dx_2, \varpi_2 = dy_2 - p_2^1 dx_1 - p_2^2 dx_2$.

We select two 1-forms among the 1-forms $\{dx_1, dx_2, dp_1^1, dp_1^2, dp_2^1, dp_2^2\}$ to cover an open subset $\pi^{-1}(U)$ in $J(C^1, 2)$, where $\pi : J(C^1, 2) \to J^1(M, 2)$ is the projection. As an example, we consider an open subset $U_{p_1^1, p_2^2} \subset \pi^{-1}(U)$, where

$$U_{p_1^1, p_2^2} := \{w \in \pi^{-1}(U) \mid dp_1^1 \wedge dp_2^2|_w \neq 0\}.$$ 

Then, for $w \in U_{p_1^1, p_2^2}$, restricting $dx_1, dx_2, dp_1^1, dp_2^2$ to $w$, we can introduce the inhomogeneous coordinate in $U_{p_1^1, p_2^2}$ of $J(C^1, 2)$ around $w$ as follows:

$$\begin{aligned} 
&dx_1|_w = A(w)dp_1^1|_w + B(w)dp_2^2|_w \\
&dx_2|_w = C(w)dp_1^1|_w + D(w)dp_2^2|_w \\
&dp_1^1|_w = E(w)dp_1^1|_w + F(w)dp_2^2|_w \\
&dp_2^2|_w = G(w)dp_1^1|_w + H(w)dp_2^2|_w.
\end{aligned}$$

Moreover a 2-dim integral element $w$ satisfies $d\varpi_1|_w = 0, d\varpi_2|_w = 0$, that is $d\varpi_1|_w = (-B(w) + C(w))dp_1^1 \wedge dp_2^2|_w, d\varpi_2|_w = (-E(w)B(w) - F(w)A(w) - G(w)D(w) + C(w)H(w))dp_1^1 \wedge dp_2^2|_w$. In this way, we obtain the defining equations $f_1 = f_2 = 0$ of $\Sigma(J^1(M^{2+2}, 2))$ in the inhomogeneous coordinate $U_{p_1^1, p_2^2}$ of $J(C^1, 2)$, where

$$\begin{aligned}
&f_1 = -B + C, \\
&f_2 = -EB + FA - GD + CH.
\end{aligned}$$

In this case the defining functions $f_1$ and $f_2$ degenerate at $S = \{A = B = C = D = F = G = 0, E = F\}$. Thus $S$ is the singular locus of $\Sigma(J^1(M^{2+2}, 2))$ in $U_{p_1^1, p_2^2}$.

Now we count the number of defining equations and the codimension of $\Sigma(J^k(M, n))$ in $J(C^k, n)$ for general cases before the proof of the other cases.

First, we precisely recall the construction of $\Sigma(J^k(M, n))$ from $J^k(M, n)$.

For $w_0 \in \Sigma(J^k(M, n))$, let $p(w_0) = v_0 \in J^k(M, n)$, where $p : \Sigma(J^k(M, n)) \to J^k(M, n)$ is the projection. And let $\{(U, (x_i, y_j, p_i^j)) \mid 1 \leq |I| \leq k, 1 \leq i \leq n, 1 \leq j \leq m\}$ be a canonical coordinate in $J^k(M, n)$ around $v_0$, where $I$ is a multi-index, that is

$I = (i_1, \ldots, i_s), i_j \in \{1, \ldots, n\} (j = 1, \ldots, r), |I| = r$. And $p_{I_1} = p_{I_2}$, if $|I_1| = |I_2|$ and there exists $\sigma \in S_{|I_1|}$ (symmetric group) such that $\sigma(I_1) = I_2$.

Then the canonical system $C^k$ is expressed by $\{\varpi_I^j = 0 \mid 0 \leq |I| \leq k - 1\}$, where

$$\varpi_I^j = dy_j - \sum_i p_i^j dx_i, \varpi_I^j = dp_I^1 - \sum_i p_I^j dx_i.$$ From rank $C^k = n + m \cdot n H_k$, we have

$$\dim \text{Gr}(C^k(v_0), n) = \{(n + m \cdot n H_k) - n\} \cdot n = m \cdot n \cdot \left(\begin{array}{c} n + k - 1 \\ k \end{array}\right).$$

This is the fiber dimension of $\pi : J(C^k, n) \to J^k(M, n)$, where $\pi$ is the projection.
In fact, we select \( n \) 1-forms \( \eta_1, \cdots, \eta_n \) among 1-forms \( \{dx_i, dp_i\} \) \((|I| = k)\) such that \( \eta_1 \wedge \cdots \wedge \eta_n |_{w_0} \neq 0 \). Put

\[
U_{\eta_1, \cdots, \eta_n} := \{w \in \pi^{-1}(U) \mid \eta_1 \wedge \cdots \wedge \eta_n |_{w} \neq 0\}. 
\]

Then, for \( w \in U_{\eta_1, \cdots, \eta_n} \), restricting each 1-form \( \xi_\alpha \) of \( \{dx_i, dp_i\} \) other than \( \{\eta_1, \cdots, \eta_n\} \) to \( w \), we can introduce the inhomogeneous coordinate in \( U_{\eta_1, \cdots, \eta_n} \) of \( J(C^k, n) \) around \( w_0 \) as follows;

\[
\xi_\alpha |_w = \sum_{i=1}^{n} a^\alpha_i(w) \eta_i |_w \quad (\alpha = 1, 2, \cdots, m \cdot nH_k).
\]

Moreover an \( n \)-dim integral element \( w \) satisfies \( d\varpi_j |_w = 0 \) \((|I| = k - 1)\)(the number of \( d\varpi_j |_w \) equals to \( m \cdot nH_{k-1} \));

\[
d\varpi_j |_w = \sum_{i<l} f_{il}(w) \eta_i \wedge \eta_l |_w.
\]

So we get the defining equations \( f_{il} = 0 \) of \( \Sigma(J^k(M, n)) \) in \( J(C^k, n) \). Thus the number of the defining equations is

\[
(m \cdot nH_{k-1}) \cdot \frac{n(n-1)}{2}.
\]

(The precise expressions of defining equations in the selected inhomogeneous coordinate will appear in each case below.)

Here the fiber dimension of \( J^{k+1}(M, n) \to J^k(M, n) \) is

\[
m \cdot nH_{k+1} = m \cdot \left( \frac{n+k}{k+1} \right).
\]

Note that \( \Sigma(J^k(M, n)) \) is a subvariety of \( J(C^k, n) \) containing \( J^{k+1}(M, n) \) as an open dense subset. Therefore, the codimension of \( \Sigma(J^k(M, n)) \) in \( J(C^k, n) \) is

\[
m \cdot n \cdot \left( \frac{n+k-1}{k} \right) - m \cdot \left( \frac{n+k}{k+1} \right) = \frac{mk}{(k+1)!} (n+k-1) \cdots n \cdot (n-1).
\]

Then, the difference of the number of defining equations and the codimension is

\[
\frac{mk(k-1)}{2(k+1)!} (n+k-2) \cdots n \cdot (n-1) \cdot (n-2) \geq 0.
\]

Hence, the codimension is less than the number of defining equations, in general. So we divide the proof into the cases that the number of the defining equations equals to the codimension or not. That is, we divide into the cases (2) \( k = 1 \), (3) \( n = 2 \) and (4) others.

\[
(2) \; n \geq 3, m \geq 2, k = 1 \text{ cases};
\]

For \( w \in \Sigma(J^1(M^{m+n}, n)) \), let \( p(w) = v \in J^1(M^{m+n}, n) \), where \( p : \Sigma(J^1(M^{m+n}, n) \to J^1(M^{m+n}, n) \) is the projection. And let \( (U, (x_i, y_j, p_i)) \) be a canonical coordinate in \( J^1(M^{m+n}, n) \) around \( v \). Then the canonical system \( C^1 \) is expressed by \( \{\varpi^j = 0\} \), where

\[
\varpi^j = dy^j - \sum_{l=1}^{n} p^j_l dx_l.
\]
We select \( n \) 1-forms among the 1-forms \( \{dx_i, dp_i\} \) to cover an open set \( \pi^{-1}(U) \) in \( J(C^1, n) \), where \( \pi : J(C^1, n) \to J^1(M^m+n, n) \) is the projection. Especially, we consider an open set \( U_{p_1, \ldots, p_n} \subset \pi^{-1}(U) \), where
\[
U_{p_1, \ldots, p_n} := \{ w \in \pi^{-1}(U) \mid dp_1 \wedge \cdots \wedge dp_n |_w \neq 0 \}.
\]

For \( w \in U_{p_1, \ldots, p_n} \), restricting \( dx_i, dp_i \) \( (j \neq 1) \) to \( w \), we have the inhomogeneous coordinate in \( U_{p_1, \ldots, p_n} \) of \( J(C^1, n) \) around \( w \) as follows;
\[
\begin{align*}
(dx_i |_w &= \sum_{i=1}^n a_i^j(w) dp_i |_w \quad (j \neq 1), \\
(dp_i |_w &= \sum_{i=1}^n b_i^j(w) dp_i |_w \quad (j \neq 1).
\end{align*}
\]

Moreover an \( n \)-dim integral element \( w \) satisfies \( d\varpi |_w = 0 \);
\[
\begin{align*}
d\varpi |_w &= -\sum_{h=1}^n (dp_i |_w \wedge \sum_{i=1}^n a_h^i(w) dp_i |_w) \\
d\varpi |_w &= -\sum_{h=1}^n \{ (\sum_{i=1}^n b_h^j(w) dp_i |_w) \wedge (\sum_{i=1}^n a_h^i(w) dp_i |_w) \} \quad (j \neq 1).
\end{align*}
\]

In this case, the number of defining equations of \( \Sigma(J^1(M, n)) \) in \( J(C^1, n) \) coincides with the codimension of \( \Sigma(J^1(M, n)) \) in \( J(C^1, n) \). So the appearance of the homogeneous quadratic relations from the second group of the above defining equations implies the drop of rank of defining equations at the origin of the inhomogeneous coordinate. Hence \( \Sigma(J^1(M, n)) \) is not a manifold, by the implicit function theorem.

(3) \( n = 2 \) cases;
we divide the proof according to \( m = 1 \) or greater.

(3)-(i) \( n = 2, m = 1, k \geq 3 \) cases;

For \( w \in \Sigma(J^k(M^{1+2}, 2)) \), let \( p(w) = v \in J^k(M^{1+2}, 2) \), where \( p : \Sigma(J^k(M^{1+2}, 2) \to J^k(M^{1+2}, 2) \) is the projection. And let \( (U, (x_1, x_2, y, p_1, p_2, \ldots, p_t)) \) \( (|I| \leq k) \) be a canonical coordinate in \( J^k(M^{1+2}, 2) \) around \( v \), where \( I = (i_1, \ldots, i_r), i_j \in \{1, 2\} \) \( (j = 1, \ldots, r) \). Then the canonical system \( C^k \) is expressed by \( \{ \varpi_0 = 0 \ (0 \leq |I| \leq k - 1) \} \), where \( \varpi_0 = dy - p_1 dx_1 - p_2 dx_2, \varpi_I = dp_I - p_1 dx_1 - p_2 dx_2 \).

We select two 1-forms among the 1-forms \( \{dx_1, dx_2, dp_I\} \) \( (|I| = k) \) to cover an open set \( \pi^{-1}(U) \) in \( J(C^k, 2) \), where \( \pi : J(C^k, 2) \to J^k(M^{1+2}, 2) \). Especially, we consider an open set \( U_{p_1, p_2} \subset \pi^{-1}(U) \), where
\[
U_{p_1, p_2} := \{ w \in \pi^{-1}(U) \mid dp_{1\cdots 1} \wedge dp_{1\cdots 2} |_w \neq 0 \}.
\]

For \( w \in U_{p_1, p_2} \), restricting \( dx_1, dx_2, dp_I \) \( (|I| = k, I \neq (1, \cdots, 1), (1, \cdots, 1, 2)) \) to \( w \), we have the inhomogeneous coordinate;
\[
\begin{align*}
(dx_1 |_w &= a_1(w) dp_{1\cdots 1} |_w + a_2(w) dp_{1\cdots 2} |_w \\
(dx_2 |_w &= b_1(w) dp_{1\cdots 1} |_w + b_2(w) dp_{1\cdots 2} |_w \\
(dp_I |_w &= c_I^1(w) dp_{1\cdots 1} |_w + c_I^2(w) dp_{1\cdots 2} |_w).
\end{align*}
\]

Moreover a 2-dim integral element \( w \) satisfies \( d\varpi_I |_w = 0 \) \( (|I| = k - 1) \);
\[
\begin{align*}
    d\omega_{1-1}|_w &= (-a_2(w) + b_1(w))dp_{1-1} \wedge dp_{1-12}|_w, \\
    d\omega_{1-12}|_w &= (a_1(w) - c_{1-122}(w)b_2(w) + b_1(w)c_{1-1222}(w))dp_{1-1} \wedge dp_{1-12}|_w, \\
    d\omega_{1-122}|_w &= (-c_{1-122}(w)a_2(w) + c_{2-122}(w)a_1(w) - c_{1-1222}(w)b_2(w) + c_{2-122}(w)b_1(w))dp_{1-1} \wedge dp_{1-12}|_w, \\
    d\omega_{2-2}|_w &= (-c_{12-2}(w)a_2(w) + c_{12-2}(w)a_1(w) - c_{22-2}(w)b_2(w) + \cdots + c_{22}(w)b_1(w))dp_{1-1} \wedge dp_{1-12}|_w.
\end{align*}
\]

Hence \(\Sigma(J^k(M^{1+2}, 2))\) is not a manifold by the same reasoning as in (2).

(3)-(ii) \(n = 2, m \geq 2, k \geq 2\) cases;

For \(w \in \Sigma(J^k(M^{m+2}, 2))\), let \(p(w) = v \in J^k(M^{m+2}, 2)\), where \(p : \Sigma(J^k(M^{m+2}, 2) \to J^k(M^{m+2}, 2)\) is the projection. And let \((U, (x_1, x_2, y^i, p^i_1, p^i_2, \ldots, p^i_j))\) \(|I| \leq k, 1 \leq i \leq m\) be a canonical coordinate in \(J^k(M^{m+2}, 2)\) around \(v\), where \(I = (i_1, \ldots, i_r), i_j \in \{1, 2\} |j = 1, \ldots, r\). Then the canonical system \(C^k\) is expressed by \(\{\omega^i = 0 (0 \leq |I| \leq k - 1, 1 \leq i \leq m}\}\), where \(\omega^i = dp_i^1 - p^i_1dx_1 - p^i_2dx_2\).

We select two 1-forms among the 1-forms \(\{dx_1, dx_2, dp_i^1\}\) \(|I| = k\) to cover an open set \(\pi^{-1}(U)\) in \(J(C^k, 2)\), where \(\pi : J(C^k, 2) \to J^k(M^{m+2}, 2)\) is the projection. Especially, we consider an open set \(U_{p^1_1, p^2_1, \ldots, p^r_1} \subset \pi^{-1}(U)\), where

\[
U_{p^1_1, p^2_1, \ldots, p^r_1, \ldots, p^r_1} := \{w \in \pi^{-1}(U) \mid dp^1_{1-1} \wedge dp^2_{1-1}|_w \neq 0\}.
\]

For \(w \in U_{p^1_1, p^2_1, \ldots, p^r_1, \ldots, p^r_1} \), restricting \(dx_1, dx_2, dp_i^1\) \(|I| = k, (i, I) \neq (1, 1, \ldots, 1), (2, 1, \ldots, 1)\) to \(w\), we have

\[
\begin{align*}
    dx_1|_w &= a_1(w)dp^1_{1-1}|_w + a_2(w)dp^2_{1-1}|_w, \\
    dx_2|_w &= b_1(w)dp^1_{1-1}|_w + b_2(w)dp^2_{1-1}|_w, \\
    dp_i^1|_w &= c_{i1}(w)dp^1_{1-1}|_w + c_{i2}(w)dp^2_{1-1}|_w.
\end{align*}
\]

Moreover a 2-dim integrable element \(w\) satisfies \(d\omega^i|_w = 0 (|I| = k - 1)\);

\[
\begin{align*}
    d\omega_{1-1}|_w &= (-a_2(w) - (c_{1-12}(w)b_2(w) - d_{1-12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w, \\
    d\omega_{1}|_w &= (-a_1(w) - (c_{1-12}(w)b_2(w) - d_{1-12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{2}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{1-12}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{1}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{2}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{2}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{1-12}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{1}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{2}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)), \\
    d\omega_{1-12}|_w &= (-c_{11}(w)a_2(w) - d_{11}(w)a_1(w)) - (c_{12}(w)b_2(w) - d_{12}(w)b_1(w)))dp^1_{1-1} \wedge dp^2_{1-1}|_w (|I| = k - 1, I \neq (1 \ldots 1)).
\end{align*}
\]

Hence \(\Sigma(J^k(M^{m+2}, 2))\) is not a manifold by the same reasoning as in (2).

(4) \(n \geq 3\) cases;

In these cases, we also divide the proof according to \(m = 1\) or greater.

(4)-(i) \(n \geq 3, m = 1, k \geq 2\) cases;
For $w \in \Sigma(J^k(M^{1+n}, n))$, let $p(w) = v \in J^k(M^{1+n}, n)$, where $p : \Sigma(J^k(M^{1+n}, n) \to J^k(M^{1+n}, n)$ is the projection. And let $(U, (x_i, y, p_I)) (|I| \leq k)$ be a canonical coordinate in $J^k(M^{1+n}, n)$ around $v$, where $I = (i_1, \ldots, i_r), i_j \in \{1, \ldots, n\} (j = 1, \ldots, r)$. Then the canonical system $C^k$ is expressed by $\{ \varpi_I = 0 (0 \leq |I| \leq k - 1) \}$, where $\varpi_0 = dy - \sum_{i=1}^n p_i dx_i, \varpi_I = dp_I - \sum_{i=1}^n p_I dx_i$.

We select $n$ 1-forms among the 1-forms $\{dx_i, dp_I\} (|I| = k)$ to cover an open set $\pi^{-1}(U)$ in $J(C^k, n)$, where $\pi : J(C^k, n) \to J^k(M^{1+n}, n)$ is the projection. Especially, we consider the canonical system $\pi$ of $\Upsilon_{p_1, \ldots, p_n}$ around $v$, where $\Upsilon_{p_1, \ldots, p_n}(U, (x_i, y, p_I)) \in \pi^{-1}(U), where $w \in U_{p_1, \ldots, p_n} := \{ w \in \pi^{-1}(U) \mid dp_{p_1} \wedge \cdots \wedge dp_{p_n} |w| \neq 0 \}.$

For $w \in U_{p_1, \ldots, p_n}$, restricting $dx_i, dp_I (|I| = k, I \neq (i, \ldots, i))$ to $w$, we have

$$
\begin{align*}
  d\varpi_{p_1} & = -dp_{p_1} \wedge (\sum_{j=1}^n a^i_j(w) dp_{p_j})_w \\
  \vdots
  \end{align*}
$$

Moreover an $n$-dim integral element $w$ satisfies $d\varpi_I = 0 (|I| = k - 1)$.

In this case, the number of defining equations exceeds the codimension of $\Sigma(J^k(M^{1+n}, n))$. But the rank of defining equations at the origin is $n(n - 1)$, which easily follows from the above equations. Then the difference of the codimension and the rank of defining equations at the origin is $1 \cdot k \binom{n+k-1}{k} - (n(n - 1) - n(n - 1)).$

We can check the value is positive by induction on $k$. Thus the rank at the origin is strictly less than the codimension of $\Sigma(J^k(M^{1+n}, n))$. Hence $\Sigma(J^k(M^{1+n}, n))$ is not a manifold.

(4)-(ii) $n \geq 3, m \geq 2, k \geq 1$ cases;

For $w \in \Sigma(J^k(M^{m+n}, n))$, let $p(w) = v \in J^k(M^{m+n}, n)$, where $p : \Sigma(J^k(M^{m+n}, n) \to J^k(M^{m+n}, n)$ is the projection. And let $(U, (x_i, y, p_I)) (|I| \leq k)$ be a canonical coordinate in $J^k(M^{m+n}, n)$ around $v$, where $I = (i_1, \ldots, i_r), i_j \in \{1, \ldots, n\} (j = 1, \ldots, r)$. Then the canonical system $C^k$ is expressed by $\{ \varpi_I = 0 (0 \leq |I| \leq k - 1), 1 \leq j \leq m \}$, where $\varpi_0 = dy - \sum_{i=1}^n p_i dx_i, \varpi_I = dp_I - \sum_{i=1}^n p_I dx_i$.

We select $n$ 1-forms among the 1-forms $(dx_i, dp_I) (|I| = k)$ to cover an open set $\pi^{-1}(U)$ in $J(C^k, n)$, where $\pi : J(C^k, n) \to J^k(M^{m+n}, n)$ is the projection. Especially,
we consider an open set \( U_{p_1, \ldots, p_n} \subset \pi^{-1}(U) \), where
\[
U_{p_1, \ldots, p_n} := \{ w \in \pi^{-1}(U) \mid dp_{p_1} \wedge \cdots \wedge dp_{p_n} |_w \neq 0 \}.
\]

For \( w \in U_{p_1, \ldots, p_n} \), restricting \( dx_i, dp_I \ (|I| = k, (j, I) \neq (1, (i, \ldots, i))) \) to \( w \), we have
\[
\begin{align*}
    dx_i |_w &= \sum_{i=1}^n a_i^I(w) dp_I |_w \\
    dp_I |_w &= \sum_{i=1}^n b_i^I(w) dp_I |_w \quad (|I| = k, I \neq (i, \ldots, i)) \\
    dp_I |_w &= \sum_{i=1}^n b_i^I(w) dp_I |_w \quad (|I| = k, 2 \leq j \leq m).
\end{align*}
\]
Moreover an \( n \)-dim integral element \( w \) satisfies \( d\varpi |_w = 0 \ (|I| = k - 1) \):
\[
\begin{align*}
    d\varpi^4_{1, \ldots, 1} |_w &= -dp_{1, \ldots, 1} |_w \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) + \sum_{i=2}^n (\sum_{l=1}^n b_l^i(w) dp_{l, \ldots, l} |_w) \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) \\
    \vdots \\
    d\varpi^4_{1, \ldots, 1} |_w &= -dp_{1, \ldots, 1} |_w \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) + \sum_{j \neq 1} (\sum_{l=1}^n b_l^i(w) dp_{l, \ldots, l} |_w) \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) \\
    \vdots \\
    d\varpi^4_I |_w &= -dp_{1, \ldots, 1} |_w \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) + \sum_{h=1}^n (\sum_{l=1}^n b_l^i(w) dp_{l, \ldots, l} |_w) \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) \quad (|I| = k - 1, I \neq (i, \ldots, i)) \\
    d\varpi^4_I |_w &= -dp_{1, \ldots, 1} |_w \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) + \sum_{h=1}^n (\sum_{l=1}^n b_l^i(w) dp_{l, \ldots, l} |_w) \wedge (\sum_{i=1}^n a_i^I(w) dp_I |_w) \quad (|I| = k - 1, 2 \leq j \leq m).
\end{align*}
\]

In this case, the number of defining equations exceeds the codimension of \( \Sigma(J^k(M^{m+n}, n)) \). The rank of defining equations at the origin is \( n(n-1) \), which follows from the above equations. Thus the rank at the origin is strictly less than the codimension of \( \Sigma(J^k(M^{m+n}, n)) \). Hence \( \Sigma(J^k(M^{m+n}, n)) \) is not a manifold.

\[\square\]

References


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