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An equivalence problem of homogeneous sub-Riemannian structures

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1 Introduction

A sub-Riemannian manifold (M, D, g) is a differential manifold M equipped with a subbundle D of the tangent bundle TM of M and a Riemannian metric g on D . In particular, it is called a sub-Riemannian contact manifold if D is a contact structure, i.e., a subbundle of codimension 1 and non-degenerate.

An infinitesimal automorphism of a sub-Riemannian manifold (M, D, g) is a local vector field X on M such that $L_X D \subset D$ and $L_X g = 0$. Denote by \mathcal{L} the sheaf of the germs of infinitesimal automorphisms of (M, D, g) and by \mathcal{L}_a the stalk of \mathcal{L} at $a \in M$. We say that \mathcal{L} is transitive, or (M, D, g) is homogeneous if the evaluation map $\mathcal{L}_a \ni [X]_a \mapsto X_a \in T_a M$ is surjective for all $a \in M$.

In this paper we study the structure of the Lie algebra \mathcal{L}_a for a point a of a homogeneous sub-Riemannian contact manifold (M, D, g) from the viewpoint of nilpotent geometry. We show that the formal algebra L of \mathcal{L}_a (and therefore \mathcal{L}_a) is of finite dimension less than or equal to $(n + 1)^2$ if $\dim M = 2n + 1$. We then completely determine the structures of the Lie algebras L which attain the maximal dimension, which then leads to the determination of the Lie algebras \mathcal{L}_a which attain the maximal dimension. We also describe the standard concrete subriemannian manifolds on which these Lie algebra sheaves are realized.

2 Sub-Riemannian contact transitive filtered Lie algebras

Let (M, D, g) be a homogeneous sub-Riemannian contact manifold of dimension $(2n + 1)$ and \mathcal{L} the sheaf of germs of infinitesimal automorphisms of (M, D, g) as defined in Introduction. First of all let us introduce the contact filtration $\{\mathcal{L}_a^p\}_{p \in \mathbf{Z}}$ of \mathcal{L}_a defined inductively as follows:

- (i) $\mathcal{L}_a^p = \mathcal{L}_a$ ($p \leq -2$)
- (ii) $\mathcal{L}_a^{-1} = \{[X]_a \in \mathcal{L}_a; X_a \in D_a\}$
- (iii) $\mathcal{L}_a^0 = \{[X]_a \in \mathcal{L}_a; X_a = 0\}$
- (iv) $\mathcal{L}_a^{p+1} = \{\xi \in \mathcal{L}_a^p; [\xi, \eta] \in \mathcal{L}_a^{p+q+1} \text{ for all } \eta \in \mathcal{L}_a^q, q < 0\}$ ($p \geq 0$).

Then it is easy to see that

$$[\mathcal{L}_a^p, \mathcal{L}_a^q] \subset \mathcal{L}_a^{p+q} \quad \text{for all } p, q \in \mathbf{Z},$$

and that

$$\dim \mathcal{L}_a^p / \mathcal{L}_a^{p+1} < \infty.$$

Passing to the projective limit by setting

$$L = \lim_{\leftarrow k} \mathcal{L}_a / \mathcal{L}_a^k,$$

we obtain a Lie algebra L , which also carries a filtration $\{L^p\}_{p \in \mathbf{Z}}$ given by

$$L^p = \lim_{\leftarrow k} \mathcal{L}_a^p / \mathcal{L}_a^k.$$

Then we see that $(L, \{L^p\})$ is a transitive filtered Lie algebra of depth 2 in the sense of Morimoto[6]: A transitive filtered Lie algebra (TFLA) of depth μ , with μ being a positive integer, is a Lie algebra L endowed with a filtration $\{L^p\}_{p \in \mathbf{Z}}$ of subspaces of L satisfying the following conditions:

$$(F1) \quad L = L^{-\mu},$$

$$(F2) \quad L^p \supset L^{p+1},$$

$$(F3) \quad [L^p, L^q] \subset L^{p+q},$$

$$(F4) \quad \bigcap_{p \in \mathbf{Z}} L^p = 0,$$

$$(F5) \quad \dim L^p/L^{p+1} < \infty,$$

$$(F6) \quad L^{p+1} = \{X \in L^p; [X, L^a] \subset L^{p+a+1} \text{ for all } a < 0\}, \text{ for any } p \geq 0.$$

The TFLA $(L, \{L^p\})$ thus obtained is called the formal algebra of \mathcal{L} at a .

Let $\mathfrak{l} = \bigoplus \mathfrak{l}_p$ be the graded Lie algebra associated to the TFLA $(L, \{L^p\})$ defined by

$$\mathfrak{l}_p = L^p/L^{p+1}.$$

Then it is easy to see that $\mathfrak{l} = \bigoplus \mathfrak{l}_p$ satisfies the following properties:

- (i) $\mathfrak{l}_- = \bigoplus_{p < 0} \mathfrak{l}_p$ is isomorphic to the $(2n+1)$ -dimensional Heisenberg Lie algebra $\mathfrak{c}_-(n) = \mathfrak{c}_{-2}(n) \oplus \mathfrak{c}_{-1}(n)$, where $\mathfrak{c}_{-2}(n) = \mathbf{R}$, $\mathfrak{c}_{-1}(n) = \mathbf{R}^{2n}$, and the bracket operation is given by $[e_i, e_j] = \delta_{n, j-i} f$ for $i < j$ and trivial for the other pairs with respect to the standard bases $\{f\}$ and $\{e_1, e_2, \dots, e_{2n}\}$ of $\mathfrak{c}_{-2}(n)$ and $\mathfrak{c}_{-1}(n)$ respectively.
- (ii) $\bigoplus \mathfrak{l}_p$ is transitive, that is, the condition that $p \geq 0$, $x \in \mathfrak{l}_p$ $[x, \mathfrak{l}_-] = 0$ implies $x = 0$.
- (iii) There exists a positive definite inner product $g : \mathfrak{l}_{-1} \times \mathfrak{l}_{-1} \rightarrow \mathbf{R}$ such that

$$g([A, x], y) + g(x, [A, y]) = 0 \quad \text{for all } A \in \mathfrak{l}_0 \text{ and } x, y \in \mathfrak{l}_{-1}.$$

A graded Lie algebra $\bigoplus \mathfrak{l}_p$ satisfying the above conditions will be called a *sub-Riemannian contact* transitive graded Lie algebra (TGLA) and a filtered Lie algebra $(L, \{L^p\})$ whose associated graded Lie algebra is a sub-Riemannian contact TGLA will be called a *sub-Riemannian contact* transitive filtered Lie algebra (TFLA).

3 Sub-Riemannian contact graded Lie algebras

We call a pair (\mathfrak{l}_-, g) a *sub-Riemannian Heisenberg Lie algebra* if $\mathfrak{l}_- = \mathfrak{l}_{-2} \oplus \mathfrak{l}_{-1}$ is a graded Lie algebra isomorphic to the Heisenberg Lie algebra $\mathfrak{c}_-(n)$ and g is an inner product on \mathfrak{l}_{-1} . Such pairs are classified as follows: For an n -tuple of positive numbers $\lambda = (\lambda_1, \dots, \lambda_n)$ such that $\lambda_1 \geq \dots \geq \lambda_n$ and $\lambda_1 \cdots \lambda_n = 1$, we define an inner product g_λ on $\mathfrak{c}_{-1}(n)$ by

$$g_\lambda(e_i, e_j) = 0 \ (i \neq j), \quad g_\lambda(e_k, e_k) = 1, \quad g_\lambda(e_{n+k}, e_{n+k}) = \lambda_k \ (1 \leq k \leq n),$$

where $\{e_1, \dots, e_{2n}\}$ is the basis of $\mathfrak{c}_{-1}(n)$. From the normal form of a skew symmetric matrix under the orthogonal group, we see:

Proposition 1 *For an sub-Riemannian Heisenberg Lie algebra (\mathfrak{l}_-, g) , there is a unique $\lambda = (\lambda_1, \dots, \lambda_n)$ such that (\mathfrak{l}_-, g) is isomorphic to $(\mathfrak{c}_-(n), g_\lambda)$.*

Next we define $\mathfrak{c}_0(n, g_\lambda)$ to be the Lie algebra consisting of all $\alpha \in \text{Hom}(\mathfrak{l}_-, \mathfrak{l}_-)$ such that

$$\begin{cases} \text{(i)} \ \alpha(\mathfrak{l}_p) \subset \mathfrak{l}_p, \ p < 0 \\ \text{(ii)} \ \alpha([x, y]) = [\alpha(x), y] + [x, \alpha(y)], \ x, y \in \mathfrak{l}_- \\ \text{(iii)} \ g(\alpha(x), y) + g(x, \alpha(y)) = 0, \ x, y \in \mathfrak{l}_{-1}. \end{cases}$$

From (i) and (ii) the matrix representation of $X \in \mathfrak{c}_0(n, g_\lambda)$ with respect to the basis $\{f, e_1, \dots, e_{2n}\}$ has the following form.

$$X = \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & A \end{array} \right) + c \left(\begin{array}{c|c} 2 & 0 \\ \hline 0 & 1 \\ & \ddots \\ & 1 \end{array} \right),$$

where

$$A = \left(\begin{array}{c|c} A_{11} & A_{12} \\ \hline A_{21} & A_{22} \end{array} \right) \in sp(n, \mathbf{R}),$$

that is, $A_{22} = -{}^t A_{11}$, A_{12} and A_{21} are symmetric matrices of degree n . Then by (iii) we have

$${}^t \tilde{A}K + K\tilde{A} = 0,$$

where

$$\tilde{A} = A + cI_{2n}, \quad K = \left(\begin{array}{c|ccc} 1 & & & \\ & \ddots & & \\ & & 1 & \\ \hline & & & \lambda_1 \\ & 0 & & \ddots \\ & & & & \lambda_n \end{array} \right).$$

It follows from this that the trace of \tilde{A} vanishes, but $A \in sp(n, \mathbf{R})$ is also traceless, therefore we see that the constant $c = 0$. Using these facts, we have the following proposition.

Proposition 2 *If $\mathfrak{l} = \bigoplus_p \mathfrak{l}_p$ is a subriemannian contact TGLA, then $\mathfrak{l}_p = 0$ for $p \geq 1$, and therefore \mathfrak{l} is finite dimensional.*

The dimension of $\mathfrak{c}_0(n, g_\lambda)$ will be maximal, when all the eigenvalues coincide, i.e., $\lambda = (1, \dots, 1)$. Then $X \in \mathfrak{c}_0(n, g_\lambda)$ can be expressed as:

$$X = \left(\begin{array}{c|cc} 0 & & 0 \\ \hline & A_{11} & A_{12} \\ 0 & & \\ \hline & -A_{12} & A_{11} \end{array} \right),$$

where A_{11} is skew symmetric and A_{12} is symmetric. It then turns out that $\mathfrak{c}_0(n, g_{(1, \dots, 1)})$ is isomorphic to $\mathfrak{u}(n)$, the Lie algebra of unitary group. Thus we have shown:

Proposition 3 *If a sub-Riemannian contact TGLA \mathfrak{l} has the maximal dimension $(n+1)^2$, it is isomorphic to the TGLA $\mathfrak{k}_{-2} \oplus \mathfrak{k}_{-1} \oplus \mathfrak{k}_0$, where $\mathfrak{k}_{-2} = \mathbf{R}$, $\mathfrak{k}_{-1} = \mathbf{C}^n \cong \mathbf{R}^{2n}$, $\mathfrak{k}_0 = \mathfrak{u}(n)$, and the bracket operation is given by*

$$(i) \quad [,] : \mathfrak{k}_{-2} \times \mathfrak{k}_0 \rightarrow 0$$

- (ii) $[\cdot, \cdot] : \mathfrak{k}_0 \times \mathfrak{k}_{-1} \rightarrow \mathfrak{k}_{-1}; \quad [A, x] := Ax \quad (A \in \mathfrak{k}_0, x \in \mathfrak{k}_{-1})$
- (iii) $[\cdot, \cdot] : \mathfrak{k}_0 \times \mathfrak{k}_0 \rightarrow \mathfrak{k}_0; \quad [X, Y] := XY - YX \quad (X, Y \in \mathfrak{k}_0)$
- (iv) $[\cdot, \cdot] : \mathfrak{k}_{-1} \times \mathfrak{k}_{-1} \rightarrow \mathfrak{k}_{-2}; \quad [Z, W] := \text{Im}h(Z, W), \text{ where } h(\cdot, \cdot) \text{ is the canonical Hermitian product on } \mathbb{C}^n.$

4 Cohomology group $H(\mathfrak{k}_-, \mathfrak{k})$

In order to determine the TFLA's whose associated graded Lie algebras are isomorphic to \mathfrak{k} , we need to study the cohomology group $H(\mathfrak{k}_-, \mathfrak{k})$. Let us now recall the definition of the cohomology group $H(\mathfrak{g}_-, \mathfrak{g})$ for a transitive graded Lie algebra \mathfrak{g} . We set $\mathfrak{g}_- = \bigoplus_{p < 0} \mathfrak{g}_p$, which is a nilpotent subalgebra of \mathfrak{g} , and consider the cohomology group associated with the adjoint representation of \mathfrak{g}_- on \mathfrak{g} , namely the cohomology group $H(\mathfrak{g}_-, \mathfrak{g}) = \bigoplus H^p(\mathfrak{g}_-, \mathfrak{g})$ of the cochain complex $(\text{Hom}(\wedge^p \mathfrak{g}_-, \mathfrak{g}), \partial)$, where the coboundary operator $\partial : \text{Hom}(\wedge^p \mathfrak{g}_-, \mathfrak{g}) \rightarrow \text{Hom}(\wedge^{p+1} \mathfrak{g}_-, \mathfrak{g})$ is defined by

$$\begin{aligned} & (\partial\omega)(X_1, X_2, \dots, X_{p+1}) \\ &= \sum_{i=1}^{n+1} (-1)^{i-1} [X_i, \omega(X_1, \dots, \hat{X}_i, \dots, X_{p+1})] \\ &+ \sum_{1 \leq i < j \leq p+1} (-1)^{i+j} \omega([X_i, X_j], X_1, \dots, \hat{X}_i, \dots, \hat{X}_j, \dots, X_{p+1}) \end{aligned}$$

for $\omega \in \text{Hom}(\wedge^p \mathfrak{g}_-, \mathfrak{g}), X_1, X_2, \dots, X_{p+1} \in \mathfrak{g}_-$. Since both \mathfrak{g}_- and \mathfrak{g} are graded, we can define a bigradation $\bigoplus H_r^p(\mathfrak{g}_-, \mathfrak{g})$ of $H(\mathfrak{g}_-, \mathfrak{g})$ as follows: Denote by $\text{Hom}(\wedge^p \mathfrak{g}_-, \mathfrak{g})_r$ the set of all homogeneous p -cochains ω of degree r (i.e., $\omega(\mathfrak{g}_{a_1} \wedge \dots \wedge \mathfrak{g}_{a_p}) \subset \mathfrak{g}_{a_1 + \dots + a_p + r}$ for any $a_1, \dots, a_p \leq 0$), and set

$$\text{Hom}(\wedge \mathfrak{g}_-, \mathfrak{g})_r = \bigoplus_p \text{Hom}(\wedge^p \mathfrak{g}_-, \mathfrak{g})_r.$$

Note that ∂ preserves the degree. Hence $\text{Hom}(\wedge \mathfrak{g}_-, \mathfrak{g})_r$ is a subcomplex and the direct sum decomposition

$$\text{Hom}(\wedge \mathfrak{g}_-, \mathfrak{g}) = \bigoplus_r \text{Hom}(\wedge \mathfrak{g}_-, \mathfrak{g})_r$$

yields that of the cohomology group:

$$H(\mathfrak{g}_-, \mathfrak{g}) = \bigoplus H_r(\mathfrak{g}_-, \mathfrak{g}) = \bigoplus H_r^p(\mathfrak{g}_-, \mathfrak{g}).$$

On the other hand we note that \mathfrak{g}_0 naturally acts on $\text{Hom}(\wedge^p \mathfrak{g}_-, \mathfrak{g})_r$, and we denote its representation by ρ , which is given by: for $X_1, \dots, X_p \in \mathfrak{g}_-$,

$$(\rho(A)\alpha)(X_1, \dots, X_p) = [A, \alpha(X_1, \dots, X_p)] - \sum_{i=1}^p \alpha(X_1, \dots, [A, X_i], \dots, X_p).$$

Then we have

$$\partial\rho(A) = \rho(A)\partial \quad \text{for any } A \in \mathfrak{g}_0.$$

Therefore it induces the representation $\bar{\rho}$ of \mathfrak{g}_0 on $H_r^p(\mathfrak{g}_-, \mathfrak{g})$. Now we define the set of all \mathfrak{g}_0 -invariant elements by

$$IH_r^p(\mathfrak{g}_-, \mathfrak{g}) = \{\alpha \in H_r^p(\mathfrak{g}_-, \mathfrak{g}); \bar{\rho}(A)\alpha = 0 \text{ for all } A \in \mathfrak{l}_0\}.$$

Then we have the following proposition for the subriemannian contact TGLA \mathfrak{k} of dimension $(n+1)^2$:

Proposition 4 (i) $IH_1^2(\mathfrak{k}_-, \mathfrak{k}) = 0$.

(ii) $IH_2^2(\mathfrak{k}_-, \mathfrak{k})$ is 1-dimensional and generated by the equivalence class $[\omega]$ of a cocycle $\omega \in \text{Hom}(\wedge^2 \mathfrak{k}_{-1}, \mathfrak{k}_0)$ given by:

$$\begin{cases} \omega(e_i \wedge e_j) = \omega(e_{n+i} \wedge e_{n+j}) = -E_{ij} + E_{ji} \\ \omega(e_i \wedge e_{n+j}) = \sqrt{-1}(E_{ij} + E_{ji} + 2\delta_{ij}I_n), \end{cases}$$

where $\{e_1, e_2, \dots, e_{2n}\}$ is the standard basis of \mathfrak{k}_{-1} and E_{ij} denotes the (i, j) matrix unit in $gl(n, \mathbf{C})$. Moreover, ω itself is \mathfrak{k}_0 -invariant, that is, $\rho(A)\omega = 0$ for $A \in \mathfrak{k}_0$, where ρ is the representation of \mathfrak{k}_0 on $\text{Hom}(\mathfrak{k}_-, \mathfrak{k})$.

(iii) $H_r^2(\mathfrak{k}_-, \mathfrak{k}) = 0$ for $r \geq 3$.

The proof of the proposition is based on the decomposition of the complex

$$\text{Hom}(\mathfrak{k}_-, \mathfrak{k})_r \longrightarrow \text{Hom}(\wedge^2 \mathfrak{k}_-, \mathfrak{k})_r \longrightarrow \text{Hom}(\wedge^3 \mathfrak{k}_-, \mathfrak{k})_r$$

into

$$\begin{array}{ccccc}
\mathrm{Hom}(\mathfrak{k}_{-2}, \mathfrak{k}_{r-2}) & \longrightarrow & \mathrm{Hom}(\mathfrak{k}_{-2} \otimes \mathfrak{k}_{-1}, \mathfrak{k}_{r-3}) & \longrightarrow & \mathrm{Hom}(\mathfrak{k}_{-2} \otimes \wedge^2 \mathfrak{k}_{-1}, \mathfrak{k}_{r-4}) \\
& \searrow & & \searrow & \\
\mathrm{Hom}(\mathfrak{k}_{-1}, \mathfrak{k}_{r-1}) & \longrightarrow & \mathrm{Hom}(\wedge^2 \mathfrak{k}_{-1}, \mathfrak{k}_{r-2}) & \longrightarrow & \mathrm{Hom}(\wedge^3 \mathfrak{k}_{-1}, \mathfrak{k}_{r-3})
\end{array}$$

and uses the knowledge on irreducible $\mathfrak{u}(n)$ -modules informed from Y. Agaoka. A detailed proof of the proposition will be published elsewhere.

5 Maximal sub-Riemannian contact transitive filtered Lie algebras

5.1 Main theorem

We define, for each $\varepsilon \in \mathbf{R}$, a TFLA K_ε as follows: Let the underlying vector space of K_ε to be the graded vector space $\mathfrak{k} = \mathfrak{k}_{-2} \oplus \mathfrak{k}_{-1} \oplus \mathfrak{k}_0$, and define the filtration $\{K_\varepsilon^p\}_{p \in \mathbf{Z}}$ of K_ε by $K_\varepsilon^p = \bigoplus_{i \geq p} \mathfrak{k}_i$, and the bracket operation $[\cdot, \cdot]_\varepsilon : K_\varepsilon \times K_\varepsilon \rightarrow K_\varepsilon$ by

$$[x, y]_\varepsilon = [x, y]_{\mathfrak{k}} + \varepsilon \omega(x, y) \quad \text{for } x, y \in K_\varepsilon,$$

where $[x, y]_{\mathfrak{k}}$ denotes the bracket of the graded Lie algebra \mathfrak{k} and ω is the cocycle in $\mathrm{Hom}(\wedge^2 \mathfrak{k}_{-1}, \mathfrak{k}_0)$ given in Proposition 4 (ii) (regarded as an element of $\mathrm{Hom}(\wedge^2 \mathfrak{k}, \mathfrak{k})$ in an obvious manner). Now our main theorem may be stated as follows:

Theorem 1 *If K is a TFLA and if there is an isomorphism $\phi : \mathrm{gr}K \rightarrow \mathfrak{k}$ of graded Lie algebras, then there exists a unique real number ε and an isomorphism $\Phi : K \rightarrow K_\varepsilon$ of filtered Lie algebras such that the associated map $\mathrm{gr}\Phi$ equals to ϕ .*

By using proposition 4 it is shown that the theorem holds. A detailed proof of the theorem is given in [3].

5.2 Realizations

Let us see how the filtered Lie algebras K_ε are realized on sub-Riemannian manifolds.

If $\varepsilon = 0$, then the filtered Lie algebra K_ε is isomorphic to $\mathfrak{k}_{-2} \oplus \mathfrak{k}_{-1} \oplus \mathfrak{k}_0$. It is realized as the Lie algebra of the infinitesimal automorphisms of the space $(\mathbf{R}^{2n+1}, D, g)$, where D is the contact structure on $\mathbf{R}^{2n+1}(x_1, \dots, x_n, y_1, \dots, y_n, z)$ defined by

$$dz - \frac{1}{2} \sum_{j=1}^{n+1} (x_j dy_j - y_j dx_j) = 0,$$

and the metric g on D is given by

$$g = (dx_1|_D)^2 + \dots + (dx_n|_D)^2 + (dy_1|_D)^2 + \dots + (dy_n|_D)^2.$$

If ε is positive, then the filtered Lie algebra K_ε is isomorphic to $(\mathfrak{u}(n+1), \{F^p\}_{p \in \mathbf{Z}})$, where $\{F^p\}_{p \in \mathbf{Z}}$ is a filtration of $\mathfrak{u}(n+1)$ given by:

$$F^p = \left\{ \left(\begin{array}{c|c} \lambda i & \xi \\ \hline -{}^t \bar{\xi} & A \end{array} \right) \middle| \lambda \in \mathbf{R}, \xi = (\xi_1, \dots, \xi_n) \in \mathbf{C}^n, A \in \mathfrak{u}(n) \right\} \quad (p \leq -2),$$

$$F^{-1} = \left\{ \left(\begin{array}{c|c} 0 & \xi \\ \hline -{}^t \bar{\xi} & A \end{array} \right) \middle| \xi = (\xi_1, \dots, \xi_n) \in \mathbf{C}^n, A \in \mathfrak{u}(n) \right\},$$

$$F^0 = \left\{ \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & A \end{array} \right) \middle| A \in \mathfrak{u}(n) \right\}, \quad F^q = 0 \quad (q \geq 1).$$

It is realized as the Lie algebra of the infinitesimal automorphisms of the sphere $(S^{2n+1}, D, g|_D)$, where S^{2n+1} is the set of all $(x_1, y_1, \dots, x_{n+1}, y_{n+1}) \in \mathbf{R}^{2n+2}$ such that

$$(x_1)^2 + (y_1)^2 + \dots + (x_{n+1})^2 + (y_{n+1})^2 = 1,$$

and D is defined by

$$\sum_i^{n+1} x_i dy_i - y_i dx_i|_{S^{2n+1}} = 0$$

and

$$g = (dx_1)^2 + (dy_1)^2 + \dots + (dx_{n+1})^2 + (dy_{n+1})^2.$$

If ε is negative, then the filtered Lie algebra K_ε is isomorphic to $(\mathfrak{u}(n, 1), \{F^p\}_{p \in \mathbf{Z}})$, where $\{F^p\}_{p \in \mathbf{Z}}$ is a filtration of $\mathfrak{u}(n, 1)$ given by:

$$F^p = \left\{ \left(\begin{array}{c|c} \lambda i & \xi \\ \hline {}^t \bar{\xi} & A \end{array} \right) \middle| \lambda \in \mathbf{R}, \xi = (\xi_1, \dots, \xi_n) \in \mathbf{C}^n, A \in \mathfrak{u}(n) \right\} \quad (p \leq -2),$$

$$F^{-1} = \left\{ \left(\begin{array}{c|c} 0 & \xi \\ \hline {}^t \bar{\xi} & A \end{array} \right) \middle| \xi = (\xi_1, \dots, \xi_n) \in \mathbf{C}^n, A \in \mathfrak{u}(n) \right\},$$

$$F^0 = \left\{ \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & A \end{array} \right) \middle| A \in \mathfrak{u}(n) \right\}, \quad F^q = 0 \quad (q \geq 1).$$

It is realized as the Lie algebra of infinitesimal automorphisms of the hypersurface $(\Sigma^{2n+1}, D, g|_D)$, where Σ^{2n+1} is the set of all $(x_1, y_1, \dots, x_{n+1}, y_{n+1}) \in \mathbf{R}^{2n+2}$ such that

$$(x_1)^2 + (y_1)^2 + \dots - (x_{n+1})^2 - (y_{n+1})^2 = -1$$

and D is defined by

$$\sum_{j=1}^n (y_j dx_j - x_j dy_j) - (y_{n+1} dx_{n+1} - x_{n+1} dy_{n+1}) = 0,$$

and

$$g = (dx_1)^2 + (dy_1)^2 + \cdots + (dx_n)^2 + (dy_n)^2 - (dx_{n+1})^2 - (dy_{n+1})^2$$

is a pseudo-Riemannian metric on $\mathbf{R}^{2n+2}(x_1, y_1, \dots, x_{n+1}, y_{n+1})$, whose restriction $g|_D$ on D is a positive definite inner product.

Summarizing the above discussion, we have, in particular:

Theorem 2 *If K is a maximal sub-Riemannian contact TFLA, then K is isomorphic to K_ε for $\varepsilon = -1, 0$ or 1 .*

It should be noted that there exists a Cartan connection associated with a sub-Riemannian structure (satisfying certain regularity conditions)[8]. By using this Cartan connection we can prove that $\mathcal{L}_a^p = 0$ if p is large enough, which implies that \mathcal{L}_a is in fact isomorphic to L . Thus the results above for L hold also for \mathcal{L}_a , and we have:

Theorem 3 *Let (M, D, g) be a homogeneous sub-Riemannian contact manifold of dimension $2n + 1$, and let \mathcal{L}_a be the stalk at $a \in M$ of the sheaf \mathcal{L} the of infinitesimal automorphisms of (M, D, g) . If \mathcal{L}_a attains the maximal dimension $(n + 1)^2$, then \mathcal{L}_a is isomorphic to K_ε for $\varepsilon = -1, 0$ or 1 .*

6 A remark on transitive filtered Lie algebras

In [6] Morimoto studied transitive filtered Lie algebras (TFLA's) of depth $\mu \geq 1$ and established the fundamental structure theorems which describe how a TFLA is built on its associated transitive graded Lie algebra (TGLA).

In this paper we have followed his method to study the structure of sub-Riemannian contact TFLA's. While applying it to our concrete problems we have obtained some improvement of his general theorems. In particular, we can extend Theorem 4.3 ([6], p.69) as follows:

Theorem 4 *Let L_i ($i = 1, 2$) be complete TFLA's, and let k be an integer ≥ 0 such that*

$$H_r^1(\mathfrak{gr}_-L, \mathfrak{gr}L) = IH_r^2(\mathfrak{gr}_-L, \mathfrak{gr}L) = 0 \quad \text{for } i = 1, 2, r \geq k + 1.$$

Then L_1 and L_2 are isomorphic if and only if $\text{Trun}_k L_1$ and $\text{Trun}_k L_2$ are isomorphic.

Here we follow the notation of [6]. In particular, we refer to it for the definition of a truncated transitive filtered Lie algebra $\text{Trun}_k L$ of order k ([6], p.57). As defined in section 4, $IH_r^2(\mathfrak{gr}_-L, \mathfrak{gr}L)$ denotes the space of $\mathfrak{gr}_0 L$ -invariant elements in $H_r^2(\mathfrak{gr}_-L, \mathfrak{gr}L)$

Our theorem asserts that the condition $H_r^2(\mathfrak{gr}_-L, \mathfrak{gr}L) = 0$ in the original theorem can be replaced by the weaker condition $IH_r^2(\mathfrak{gr}_-L, \mathfrak{gr}L) = 0$. Roughly speaking, given a TGLA \mathfrak{g} , we can take the smaller space $IH_r^2(\mathfrak{g}_-, \mathfrak{g})$ instead of $H_r^2(\mathfrak{g}_-, \mathfrak{g})$ as a parameter space of the moduli of the TFLA's whose associated TGLA's are equal to \mathfrak{g} .

The proof of the theorem is similar to that of the original one if we properly interpret that the formula (2.21)_k, ii) ([6], p.67) actually leads to our condition $IH_r^2(\mathfrak{gr}_-L, \mathfrak{gr}L) = 0$.

The improvement observed here seems useful also in other applications of the theorem. As a corollary of the theorem above, we have also:

Corollary 1 *If L is a TFLA satisfying $H_r^1(\mathfrak{gr}_-L, \mathfrak{gr}L) = IH_r^2(\mathfrak{gr}_-L, \mathfrak{gr}L) = 0$ for $r \geq 1$, then L is graded, that is, L can be embedded into the completion of the graded Lie algebra $\mathfrak{gr}L$.*

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