LIE ALGEBRAS OF INFINITESIMAL CR-AUTOMORPHISMS
OF FINITE TYPE, HOLOMORPHICALLY NONDEGENERATE,
WEIGHTED HOMOGENEOUS CR-GENERIC SUBMANIFOLDS OF \( \mathbb{C}^N \)

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ABSTRACT. We consider the significant class of holomorphically nondegenerate CR manifolds of finite type that are represented by some weighted homogeneous polynomials and we derive some useful features which enable us to set up a fast effective algorithm to compute their Lie algebras of infinitesimal CR-automorphisms. This algorithm mainly relies upon a natural gradation of the sought Lie algebras, and it also consists in treating separately the related graded components. While some other methods are based on constructing and solving an associated PDE systems which become time consuming as soon as the number of variables increases, the new method presented here is based on plain techniques of linear algebra. Furthermore, it benefits from a divide-and-conquer strategy to break down the computations into some simpler sub-computations. Moreover, we consider the new and effective concept of comprehensive Gröbner systems which provides us some powerful tools to treat the computations in the parametric cases. The designed algorithm is also implemented in the MAPLE software.

1. INTRODUCTION

Let \( M \subset \mathbb{C}^{n+k} \) be a Cauchy-Riemann (CR for short) submanifold of CR dimension \( n \geq 1 \) and of codimension \( k \geq 1 \) (see \cite{2} for all pertinent definitions used in this introduction) represented in coordinates \( z_j \) and \( w_l := u_l + iw_l \) for \( j = 1, \ldots, n \) and \( l = 1, \ldots, k \). As is standard in CR-geometry (\cite{4,14,7,8}), one may often assign weight \( [z_j] := 1 \) to all the complex variables \( z_j \) and weights some certain integers \( [w_l] \in \mathbb{N} \) with \( 1 \leq [w_1] \leq [w_2] \leq \cdots [w_k] \) to the variables \( w_1, \ldots, w_k \). Accordingly, the weight of the conjugation of each complex variable and of its real and imaginary parts as well are all equal to that of the variable and, moreover, the assigned weight of any constant number \( \alpha \in \mathbb{C} \) and of coordinate vector fields are:

\[
[a] := 0, \quad [\partial_{z_j}] := -[z_j], \quad [\partial_{w_l}] := -[w_l], \quad (j=1,\ldots,n, \ l=1,\ldots,k).
\]

Furthermore, the weight of a monomial \( F \) in the \( z_j, w_k, \overline{z}_j, \overline{w}_k \) is the sum taken over the weights of all variables of \( F \) with regards to their powers and also, the weight of each coordinate vector field of the form \( F \partial_x \) with \( x = z_i, w_l \) is defined as \( [F] - [x] \). For instance, we have \( [(\alpha z w_1) \partial_{w_2}] = [z] + 2[w_1] - [w_2] \).

A polynomial or a vector field is called weighted homogeneous of weight \( \alpha \in \mathbb{C} \) and of degree \( d \) whenever each of its terms is of homogeneity \( d \).

As is well-known (see \cite{4} Theorem 4.3.2 and the Remark after it or \cite{27} Theorem 2.12), every real analytic generic CR manifold \( M \) of CR dimension \( n \) and codimension \( k \) can be represented locally in a neighborhood of the origin as the graph of a function of \( z \) and \( \overline{z} \) defined equations of the form:

\[
\begin{align*}
v_1 &= \Phi_1(z, \overline{z}, u) + o([w_1]), \\
& \vdots \\
v_k &= \Phi_k(z, \overline{z}, u) + o([w_k]),
\end{align*}
\]

(1)

where the weight of all variables \( z_j \) is 1 and the weights of the variables \( w_l \) are the Hörmander numbers of \( M \) at the origin. Moreover, each function \( \Phi_j \) is a weighted homogeneous polynomial of weight \( [w_1] \) and \( o(t) \) denotes remainder terms having weights \( > t \).

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For a CR manifold $M$ passing through the origin, the Lie group $\text{Aut}_{CR}(M)$ is the holomorphic symmetry group of $M$, that is the local Lie group of local biholomorphisms mapping $M$ to itself. The Lie algebra $\mathfrak{aut}_{CR}(M)$, associated to this group, is called the Lie algebra of infinitesimal CR-automorphisms of $M$ and it consists of all holomorphic vector fields — $(1,0)$ fields with holomorphic coefficients — whose real parts are tangent to $M$. Due to the fact that many geometric features of CR manifolds can be investigated by means of their associated Lie algebras of infinitesimal CR-automorphisms and because of central applications in Cartan geometry and in Tanaka theory exist, studying such algebras have gained an increasing interest during the recent decades (cf. [7,11,33,28,38]). As is known, the Lie algebra $\mathfrak{aut}_{CR}(M)$ is finite dimensional if and only if $M$ is holomorphically nondegenerate and of finite type ([4,38],[18],[19],[27]).

Consider the complex space $\mathbb{C}^{n+k}$ equipped with the coordinates $z_1, \ldots, z_n, w_1, \ldots, w_k$, where $w_j := u_j + iv_j$, assume again that certain weights have been assigned, and consider holomorphically nondegenerate weighted homogeneous CR manifolds $M \subset \mathbb{C}^{n+k}$ represented as graphs of $k$ certain polynomials:

$$M := \{ (z, w) : \begin{cases} \Xi_1(v_1, z, \bar{z}, u) := v_1 - \Phi_1(z, \bar{z}, u) = 0, \\
\Xi_2(v_2, z, \bar{z}, u) := v_2 - \Phi_2(z, \bar{z}, u) = 0, \\
\vdots \\
\Xi_j(v_j, z, \bar{z}, u) := v_j - \Phi_j(z, \bar{z}, u) = 0, \\
\vdots \\
\Xi_k(v_k, z, \bar{z}, u) := v_k - \Phi_k(z, \bar{z}, u) = 0, \end{cases} \}$$

with the right-hand sides $\Phi_j$ being weighted homogeneous polynomials of weight equal to that $[v_j] = [w_j]$ of the left-hand sides. We will also assume that such $M$ are homogeneous in Lie theory’s sense, namely that $\text{Aut}_{CR}(M)$ is locally transitive near the origin. Since it may arise some confusion with the ‘homogeneous spaces’ terminology, let us stress that we will always use weighted homogeneous about functions, and plainly homogeneous about $\text{Aut}_{CR}(M)$.

The so introduced class of CR-generic manifolds is already an extremely wide class in CR-geometry which includes of course well known quadric CR-models such as those of Poincaré [32] or of Chern-Moser [15], and also, there is nowadays an extensive literature dealing with constructing a great number of such weighted homogeneous CR manifolds (see for example [3,4,13,24,36] and [6–9]), their Lie groups being far from being completely understood.

Indeed, in a series of recent papers (for instance [6–10]), Valerii Beloshapka studied extensively the subject of model surfaces and found some considerable results in this respect. Specifically in [7], he introduced and established the structure of some nondegenerate models associated (uniquely) to totally nondegenerate germs having arbitrary CR dimensions and real codimensions. He also developed systematic tools for their construction. All of these models are again included in our already mentioned class of CR manifolds. Each of Beloshapka’s model $M \subset \mathbb{C}^{n+k}$ of certain CR dimension and codimension $n$ and $k$ enjoys some nice properties ([7], page 484, Theorem 14) which have been encouraging enough to merit further investigation. In particular, computing their Lie algebras of infinitesimal CR-automorphisms and studying their structures may reveal some interesting features of these CR-models, and also of all totally nondegenerate CR manifolds corresponding to them (cf. [12]).

It is worth noting that, traditionally the subject of computing Lie algebras of infinitesimal CR-automorphisms is concerned with expensive computations and the cost of calculations increases as much as the number of the variables — namely the dimension or codimension of the CR manifolds — increases. Indeed, solving the PDE systems arising during these computations (see subsection 2.1) forms the most complicated part of the procedure. That may be the reason why, in contrast to the importance of the subject, the number of the relevant computational works is still limited (one finds some of them in [28,10,36,24]).

Very recently, the authors provided in [34] a new general algorithm to compute the desired algebras by means of the effective techniques of differential algebra (see [2] below for a brief description of the algorithm). It enables one to use conveniently the ability of computer algebra for managing the associated
computations of the concerning PDE systems. Although this (general) algorithm is able to decrease a lot the complexity of the computations and in particular to utilize systematically the ability of computer algebra, but because of dealing with the PDE systems — which are complicated in their spirit — the computations are still expensive in essence.

In the present paper we aim to study, by means of a weight analysis approach and with an algorithmic treatment, the intrinsic properties of the under consideration CR manifolds in order to provide an effective algorithm — entirely different and more powerful than that of [34] — to compute the associated Lie algebras of infinitesimal CR-automorphisms. The results enable us to bypass constructing and solving the arising systems of PDE (which is the classical method of [10 28 33 24 36 34]) and to reach the sought algebras by employing just simple techniques of linear algebra. This decreases considerably the cost of computations, hence simultaneously increases the performance of the algorithm.

We show that for a homogeneous CR manifold $M$ represented as (2), the sought algebra $\mathfrak{g} := \mathfrak{aut}_{CR}(M)$ takes the graded form (in the sense of Tanaka):

$$
\mathfrak{g} = \bigoplus_{\rho} \mathfrak{g}_{\rho} \oplus \cdots \oplus \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1 \oplus \cdots \oplus \mathfrak{g}_{\varrho} \quad \rho, \varrho \in \mathbb{N}.
$$

where each component $\mathfrak{g}_t$ is the Lie subalgebra of all weighted homogeneous vector fields having weight $t$. Summarizing, the results provide us with the ways of:

- using a divide-and-conquer method to break down the computations of the sought (graded) algebra $\mathfrak{g}$ into some simpler sub-computations of its (homogeneous) components $\mathfrak{g}_t$;
- employing some simple techniques of linear algebra for computing these components $\mathfrak{g}_t$ of infinitesimal CR-automorphisms without relying on solving the PDE systems;

We also find a simple criterion for how long it is necessary to compute the homogeneous components $\mathfrak{g}_t$ of $\mathfrak{g}$. In other words, it supplies us to recognize — in an algorithmic point of view — where the maximum homogeneity $\varrho$ in (3) is, while the minimum homogeneity $\rho$ is easy to determine. This criterion fails when $\text{Aut}_{CR}(M)$, or equivalently $\mathfrak{aut}_{CR}(M)$, is not locally transitive. However without local transitivity, one still is able to compute the homogeneous components $\mathfrak{g}_t$, separately.

One of the main — somehow hidden — obstacles appearing among the computations arises when the set of defining equations includes some certain parametric polynomials. This case is quite usual as one observes in [7 10 24 36]. To treat such cases, we suggest the modern and effective concept of comprehensive Gröbner systems [41 20 21 30 31] which enables us to consider and solve (linear) parametric systems appearing among the computations.

This weight analysis computational approach to the determination of infinitesimal CR-automorphisms can provide useful tools to study some general problems in CR-geometry, as for instance the models of Kolar ([22]), and also, it can offer numerical evidence to support a recent conjecture of Beloshapka [6] which asserts that:

**Beloshapka’s Maximum conjecture:** For a homogeneous CR-model as those of [7] with the graded Lie algebra of infinitesimal CR-automorphisms like (3), if $3 \leq \rho < \infty$ then the corresponding universal CR manifold has ‘rigidity’ i.e. $\varrho = 0$.

This paper is organized as follows. Section 2 presents a brief description of required very basic definitions, notations and terminology and also a presentation of our recently prepared algorithm [34]. In Section 3 we inspect some of the Lie algebras computed in [10 28 36 24] and we observe a striking similarity in the coefficients of the appearing holomorphic vector fields. This leads us to discover the key entrance to the desired algorithm. In Section 4 we employ the results of the previous section to provide the strategy of computing separately the homogeneous components of the sought algebras. We also provide the necessary criterion for terminating such computations. Section 5 presents the desired algorithm of computing the Lie algebras of infinitesimal CR-automorphisms associated to the universal CR manifolds by using the results obtained in the earlier sections. Finally, in section 6 we introduce briefly the modern concept of comprehensive Gröbner systems and show how it provides some effective tools to consider and solve appearing (linear) parametric systems.
The algorithm designed in this paper is implemented in MAPLE 15 as the library CRAUT, accessible online as [35]. To do this, at first we needed to implement the algorithm PGB introduced in the recently published paper [21] which enables us to consider the parametric defining equations in CRAUT.

2. Basic preliminaries and definitions

On an arbitrary even-dimensional real vector space $V$, a complex structure map $J : V \rightarrow V$ is an $\mathbb{R}$-linear map satisfying $J \circ J = -\text{Id}_V$. For example, in the simple case $V := T_p\mathbb{R}^{2N} = T_p\mathbb{C}^N$, $N \in \mathbb{N}$ with the local coordinates $(z_1 := x_1 + i y_1, \ldots, z_N := x_N + i y_N)$ and with $p \in \mathbb{C}^N$, one defines the (standard) complex structure map by:

$$J\left(\frac{\partial}{\partial x_j}\right) = \frac{\partial}{\partial y_j}, \quad J\left(\frac{\partial}{\partial y_j}\right) = -\frac{\partial}{\partial x_j}, \quad j = 1, \ldots, N.$$ 

One should notice that in general, an arbitrary subspace $H_p$ of $T_p\mathbb{C}^N$ is not invariant under the complex structure map $J$. Thus, one may give special designation to the largest $J$-invariant subspace of $H_p$ as:

$$H_p \cap J(H_p) =: H_p^c,$$

which is called the complex tangent subspace of $H_p$. Due to the equality $J \circ J = -\text{Id}$, this space is even-dimensional, too.

Similarly, one also introduces the smallest $J$-invariant real subspace of $T_p\mathbb{C}^N$ which contains $H_p$:

$$H_p^{ic} := H_p + J(H_p)$$

and one calls its the intrinsic complexification of $H_p$.

As an application, consider the linear subspace $H_p := T_pM$ of $\mathbb{C}^N$, for some arbitrary connected differentiable submanifold $M$ of $\mathbb{C}^N$. In general, it is not at all true that the complex-tangent planes:

$$T^c_pM = T_pM \cap J(T_pM)$$

have constant dimensions as $p$ varies in $M$.

**Definition 2.1.** Let $M$ be a real analytic submanifold of $\mathbb{C}^N$. Then $M$ is called Cauchy-Riemann (CR for short), if the complex dimensions of $T^c_pM$ are constant as $p$ varies on $M$. Furthermore, $M$ is called generic whenever:

$$T^c_pM := T_pM + J(T_pM) = T_p\mathbb{C}^N$$

for each $p \in M$, which implies that $M$ is CR thanks to elementary linear algebra.

One knows ([14], [4], [27]) that any CR real analytic $M \subset \mathbb{C}^N$ is contained in a thin strip-like complex submanifold $C' \cong \mathbb{C}^{N'}$ with $N' \leq N$ in which $M \subset \mathbb{C}^{N'}$ is CR-generic, hence there is no restriction to assume that $M$ is CR-generic, as we will always do here, since we are interested in local CR geometry.

For such a CR-generic manifold $M$, we call the complex dimension of $T^c_pM$ by the CR-dimension of $M$. Moreover, the subtraction of the real dimension of $T^c_pM$ from that of $T_pM$, which is in fact the real dimension of the so-called totally real part $T^r_pM/T^c_pM$ of $T_pM$, coincides then with the real codimension of $M \subset \mathbb{C}^N$.

A tangent vector field:

$$X := \sum_{j=1}^{N} \left( a_j \frac{\partial}{\partial Z_j} + b_j \frac{\partial}{\partial Z_j} \right)$$

of the complexified space $\mathbb{C}T_p\mathbb{C}^N := \mathbb{C} \otimes T_p\mathbb{C}^N$ is called of type $(1,0)$ whenever all $b_j \equiv 0$ and is called of type $(0,1)$ whenever all $a_j \equiv 0$. One denotes by $T^{1,0}_p\mathbb{C}^N$ and $T^{0,1}_p\mathbb{C}^N$ the corresponding subspaces of $\mathbb{C}T_p\mathbb{C}^N$. Accordingly, for a CR manifold $M$ and an arbitrary point $p$ of it, we denote:

$$T^{1,0}_pM := T^{1,0}_p\mathbb{C}^N \cap CT_pM, \quad \text{and} \quad T^{0,1}_pM := T^{0,1}_p\mathbb{C}^N \cap CT_pM.$$ 

One easily verifies the equality $T^{0,1}_pM = T^{1,0}_pM$. It is proved that (see [3], Proposition 1.2.8) the complex tangent space $T^c_pM$ is the real part of $T^{1,0}_pM$, i.e. $T^c_pM = \{ X + \overline{X} : X \in T^{1,0}_pM \}$. Moreover, the complexified space $\mathbb{C}T_pM$ is equal to the direct sum $T^{1,0}_pM \oplus T^{0,1}_pM$. 
If \( n \) and \( k \) are the CR dimension and the real codimension of a real analytic CR-generic submanifold \( M \subset \mathbb{C}^N \), then of course \( N = n + k \), and also \( M \) can be represented (locally) by \( k \) real analytic graphed equations:

\[
\operatorname{Im} w_j := \Phi_j(z, \overline{z}, \operatorname{Re} w), \quad (j=1,\ldots,k)
\]

with some real-valued defining functions \( \Phi_j \) enjoying the no-pluriharmonic term condition:

\[
0 \equiv \Phi_j(z, 0, \operatorname{Re} w) = \Phi_j(0, \overline{z}, \operatorname{Re} w).
\]

Solving the above real-valued defining functions in \( w \) or in \( \overline{w} \), one also reformulates the defining functions of \( M \) as complex defining equations of the kind:

\[
w_j + \overline{w}_j = \Xi_j(z, \overline{z}, w), \quad (j=1,\ldots,k).
\]

The real analyticity of the functions \( \Xi_j \) enables us to employ their Taylor series for computing the associated algebras of infinitesimal CR-automorphisms (see the next subsection).

For a real analytic CR-generic manifold \( M \) represented by the above defining functions as \((5)\) and for each \( p \in M \), it is well-known (\cite{33}) that the space \( T^0_p M \) is generated by the following holomorphic vector fields, tangent to \( M \):

\[
L_j := \frac{\partial}{\partial z_j} + \sum_{l=1}^k \frac{\partial \Xi_j}{\partial z_j} (z, \overline{z}, w) \frac{\partial}{\partial \overline{w}_l} \quad (j=1,\ldots,n).
\]

**Definition 2.2.** A CR-generic submanifold \( M \subset \mathbb{C}^{n+k} \) of CR dimension \( n \) and of codimension \( k \) is called of finite type at a point \( p \in M \) whenever the above generators \( L_1, \ldots, L_n, \overline{L}_1, \ldots, \overline{L}_n \) together with all of their Lie brackets of any length span the complexified tangent space \( \mathbb{C}T_p M \) at the point \( p \).

Of course, finite-typeness at a point is an open condition. In \cite{13}, Bloom and Graham introduced an effective method to construct homogeneous CR manifolds that we now explain briefly. Consider the complex space \( \mathbb{C}^{n+k} \) equipped with the variables \( z_1, \ldots, z_n, w_1 := u_1 + iv_1, \ldots, w_k := u_k + iv_k \), assign weight 1 to the variables \( z_i \) and assign some arbitrary weights \( \ell_j \) to each \( w_j \) for \( j = 1, \ldots, k \). Then a CR manifold \( M \subset \mathbb{C}^{n+k} \) is called represented in Bloom-Graham normal form \((13,14)\) whenever it is defined as the graph of some real-valued function \( v_j \):

\[
v_j = \Phi_j(z, \overline{z}, u_1, \ldots, u_{j-1}) + o(\ell_j) \quad (j=1,\ldots,k),
\]

where each \( \Phi_j \) is a weighted homogeneous polynomial of the weight \( \ell_j \) enjoying the following two statements:

\[\begin{align*}
(i) \quad \text{there are no pure terms } z^\alpha u^\beta \text{ or } z^\alpha \overline{w}^\beta \text{ among the polynomials } \Phi_j \text{ for some integers } \alpha \text{ and } \beta; \\
(ii) \quad \text{for each } 1 \leq j < i \text{ and for any nonnegative integers } \alpha_1, \ldots, \alpha_j, \text{ the polynomial } \Phi_i \text{ does not include any term of the form } u_1^{\alpha_1} \cdots u_j^{\alpha_j} \Phi_j.
\end{align*}\]

Every CR manifold represented in this form is of finite type (see \cite{14} page 181). Bloom and Graham also showed that every CR manifold represented by the above expressions \((6)\) can be transformed to such a normal form by means of some algebraic changes of coordinates (see \cite{13}, Theorem 6.2).

**Definition 2.3.** A real analytic CR-generic manifold \( M \subset \mathbb{C}^N \) with coordinates \( (Z_1, \ldots, Z_N) \) is called holomorphically nondegenerate at \( p \in M \) if there is no local nonzero vector field of type \((1, 0)\):

\[
X := \sum_{j=1}^N f_j(Z_1, \ldots, Z_N) \frac{\partial}{\partial Z_j}
\]

having coefficients \( f_j \) holomorphic in a neighborhood of \( p \) such that \( X|_M \) is tangent to \( M \) near \( p \).

Every connected real analytic generic CR manifold is either holomorphically nondegenerate at every point or at no point \((27)\).

\[\text{(1) There is also a more general definition of Bloom-Graham normal form which one can find it for example in [5].}\]
**Definition 2.4.** ([13, 10, 28]) A (local) infinitesimal CR-automorphism of $M$, when understood extrinsically, is a local holomorphic vector field:

\[ X = \sum_{i=1}^{n} Z^i(z, w) \frac{\partial}{\partial z_i} + \sum_{j=1}^{k} W^j(z, w) \frac{\partial}{\partial w_j} \]

whose real part $\text{Re} X = \frac{1}{2}(X + \overline{X})$ is tangent to $M$.

The collection of all infinitesimal CR-automorphisms of $M$ constitutes a Lie algebra which is called the Lie algebra of infinitesimal CR-automorphisms of $M$ and is denoted by $\mathfrak{aut}_{CR}(M)$.

The notion of holomorphically nondegeneracy was raised by Nancy Stanton in [38] where she proved that for a hypersurface $M \subset \mathbb{C}^{n+1}$ (always generic), $\mathfrak{aut}_{CR}(M)$ is finite-dimensional if and only if $M$ is holomorphically nondegenerate. Amazingly enough, one realizes that the concept of tangent vector fields completely independent of $Z_1, \ldots, Z_N$ which points out a strong degeneracy can in fact be traced back at least to Sophus Lie’s works (cf. pp. 13–14 of [29]). In general codimension $k \geq 1$, the Lie algebra $\mathfrak{aut}_{CR}(M)$ of infinitesimal CR-automorphisms of a CR-generic real analytic $M \subset \mathbb{C}^{n+k}$ is finite-dimensional if and only if $M$ is holomorphically nondegenerate and of finite type ([18]).

Determining such Lie algebras $\mathfrak{aut}_{CR}(M)$ is the same as knowing the CR-symmetries of $M$, a question which lies at the heart of the (open) problem of classifying all local analytic CR manifolds up to biholomorphisms. In the groundbreaking works of Sophus Lie and his followers (Friedrich Engel, Georg Scheffers, Gerhard Kowalewski, Ugo Amaldi and others), the most fundamental question in concern was to draw up lists of possible Lie algebras $\mathfrak{aut}_{CR}(M)$ which would classify all possible $M$’s according to their CR symmetries.

### 2.1. The main idea.

Now, let us explain briefly the main strategy used in [34] for computing the Lie algebra $\mathfrak{aut}_{CR}(M)$ associated to an arbitrary real analytic generic CR manifold $M \subset \mathbb{C}^{n+k}$, represented as the graph of the $k$ complex defining equations as (5). For this, we shall proceed to do successively the following steps:

- According to the definition, a holomorphic vector field:

\[ X = \sum_{j=1}^{n} Z^j(z, w) \frac{\partial}{\partial z_j} + \sum_{l=1}^{k} W^l(z, w) \frac{\partial}{\partial w_l} \]

belongs to $\mathfrak{aut}_{CR}(M)$ whenever it enjoys the tangency equations:

\[ 0 \equiv (X + \overline{X})[\mathfrak{m}_j + w_j - \Xi_j(\tau, z, w)] = \]

\[ = \mathfrak{X} [\mathfrak{m}_j + w_j - \Xi_j(\tau, z, w)] + \mathfrak{X} [\mathfrak{m}_j + w_j - \Xi_j(\tau, z, w)] \]

\[ = W^j(\tau, w) - \sum_{i=1}^{n} Z^i(\tau, w) \frac{\partial \Xi_j}{\partial z_i}(\tau, z, w) + \]

\[ + W^j(z, w) - \sum_{i=1}^{n} Z^i(z, w) \frac{\partial \Xi_j}{\partial z_i}(\tau, z, w) - \sum_{l=1}^{k} W^l(z, w) \frac{\partial \Xi_j}{\partial w_l}(\tau, z, w) \]

\[ (j = 1 \ldots k) . \]

For each $j = 1, \ldots, k$, let us refer to the above equality as the $j$-th tangency equation of $M$.

Now, the Taylor series formulae:

\[ Z^i(z, w) = \sum_{\alpha \in \mathbb{N}^n} z^n Z^i_{\alpha}(w) \quad \text{and} \quad W^j(z, w) = \sum_{\alpha \in \mathbb{N}^n} z^n W^j_{\alpha}(w) , \]
bring the tangency equation into the form:

\[
0 \equiv \sum_{\alpha \in \mathbb{N}^n} z^n W_\alpha (-w + \Xi) \sum_{k=1}^{n} \sum_{\alpha \in \mathbb{N}^n} z^\alpha \sum_{j=1}^{k} \frac{\partial \Xi_j}{\partial z_k} (\Xi, z, w) + \\
+ \sum_{\beta \in \mathbb{N}^n} z^\beta W_\beta (w) \sum_{k=1}^{n} \sum_{\beta \in \mathbb{N}^n} z^\beta \sum_{j=1}^{k} \frac{\partial \Xi_j}{\partial z_k} (\Xi, z, w) - \sum_{l=1}^{k} \sum_{\beta \in \mathbb{N}^n} z^\beta W_\beta (w) \frac{\partial \Xi_j}{\partial w_l} (\Xi, z, w) \tag{10}
\]

- After this, one replaces the appearing functions \( W_\alpha (-w + \Xi) \) and \( Z_\alpha (-w + \Xi) \) according to the following slightly artificial expansions:

\[
\Xi (-w + \Xi) = \Xi (w + (2w + \Xi)) = \sum_{\gamma \in \mathbb{N}^d} \frac{\partial \gamma} {\partial w_\gamma} (w) 1_{\gamma} (-2w + \Xi(z, w)) \gamma,
\]

and one next substitutes each \(-2w_j + \Xi_j\) with:

\[
-2w_j + \Xi_j (\Xi, z, w) = \sum_{\alpha \in \mathbb{N}^n} \sum_{\beta \in \mathbb{N}^n} z^\alpha z^\beta \Xi_{j, \alpha, \beta} (w) \quad (j = 1 \ldots k).
\]

- Modifying the equations (10) by the two already presented formulae, we reach \( k \) homogeneous equations so that their right hand sides are some certain combinations of the (yet unknown) functions \( Z_\alpha (w) \) and \( W_\beta (w) \), their derivations and also the variables \( w_1, \ldots, w_k \) with the coefficients of the form \( z^\mu z^\nu \) for \( \mu = (\mu_1, \ldots, \mu_n) \) and \( \nu = (\nu_1, \ldots, \nu_n) \) (here we set \( z_\mu := z_1^{\mu_1} \ldots z_n^{\mu_n} \)). To satisfy these equations, one should extract the coefficients of the various monomials \( z^\mu z^\nu \) and equate them to zero. Then, one attains a (usually lengthy and complicated) homogeneous linear system of complex partial differential equations with the unknowns \( Z_\alpha (z, w) \) and \( W_\beta (z, w) \) — namely a linear system of differential polynomials of the differential algebra \( R := \mathbb{C}(w, \Xi)[Z_\alpha, W_\beta] \). The solution of this system yields the desired coefficients \( Z_\alpha (z, w) \) and \( W_\beta (z, w) \) in [19].

- To solve this already constructed PDE system, we employ the effective tools of differential algebra, equipped with some additional operators such as \( \text{bar-reduction} \). For more details we refer the reader to [34].

Let us conclude this section by a short discussion of the abilities and advantages of the algorithm introduced in [34] and also the difficulties and weaknesses inherent in it. This algorithm manages to compute systematically the desired algebras associated to arbitrary CR manifolds \( M \subset \mathbb{C}^{n+k} \). Moreover, it employs the powerful techniques of differential algebra and the ability of computer algebra to provide a more effective method. In fact, it handles more appropriately the most complicated part of the computations, namely solving the associated PDE systems (cf. [10] [24] [33] [28] [36]). Specifically, for the significant class of rigid CR manifolds — those whose defining equations \( \Xi \) are independent of the variables \( w \) — the computations are considerably eased up. However, the main obstacle we encounter is that, because of the complexity of the PDE systems, as much as the number of variables \( z_k \) and \( w_l \) increases, then the cost of the associated computation grows extensively and the implementation of the algorithm rapidly reveals limits concerning the capacity of computer systems.

3. RIGIDITY OF HOMOGENEOUS CR MANIFOLDS AND SIMILARITY IN THE EXPRESSIONS OF THE CORRESPONDING SOUGHT FUNCTIONS

Consider the complex space \( \mathbb{C}^{n+k} \) equipped with \( n \) complex variables \( z_1, \ldots, z_n \) of weight one, identically, and \( k \) complex variables \( w_1 := u_1 + iv_1, \ldots, w_k := u_k + iv_k \) of certain weights \( 1 < [w_1] \leq \)
and define the homogeneous manifold $M$ of CR dimension $n$ and codimension $k$ as:

\[
M := \{ (z, w) : \begin{cases}
\Xi_1(v_1, z, \overline{z}, u) := v_1 - \Phi_1(z, \overline{z}, u) \equiv 0, \\
\Xi_2(v_2, z, \overline{z}, u) := v_2 - \Phi_2(z, \overline{z}, u) \equiv 0, \\
\vdots \\
\Xi_j(v_j, z, \overline{z}, u) := v_j - \Phi_j(z, \overline{z}, u) \equiv 0, \\
\vdots \\
\Xi_k(v_k, z, \overline{z}, u) := v_k - \Phi_k(z, \overline{z}, u) \equiv 0,
\end{cases}\}
\]  

(11)

with the weighted homogeneous polynomials $\Phi_j$ of the certain weight $|w_j|$ for $j = 1, \ldots, k$. Throughout this paper we assume that these manifolds are holomorphically nondegenerate and of finite type, which guarantees the finite dimensionality of their associated algebras of infinitesimal CR-automorphisms.

### 3.1. Gradation and Polynomiality

At first, let us show two significant intrinsic features of the already mentioned homogeneous CR manifolds, namely gradation (in the sense of Tanaka) and polynomiality of their associated algebras of infinitesimal CR-automorphisms.

For a CR manifold $M$ as above, consider the holomorphic vector field:

\[
X := \sum_{j=1}^{n} Z^j(z, w) \partial_{x_j} + \sum_{l=1}^{k} W^l(z, w) \partial_{w_l}
\]

as an element of $g := \text{aut}_{CR}(M)$. Since the above coefficients $Z^j$ and $W^l$ are all holomorphic, then one can expand them as their Taylor series and thus decompose $X$ into its weighted homogeneous components as follows:

\[
X := X_{-\rho} + \cdots + X_{-1} + X_0 + X_1 + \cdots + X_t + \cdots, \quad (\rho, t \in \mathbb{N}).
\]

We need the following facts:

**Lemma 3.1.** The minimum homogeneous component $X_{-\rho}$ in the above decomposition of $X$ is of the weight $-\rho = -|w_k|$, where $w_k$ has the maximum homogeneity among the complex variables appearing in (11).

**Proof.** It is just enough to observe that the tangent space of holomorphic vector fields can be generated by the standard fields $\partial_{x_j}, \partial_{w_l}$ of the certain weights $-|z_j|$ and $-|w_l|$ for $j = 1, \ldots, n$ and $l = 1, \ldots, k$. Among these standard fields, the minimum homogeneity belongs to $\partial_{w_k}$. This completes the proof. □

**Lemma 3.2.** Each of the above weighted homogeneous components $X_t$, $t \geq -\rho$ is again an infinitesimal CR-automorphism, namely belongs to $g$.

**Proof.** Since $X$ is an infinitesimal CR-automorphism then we have:

\[
0 \equiv (X + \overline{X})|_{\xi_j}, \quad (j=1, \ldots, k).
\]

Now, for each component $X_t$ of homogeneity $t$ and since each defining function $\Xi_j$ is homogeneous of weight $\ell_j := |w_j|$ then one verifies that the polynomial $(X_t + \overline{X_t})|_{\xi_j}$ is either zero or a homogeneous polynomial of weight $t + \ell_j$. Hence we have:

\[
0 \equiv (X + \overline{X})|_{\xi_j} = \left( \sum_{l=\rho}^{t} P_{t, l} |_{\xi_j} \right) \left( \sum_{l=0}^{\rho} |_{\xi_j} \right) \left( \sum_{l=t+1}^{\infty} P_{t, l} |_{\xi_j} \right),
\]

in which each polynomial function $P_{t, j}$ is either zero or a homogeneous polynomial of the weight $t + \ell_j$. Hence, we have some certain weighted homogeneous polynomials $P_{t, j}$ with distinct homogeneities and consequently with linear independency. Hence, one obtains from (13) that:

\[
0 \equiv P_{t, j}(z, w) = (X_t + \overline{X_t})|_{\xi_j}, \quad t \geq -\rho, \quad (j=1, \ldots, k).
\]

This equivalently means that each component $X_t$ of $X$ is an infinitesimal CR-automorphism. □

Now, we can prove the polynomiality of the sought algebras:
Corollary 3.3. If:

\[ X_t := \sum_{j=1}^{n} Z_t^j(z, w) \partial z_j + \sum_{l=1}^{k} W_t^l(z, w) \partial w_l \]

is a weighted homogeneous CR-automorphism of weight \( t \geq -\rho \) then, its coefficients \( Z_t^j(z, w) \) and \( W_t^l(z, w) \) are weighted homogeneous polynomials of the weights \( 0, \ldots, t-1 \).

Proof. It is a straightforward consequence of the decomposition \([12]\).

Now, let us consider the gradation of \( \mathfrak{g} \). First we need the following definition:

Definition 3.4. The Lie algebra \( \mathfrak{g} := \mathfrak{aut}_{CR} (M) \) of an arbitrary CR manifold is called graded in the sense of Tanaka, whenever it can be expressed in the form:

\[ \mathfrak{g} := \mathfrak{g}_{-\rho} \oplus \mathfrak{g}_{-\rho+1} \oplus \cdots \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1 \oplus \cdots \oplus \mathfrak{g}_\rho, \quad \rho, \varrho \in \mathbb{N} \]

with \( [\mathfrak{g}_i, \mathfrak{g}_j] \subset \mathfrak{g}_{i+j} \). Furthermore, we say that \( M \) has rigidity if the positive part:

\[ \mathfrak{g}_+ := \mathfrak{g}_1 \oplus \cdots \oplus \mathfrak{g}_\rho \]

of \( \mathfrak{aut}_{CR} (M) \) is zero.

Proposition 3.5. For a finite type holomorphically nondegenerate CR manifold \( M \subset \mathbb{C}^{n+k} \) represented by the above defining function \([11]\), the associated Lie algebra \( \mathfrak{g} \) of infinitesimal CR-automorphisms is a graded Lie algebra, in the sense of Tanaka, of the form:

\[ \mathfrak{g} := \mathfrak{g}_{-\rho} \oplus \cdots \oplus \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1 \oplus \cdots \oplus \mathfrak{g}_\rho, \quad \rho, \varrho \in \mathbb{N}. \]

Proof. According to the above two lemmas, if \( \mathfrak{g}_t \) is the collection of infinitesimal CR-automorphisms of weight \( t \), then \( \mathfrak{g} \) admits a gradation like:

\[ \mathfrak{g} := \mathfrak{g}_{-\alpha} \oplus \cdots \oplus \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1 \oplus \cdots \oplus \mathfrak{g}_t \oplus \cdots. \]

Furthermore, holomorphically nondegeneracy and finite typness of \( M \) guarantees that \( \mathfrak{g} \) is finite dimensional and hence there exists an integer \( \rho \) in which \( g_\beta \equiv 0 \) for each \( \beta > \rho \). Now it remains to show that this gradation is in the sense of Tanaka. Namely, we shall prove that for each two homogeneous infinitesimal CR-automorphisms \( X_1 \) and \( X_2 \) of certain homogeneities \( t_1 \) and \( t_2 \), the Lie bracket \([X_1, X_2] \) belongs to \( \mathfrak{g}_{t_1+t_2} \). For this, it is enough to show that this statement for vector fields of the forms \( X_i := F_i(z, w) \frac{\partial}{\partial z_i}, i = 1, 2 \) where \( z_i \) is a complex variable \( z_* \) or \( w_* \). According to the homogeneities of these vector fields, \( F_1 \) and \( F_2 \) are two polynomials of the weights \( t_1 + [x_1] \) and \( t_2 + [x_2] \), respectively. Now, we have:

\[ [X_1, X_2] = F_1 \frac{\partial F_2}{\partial x_1} \frac{\partial}{\partial x_2} - F_2 \frac{\partial F_1}{\partial x_2} \frac{\partial}{\partial x_1}. \]

In this expression, the derivations \( \frac{\partial F_2}{\partial x_1} \) and \( \frac{\partial F_1}{\partial x_2} \) are either zero or homogeneous polynomials of the weights \( t_2 + [x_2] - [x_1] \) and \( t_2 + [x_1] - [x_2] \), respectively. Now, simple simplifications yields that the above Lie bracket is a homogeneous vector field of the weight \( t_1 + t_2 \), as desired. \( \square \)

3.2. A comparison between the so far achieved results. For a CR manifold \( M \subset \mathbb{C}^{n+k} \), of fixed CR-dimension \( n \) and codimension \( k \) represented in coordinates \( z_1, \ldots, z_n, w_1, \ldots, w_k \) as \([11]\), consider the infinitesimal CR-automorphism:

\[ X := \sum_{j=1}^{n} Z^j(z, w) \partial z_j + \sum_{l=1}^{k} W^l(z, w) \partial w_l. \]

In this subsection, we have a general look at the results through literatures. In \([36]\), Shananina computed the Lie algebras of infinitesimal CR-automorphisms associated to the Beloshapka’s homogeneous models — included in the class of under consideration CR manifolds — with \( n = 1 \) and \( k = 3, \ldots, 7 \) and presented the expressions of the associated holomorphic coefficients \( Z(z, w) \) and \( W^l(z, w), l = 1, \ldots, k \) in Theorem 1 page 386 of his paper (he used the notations \( f(z, w) \) and \( g^l(z, w) \), instead). Upon a close
In this case it is of degree 2 (compare the above expression of the degree of the variable $X$) from the obtained expressions of $Z(z, w)$ and $W^4(z, w)$, presented in the various types $k = 3$ to $k = 7$ are nearly the same. For instance, in the two cases $k = 3$ and $k = 4$ represented by the following defining equations:

$$
\begin{align*}
(n = 1) & : \\
& \begin{cases} \\
v_1 = z^2, \\
v_2 = z^2 + z^2, \\
v_3 = -i(z^2 - z^2), \\
v_4 = z^3 + z^3 + \lambda z^3, \quad \lambda \in \mathbb{C}
\end{cases}
\end{align*}
$$

one obtains the expressions:

$$
\begin{align*}
(n = 1, k = 3) & : \\
Z(z, w) &= a + ib + (d + i e) z, \quad W^1(z, w) = c_1 + 2(b + i a) z + 2dw_1, \\
W^2(z, w) &= c_2 + 2(b + i a) z^2 + 4aw_1 + 3dw_2 - ew_3, \\
W^3(z, w) &= c_3 + 2(a - i b) z^2 + 4bw_1 + ew_2 + 3dw_3,
\end{align*}
$$

$$
\begin{align*}
(n = 1, k = 4) & : \\
Z(z, w) &= a + ib + dz, \quad W^1(z, w) = c_1 + 2(b + i a) z + 2dw_1, \\
W^2(z, w) &= c_2 + 2(b + i a) z^2 + 4aw_1 + 3dw_2, \\
W^3(z, w) &= c_3 + 2(a - i b) z^2 + 4bw_1 + 3dw_3, \\
W^4(z, w) &= c_4 + 2(b + i a) z^3 + (2\lambda + 3)aw_2 + 2(\lambda - 3)bw_3 + 4dw_4, \\
& (a, b, c, d, w, e) \in \mathbb{R}.
\end{align*}
$$

A plain comparison between the above two sets of the functions $Z, W^1, W^2, W^3$ can demonstrate the mentioned similarity. For example, even if a function is not equal to its correspondence, the degrees of each term in both of them and the variables which appear inside are same. This type of similarity and harmony is visible among all the expressions obtained in [36] for $n = 1$ and $k = 3, \ldots, 7$. Moreover, a glance on the Beloshapka’s results for his model with $n = 1, k = 2$ in [10], page 402 (see the expressions of $f, g$ and $h$ which are $Z, W^1$ and $W^2$ in our notations) indicates such similarity, too. In contrast, the computations of the infinitesimal CR-automorphisms associated to the CR manifold with $n, k = 1$, presented in [28], says that the expressions of the two functions $Z(z, w)$ and $W^1(z, w)$ are fairly different. Namely we have:

$$
\begin{align*}
Z(z, w_1) &= a + ib + (c + id)w_1 + (f + i e + h w_1) z + (2d + 2i c) z^2, \\
W^1(z, w_1) &= f + g w_1 + h w_1^2 + (2i(a - ib) + 2i(c - id)w_1) z,
\end{align*}
$$

for some eight real integers $a, b, c, \ldots, h$. In more details, in the above expression of $Z(z, w_1)$ we see the variable $w_1$ while the functions $Z(z, w)$ in the next types are independent of the variables $w_i$. Moreover, the degree of the variable $z$ in $Z(z, w)$ in all already presented cases $n = 1$ and $k = 2, \ldots, 7$ is 1 while in this case it is of degree 2 (compare the above expression of $Z(z, w_1)$ with (14)).

On the other hand — and parallel to the similarity of the obtained holomorphic functions — we know that all the mentioned CR manifolds with $n = 1$ and $k = 2, \ldots, 7$ have rigidity while for $n, k = 1$ it does not retain this property [24].

We claim that the similarity in the expressions of the functions $Z^i(z, w)$ and $W^i(z, w)$ associated to the CR manifolds of CR-dimension and codimensions $n = 1$ and $k = 2, \ldots, 7$ has a close relationship to their rigidity property. Before considering this assertion, let us illustrate by the following example that how one can extract the infinitesimal CR-automorphisms $X$ from the obtained expressions of $Z(z, w)$ and $W^i(z, w)$.

**Example 3.6.** According to [33] (see also the case $K = 3$, [36], Theorem 1 for another presentation), an infinitesimal CR-automorphism for the CR manifold $M \subset \mathbb{C}^{1+3}$, represented in coordinates...
\( \mathbb{C}\{z, w_1, w_2, w_3\} \) as the graph of the defining functions:

\[
\begin{align*}
  w_1 - \overline{w_1} &= 2i z \overline{z}, \\
  w_2 - \overline{w_2} &= 2i z \overline{z} (z + \overline{z}), \\
  w_3 - \overline{w_3} &= 2 z \overline{z} (z - \overline{z})
\end{align*}
\]

is a holomorphic vector field:

\[
X := Z(z, w) \partial_z + \sum_{l=1}^{3} W^l(z, w) \partial_{w_l},
\]

with the desired coefficients \((cf. (14))\)

\[
\begin{align*}
  Z(z, w) &= a + i b + (d + i e) z, \\
  W^1(z, w) &= c_1 + 2 (b + i a) z + 2 d w_1, \\
  W^2(z, w) &= c_2 + 2 (b + i a) z^2 + 4 a w_1 + 3 d w_2 - e w_3, \\
  W^3(z, w) &= c_3 + 2 (a - i b) z^3 + 4 b w_1 + e w_2 + 3 d w_3,
\end{align*}
\]

for some seven real integers \(a, b, c_1, c_2, c_3, d, e\). Throughout this paper, we call such integers by the free parameters. Then, the Lie algebra \( \text{aut}_{CR}(M) \) is seven dimensional, with the basis elements extracted as the coefficients of the seven free parameters in the above general form of \(X\). Namely, it is generated by the following seven holomorphic vector fields:

\[
\begin{align*}
  a &\colon X_1 := \partial_z + 2 i z \partial_{w_1} + (2 i z^2 + 4 w_1) \partial_{w_2} + 2 z^2 \partial_{w_3}, \\
  b &\colon X_2 := i \partial_z + 2 z \partial_{w_1} + 2 z^2 \partial_{w_2} + (-2 i z^2 + 4 w_1) \partial_{w_3}, \\
  c_1 &\colon X_3 := \partial_{w_1}, \\
  c_2 &\colon X_4 := \partial_{w_2}, \\
  c_3 &\colon X_5 := \partial_{w_3}, \\
  d &\colon X_6 := z \partial_z + 2 w_1 \partial_{w_1} + 3 w_2 \partial_{w_2} + 3 w_3 \partial_{w_3}, \\
  e &\colon X_7 := i z \partial_z - w_3 \partial_{w_2} + w_2 \partial_{w_3}.
\end{align*}
\]

The weights associated in \( [36] \) to the appearing complex variables are:

\[
[z] = 1, \ [w_1] = 2, \ [w_2] = [w_3] = 3.
\]

Hence, a close look at the obtained basis holomorphic vector fields \(X_1, \ldots, X_7\) gives the following weighted homogeneities for them:

\[
\begin{array}{cccccccc}
X & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 \\
\text{Hom} & -1 & -1 & -2 & -3 & -3 & 0 & 0
\end{array}
\]

Therefore, the Lie algebra \( \text{aut}_{CR}(M) \) can be represented as:

\[
\text{aut}_{CR}(M) := g_{-3} \oplus g_{-2} \oplus g_{-1} \oplus g_0,
\]

with \(g_{-3} := \langle X_4, X_5 \rangle\), with \(g_{-2} := \langle X_6 \rangle\), with \(g_{-1} := \langle X_1, X_2 \rangle\) and with \(g_0 := \langle X_6, X_7 \rangle\). Now, one easily verifies that \(M\) is rigid.

3.3. Homogeneous components. Now, let us inspect the structure of homogeneous components of the desired algebras of infinitesimal CR-automorphisms. At first, the following proposition demonstrates the influence of the rigidity of the under consideration homogeneous CR manifold \(M\) on the structure. It also reveals the close connection between the similarity property of the holomorphic vector fields \(Z^i\) and \(W^l\) of the CR manifolds discussed in the last subsection and their rigidity.
Proposition 3.7. Let $M$ be a holomorphically nondegenerate CR manifold of CR-dimension $n$ and codimension $k$ represented as (11). Then, $M$ has rigidity if and only if for any weighted homogeneous infinitesimal CR-automorphism:

$$X := \sum_{j=1}^{n} Z^j(z, w) \partial_{z_j} + \sum_{l=1}^{k} W^l(z, w) \partial_{w_l}$$

of $M$, each weighted homogeneous polynomial $Z^j(z, w)$ (respectively $W^l(z, w)$) is of weight at most $[z_j]$ (respectively of weight at most $[w_l]$). In particular, $Z^j(z, w)$ (respectively $W^l(z, w)$) is independent of the variables of the weights $\geq [z_j]$ (respectively of the weights $\geq [w_l]$).

Proof. If $X$ is of weight homogeneity $d$, then since the standard fields $\partial_{z_j}$ and $\partial_{w_l}$ have the constant weights $-[z_j]$ and $-[w_l]$, respectively, then the weighted homogeneous polynomials $Z^j$ and $W^l$ have the constant degrees $d + [z_j]$ and $d + [w_l]$, respectively. Now, assume that $M$ has rigidity. The dimension of the Lie algebra $\mathfrak{aut}_{CR}(M)$ is equal to the number of free parameters involved in the expressions of the functions $Z^i(z, w), i = 1, \ldots, n$ and $W^l(z, w), l = 1, \ldots, k$ (see Example 3.6). Each generator is extracted from one of such free parameters as its coefficient in the general form

$$X := \sum_{j=1}^{n} Z^j(z, w) \partial_{z_j} + \sum_{l=1}^{k} W^l(z, w) \partial_{w_l}.$$  

In such expression, coefficients of the standard fields $\partial_{z_j}$ come from the found functions $Z^j(z, w)$. Now, rigidity of $M$ means to have no any (homogeneous) basis element belonging to $\mathfrak{aut}_{CR}(M)$ of the positive weighted homogeneity. Hence, when we have standard field $\partial_{z_j}$ of the weight $-[z_j]$, then no term of weight bigger than $[z_j]$ appears in its coefficient. Consequently, $Z^j(z, w) = 0$ which provides the coefficients of $\partial_{z_j}$ in the basis elements — is independent of the variables of the weights bigger than $[z_j]$. Similar fact holds when one considers the coefficients $W^l(z, w)$ of the standard fields $\partial_{w_l}$.

For the converse, if none of the (weighted homogeneous) holomorphic coefficients $Z^j(z, w), j = 1, \ldots, n$ admits the terms of weight larger than $[z_j]$, then the weight $[Z^j(z, w)] - [z_j]$ of each term $Z^j(z, w)\partial_{z_j}$ of $X$ is non-positive. Similar fact holds for the terms $W^l(z, w)\partial_{w_l}, l = 1, \ldots, k$. Consequently, $\mathfrak{aut}_{CR}(M)$ does not contain any (weighted homogeneous) basis element $X$ of the positive weight. In other words, $M$ has rigidity. □

For a graded Lie algebra:

$$\mathfrak{g} = \mathfrak{g}_{-\rho} \oplus \cdots \oplus \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1 \oplus \cdots \oplus \mathfrak{g}_\rho,$$

let us denote by $\mathfrak{g}^{(t)}$ the graded subspace:

$$\mathfrak{g}^{(t)} := \mathfrak{g}_{-\rho} \oplus \cdots \oplus \mathfrak{g}_t, \quad (t=-\rho, \ldots, \rho).$$

According to definition of the graded algebras, one easily convinces oneself that for $t = -\rho, \ldots, 0$ each subspace $\mathfrak{g}^{(t)}$ is in fact a Lie subalgebra of $\mathfrak{g}$. The idea behind the proof of Proposition 3.7 can lead one to obtain the following more general conclusion.

Proposition 3.8. Let $M$ be a homogeneous CR manifold of CR-dimension $n$ and codimension $k$ represented as (11). Let $\mathfrak{g} = \mathfrak{aut}_{CR}(M)$ be of the graded form:

$$(16) \quad \mathfrak{g} = \mathfrak{g}_{-\rho} \oplus \cdots \oplus \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1 \oplus \cdots \oplus \mathfrak{g}_\rho$$

and let the (weighted homogeneous) infinitesimal CR-automorphism:

$$X = \sum_{j=1}^{n} Z^j(z, w) \partial_{z_j} + \sum_{l=1}^{k} W^l(z, w) \partial_{w_l}$$

belongs to $\mathfrak{g}$. Then,

(i) $X$ belongs to $\mathfrak{g}_t$ for $t = -\rho, \ldots, \rho$, if and only if each coefficient $Z^j(z, w)$ (respectively $W^l(z, w)$) is homogeneous of the precise weight $[z_j] + t$ (respectively $[w_l] + t$). In particular, each $Z^j(z, w)$ (respectively $W^l(z, w)$) is independent of the variables of weights $\geq [z_j] + t$ (respectively of weights $\geq [w_l] + t$).
(ii) \( X \) belongs to \( \mathfrak{g}(t) \) if and only if each coefficient \( Z^j(z, w) \) (respectively \( W^l(z, w) \)) is homogeneous of weight at most \( [z_j] + t \) (respectively of weights at most \( [w_l] + t \)). Specifically, each function \( Z^j(z, w) \) (respectively, \( W^l(z, w) \)) is independent of the variables of weights \( \geq [z_j] + t \) (respectively of weights \( \geq [w_l] + t \)).

(iii) In particular, the negative part \( \mathfrak{g}_- = \mathfrak{g}(-1) \) of the CR manifold \( M \) is generated by the elements \( X \) of \( \mathfrak{g} \) with the coefficients \( Z^j(z, w) \) (respectively \( W^l(z, w) \)) independent of the variables of weights \( \geq [z_j] - 1 \) (respectively of weights \( \geq [w_l] - 1 \)).

Proof. The proof is similar to that of Proposition 3.7. Here, we prove the first item (i). If a holomorphic vector field \( X \) belongs to \( \mathfrak{g}_t \), then it is homogeneous of the weight \( t \). In the expression of \( X \), each standard field \( \partial_{z_j} \) is of the fixed weight \( [z_j] \) and hence having the field \( Z^j(z, w) \partial_{z_j} \) of the precise homogeneity \( t \), then the coefficient \( Z^j(z, w) \) must be of the weight \( [z_j] + t \). Similar conclusion holds for the functions \( W^l(z, w) \). The converse of the assertion can be concluded in a very similar way. In particular, since all the variables in \( Z^j(z, w) \) have the positive weight then, each function \( Z^j(z, w) \) — which must be of the weight \( [z_j] + t \) — is independent of the variables of the weights bigger than \( [z_j] + t \).

Remark 3.9. This proposition suggests an appropriate way to compute each subspace \( \mathfrak{g}(t) \) (specifically, to compute \( \mathfrak{g}^{(0)} = \mathfrak{g}_- \oplus \mathfrak{g}_0 \) in the rigid case). Namely, it states that to find each \( \mathfrak{g}(t) \) it is not necessary to compute the surrounding algebra \( \mathfrak{g}_t = \text{aut}_{\text{CR}}(M) \) of infinitesimal CR-automorphisms, but it is sufficient to compute just the (homogeneous) coefficients \( Z^j(z, w) \) and \( W^l(z, w) \) of homogeneities less than \( [z_j] + t \) and \( [w_l] + t \), respectively. This extremely reduces the size of computation. Similar process can be employed when we aim to compute only the \( t \)-th component \( \mathfrak{g}_t \) of \( \mathfrak{g} \). Moreover, one can divide the general computation of the Lie algebra \( \mathfrak{g} \) of infinitesimal CR-automorphisms into some distinct subcomputations of its components \( \mathfrak{g}_t \) for \( t = -\rho, \ldots, \varrho \). In the next section, we will use the results to provide an algorithm for computing \( \text{aut}_{\text{CR}}(M) \).

4. Computing the homogeneous components

As mentioned in Remark 3.9 to compute the holomorphic coefficients \( Z^j(z, w) \) and \( W^l(z, w) \) of the vector fields \( X \in \mathfrak{g}(t) \), one can assume these functions independent of the variables with the associated weights larger than \( [z_j] + t \) and \( [w_l] + t \), respectively. In this section, we aim to develop this result for constructing a very convenient method of computing each subspace \( \mathfrak{g}(t) \) and each component \( \mathfrak{g}_t \) associated to our homogeneous CR manifold.

4.1. Computing each component \( \mathfrak{g}_t \). For each element \( X \) of the \( t \)-th component \( \mathfrak{g}_t \), Proposition 3.8 enables one to attain an upper bound for the weight degree of each of its desired (polynomial) coefficients \( Z^j(z, w) \) and \( W^l(z, w) \). Hence, we can predict the expression of these polynomials as the elements of the polynomial ring \( \mathbb{C}[z, w] \). Then finding these expressions, it is necessary and sufficient to seek their constant coefficients. One can pick the following convenient strategy for computing the \( t \)-th component \( \mathfrak{g}_t \) of the desired algebra \( \mathfrak{g} \) as (16), for a fixed integer \( t = -\rho, \ldots, \varrho \).

(s1) First, we construct the tangency equations (8) of \( M \) corresponding to \( (\text{in general form}) \) holomorphic vector fields:

\[
X = \sum_{j=1}^{n} Z^j(z, w) \partial_{z_j} + \sum_{l=1}^{k} W^l(z, w) \partial_{w_l}
\]

of \( \mathfrak{g}_t \subset \mathfrak{g} \).

(s2) Now, to compute the coefficients \( Z^j(z, w) \) and \( W^l(z, w) \), it is no longer necessary to use the Taylor series (9) and construct and solve the arising PDE systems as is the classical method of [10, 24, 28, 34, 56]. Here there is another, entirely different and much simpler way to proceed the computation. Namely by Corollary 3.3 all desired functions \( Z^j(z, w) \) and \( W^l(z, w) \) are polynomials with bounded degrees. Then, according to Proposition 3.8, the desired coefficients...
\(Z^j(z, w)\) and \(W^j(z, w)\) are weighted homogeneous polynomials of the precise weights \([z_j] + t\) and \([w_l] + t\), respectively. Hence, we can assume the following expressions for them:

\[
\begin{align*}
Z^j(z, w) &:= \sum_{\alpha, \beta \in \mathbb{N}} c_{\alpha, \beta} \cdot z^\alpha w^\beta, \\
W^j(z, w) &:= \sum_{\alpha, \beta \in \mathbb{N}} d_{\alpha, \beta} \cdot z^\alpha w^\beta, \\
&\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (i=1, \ldots, n, ~ l=1, \ldots, k),
\end{align*}
\]

for some (unknown yet) complex free parameters \(c_{\alpha, \beta}\) and \(d_{\alpha, \beta}\). Here, by \(z^\alpha\) we mean \(z_1^{\alpha_1} \cdot \ldots \cdot z_n^{\alpha_n}\) for \(\alpha := (\alpha_1, \ldots, \alpha_n) \in \mathbb{N}^n\). Furthermore, we have:

\[
[z^\alpha] = \sum_{j=1}^{n} [z_j^{\alpha_j}] = \sum_{j=1}^{n} \alpha_j [z_j].
\]

Similar notations hold for \(w^\beta\) and \([w^\beta]\).

(s3) Determining the parameters \(c_{\alpha, \beta}\) and \(d_{\alpha, \beta}\) is in fact equivalent to find the explicit expressions of the CR-automorphisms \(X\) of \(\mathfrak{g}_L\). For this, we should just put the already assumed expressions (17) in the \(k\) tangency equations (8) and next solve the extracted (not PDE) homogeneous linear system of equations with the unknowns \(c_{\alpha, \beta}\) and \(d_{\alpha, \beta}\), and with the equations obtained as the coefficients of the various powers \(z^\alpha w^\beta\) of the variables \(z\) and \(w\).

Let us denote by \(\text{Sys}^{t,j}\) the system of equations, mentioned in the step (s3), associated to a CR manifold \(M\) of CR dimension and codimension \(n\) and \(k\), extracted from the \(j\)-th tangency equation for \(j = 1, \ldots, k\) along the way of computing the \(t\)-th component \(\mathfrak{g}_t\) of \(\mathfrak{g} = \text{aut}_{CR}(M)\). Furthermore, we denote by \(\text{Sys}^t\) the general system of equations:

\[
\text{Sys}^t := \bigcup_{j=1}^{k} \text{Sys}^{t,j}.
\]

**Definition 4.1.** A graded Lie algebra of the form:

\[
\mathfrak{g}_- := \mathfrak{g}_{-\rho} \oplus \cdots \oplus \mathfrak{g}_{-1}, \quad \rho \in \mathbb{N}
\]

is called fundamental whenever it can be generated by \(\mathfrak{g}_{-1}\).

In the case that the negative part \(\mathfrak{g}_-\) of the desired algebra \(\mathfrak{g}\) is fundamental, it is even not necessary to compute the homogeneous components \(\mathfrak{g}_{-\rho}, \ldots, \mathfrak{g}_{-2}\). In this case, one can easily compute the \((-t)\)-th components \(\mathfrak{g}_{-t}\) inductively as the length \(t\) iterated Lie brackets \(\mathfrak{g}_{-t} = [\mathfrak{g}_{-1}, \mathfrak{g}_{-t+1}]\). There are many situations where this occurs. For example, all Beloshapka’s homogeneous models enjoy it.

**Proposition 4.2.** (see [7], Proposition 4). For a Beloshapka’s homogeneous CR manifold \(M\) as those of [7], the associated Levi-Tanaka algebra is the negative part \(\mathfrak{g}_-\) of its Lie algebra of infinitesimal CR-automorphisms. Moreover, each component \(\mathfrak{g}_{-m}, \ m \in \mathbb{N}\), is a linear combination of brackets of degree \(m\) of vector fields in \(\mathfrak{g}_{-1}\).

Then, in the case that \(\mathfrak{g}_-\) is fundamental, one plainly can add the following item to the already presented strategy (s1)-(s3).

\[
\begin{enumerate}
\item[(ib)] After computing the basis elements of \(\mathfrak{g}_{-1}\), to achieve each component \(\mathfrak{g}_{-m}, \ m = 2, \ldots, \rho\) one should just compute all the length \(m\) iterated brackets like:
\[
[x_{i_1}, [x_{i_2}, \ldots, [x_{i_m}]]], \quad i_1 < i_2 < \cdots < i_m
\]

of the basis elements \(x_j\) of \(\mathfrak{g}_{-1}\).
\end{enumerate}
Example 4.3. (compare with Example [3.6].) Consider the CR-submanifold $M \subset \mathbb{C}^{1+3}$ of CR-dimension $n = 1$ and codimension $k = 3$ as in Example [3.6]. Here, we have $[z] = 1$, $[w_1] = 2$ and $[w_2] = [w_3] = 3$. According to (8), the three fundamental tangency equations are:

$$
0 \equiv \left[ W^1 - \overline{W}^1 - 2i\pi Z - 2i\overline{Z} \right]_{w = \overline{w} + \Xi(z, \overline{z}, \overline{w})},
$$

$$
0 \equiv \left[ W^2 - \overline{W}^2 - 4i\pi Z - 2i\overline{Z} - 2i\pi^2 Z - 2i\pi^2 \overline{Z} - 4iz\pi \overline{Z} \right]_{w = \overline{w} + \Xi(z, \overline{z}, \overline{w})},
$$

$$
0 \equiv \left[ W^3 - \overline{W}^3 - 4i\pi Z - 2i\overline{Z} - 2i\pi^2 Z + 2i\pi^2 \overline{Z} + 4iz\pi \overline{Z} \right]_{w = \overline{w} + \Xi(z, \overline{z}, \overline{w})}.
$$

First let us compute the subalgebra $\mathfrak{g}_{-1}$. For this aim, we may set the following expressions for the unknown functions $Z(z, w_1, w_2, w_3), W^l(z, w_1, w_2, w_3)$ for $l = 1, 2, 3$ with their homogeneities at their left hand sides (cf. (17)):

$$
\begin{align*}
1 + (-1) & : Z(z, w) := p, \\
2 + (-1) & : W^1(z, w) := q z, \\
3 + (-1) & : W^2(z, w) := r w_1 + s z^2, \\
3 + (-1) & : W^3(z, w) := t w_1 + u z^2,
\end{align*}
$$

for some six complex functions $p, q, r, s, t, u$. Putting these expressions into the tangency equations and equating to zero the coefficients of the appeared polynomials of $\mathbb{C}[z, w_1, w_2, w_3]$, we obtain the following three systems of linear homogeneous equations:

$$
\begin{align*}
\text{Sys}^{-1,1} &= \left\{ -2i p + q = 0, \quad -2i p - q = 0 \right\}, \\
\text{Sys}^{-1,2} &= \left\{ s - 2i p = 0, \quad -2p - 2\overline{p} + r = 0, \quad 2p + 2\overline{p} - r = 0 \right\}, \\
\text{Sys}^{-1,3} &= \left\{ u - 2\overline{p} = 0, \quad -2i p + 2i p + t = 0 \right\}.
\end{align*}
$$

Solving the homogeneous linear system $\text{Sys}^{-1}$ of all the above equations, we can write:

$$
p := a + ib, \quad q := s := 2(b + ia), \quad r := 4a, \quad t := 4b, \quad u := 2(a - ib),
$$

for two real constants $a$ and $b$ which brings the following general expressions for the desired holomorphic coefficients of the elements $X \in \mathfrak{g}_{-1}$ (compare with Example [3.6]):

$$
Z(z, w) = a + ib,
$$

$$
W^1(z, w) = 2(b + ia) z,
$$

$$
W^2(z, w) = 2(b + ia) z^2 + 4a w_1,
$$

$$
W^3(z, w) = 2(a - ib) z^2 + 4b w_1.
$$

Thanks to the two free parameters $a, b$ appeared in the above expressions, we will have two infinitesimal CR-automorphisms as the generators of $\mathfrak{g}_{-1}$:

$$
X_1 := \partial_z + 2i z \partial_{w_1} + (2i z^2 + 4w_1) \partial_{w_2} + 2z^2 \partial_{w_3},
$$

$$
X_2 := i \partial_z + 2z \partial_{w_1} + 2z^2 \partial_{w_2} + (-2i z^2 + 4w_1) \partial_{w_3}.
$$

Now, we can follow the step (ib) to seek the elements of the homogeneous components $\mathfrak{g}_{-2}$ and $\mathfrak{g}_{-3}$ by computing the iterated Lie brackets of $X_1$ and $X_2$ (here notice that $M$ is one of the Beloshapka’s homogeneous models and hence $\mathfrak{g}$ is fundamental. Moreover, since the maximum homogeneity of the appearing variables is 3 then, the minimum homogeneity in $\mathfrak{g}$ is $-3$). For $\mathfrak{g}_{-2}$ we have only one generator:

$$
X_3 := [X_1, X_2] = 4 \partial_{w_1}.
$$

Then, $\mathfrak{g}_{-3}$ includes two basis elements

$$
X_4 := [X_1, X_3] = -4 \partial_{w_2},
$$

$$
X_5 := [X_2, X_3] = -4 \partial_{w_3}.
$$
At present we found $5 = 2 \times 1 + 3$ basis elements for the subalgebra $\mathfrak{g}_- = \mathfrak{g}_{-3} \oplus \mathfrak{g}_{-2} \oplus \mathfrak{g}_{-1}$. Similarly, one achieves the zeroth component $\mathfrak{g}_0$ of $\mathfrak{g}$. For this, we may assume the following expressions for the functions $Z(z, w_1, w_2, w_3)$, $W^l(z, w_1, w_2, w_3)$ for $l = 1, 2, 3$ with their homogeneities at their left hand sides:

\[
\begin{align*}
1+0 : & \quad Z(z, w) := p_1 z, \\
2+0 : & \quad W^1(z, w) := q_1 w_1 + q_2 z^2, \\
3+0 : & \quad W^2(z, w) := r_1 w_2 + r_2 w_3 + r_3 z^3 + r_4 z w_1, \\
3+0 : & \quad W^3(z, w) := s_1 w_2 + s_2 w_3 + s_3 z^3 + s_4 z w_1.
\end{align*}
\]

Again, substituting the recent expressions in the tangency equations (18) and equating to zero the coefficients of the appeared polynomials of $\mathbb{C}[z, w_1, w_2, w_3]$, we get the following systems of equations:

\[
\begin{align*}
\text{Sys}^{0,1} & = \left\{ q_1 = 0, \quad -p_1 - p_1 + q_1 = 0 \right\}, \\
\text{Sys}^{0,2} & = \left\{ r_1 = 0, \quad -p_1 - p_1 + r_4 - r_4 = 0, \quad r_4 = 0, \quad r_1 - p_1 - 2 p_1 + r_1 = 0, \quad r_2 = 0 \right\}, \\
\text{Sys}^{0,3} & = \left\{ s_3 = 0, \quad s_4 - s_4 = 0, \quad s_3 = 0, \quad s_2 + i s_1 + \frac{i}{2} p_2 - i \frac{i}{2} p_1 + i \frac{i}{2} p_2 = 0, \quad -s_2 - s_2 - i \frac{i}{2} p_1 + i \frac{i}{2} p_2 = 0, \quad -s_2 - s_2 - i \frac{i}{2} p_1 + i \frac{i}{2} p_2 = 0 \right\}.
\end{align*}
\]

Solving the linear homogeneous system $\text{Sys}^0$ of all the above equations, we have the solutions:

\[
\begin{align*}
p_1 &= d + i e, \quad q_1 = 2 d, \quad r_1 = s_2 = 3 d, \quad r_2 = -e, \quad s_1 = e, \\
q_2 &= r_3 = r_4 = s_3 = 0,
\end{align*}
\]

which implies the following expressions for the desired functions:

\[
\begin{align*}
Z(z, w) &= (d + i e) z, \\
W^1(z, w) &= 2 d w_1, \\
W^2(z, w) &= 3 d w_2 - e w_3, \\
W^3(z, w) &= e w_2 + 3 d w_3,
\end{align*}
\]

where $d$ and $e$ are two real constants. Extracting the coefficients of these two integers brings the following two tangent vector fields, belonging to $\mathfrak{g}_0$:

\[
\begin{align*}
X_6 := z \partial_z + 2 w_1 \partial_{w_1} + 3 w_2 \partial_{w_2} + 3 w_3 \partial_{w_3}, \\
X_7 := i z \partial_z - w_3 \partial_{w_1} + w_2 \partial_{w_3}.
\end{align*}
\]

**Remark 4.4.** It is worth noting that for computing each subspace $\mathfrak{g}^{(l)}$, although one can achieve its basis elements by computing the corresponding components $\mathfrak{g}_s$, $l = -p, \ldots, t$, it is also possible to adopt the above strategy (s1)-(s3) by modifying the assumed expressions of the functions $Z^j(z, w)$ and $W^l(z, w)$ as follows (cf. Proposition 3.8(ii)):

\[
\begin{align*}
Z^j(z, w) &:= \sum_{\alpha \in \mathbb{N}^n, \beta \in \mathbb{N}^k, |\alpha| + |\beta| \leq |s_j| + 1} c_{\alpha, \beta} z^\alpha w^\beta, \\
W^l(z, w) &:= \sum_{\alpha \in \mathbb{N}^n, \beta \in \mathbb{N}^k, |\alpha| + |\beta| \leq |s_l| + 1} d_{\alpha, \beta} z^\alpha w^\beta, \quad (i=1, \ldots, n, \quad l=1, \ldots, k).
\end{align*}
\]

In particular when $M$ has rigidity, we can obtain the sought algebra $\mathfrak{g}$ by setting $t = 0$. 
4.2. **Finding the maximum homogeneity** \( \rho \). For an arbitrary homogeneous CR manifold, represented as (2), so far we have provided an effective way to compute homogeneous components \( g_t \) of the graded desired algebra \( g := \text{aut}_{CR}(M) \) of the form:

\[
g := g_{-\rho} \oplus \cdots \oplus g_0 \oplus \cdots \oplus g_\rho.
\]

We also find that the value of \( \rho \) in this gradation is equal to the maximum weight \( |w_k| \) appearing among the complex variables. The only not-yet-fixed problem is to answer how much we have to compute the homogeneous components \( g_t \) to arrive at the last one \( g_\rho \). Here, we do not aim to find the precise value of \( \rho \) but — in an algorithmic point of view — it suffices to find a criterion to stop the computations. For this aim, we employ the transitivity of the Lie algebra \( g \). For every homogeneous CR manifold \( M \), the associated Lie algebra of its infinitesimal CR-automorphisms is transitive:

**Definition 4.5.** A graded Lie algebra \( g \) as above is called transitive whenever for each element \( x \in g_t \) with \( t \geq 0 \), the equality \([x, g_-] = 0 \) implies that \( x = 0 \). In the case that \( g_- \) is fundamental then, the transitivity means that for any \( x \) as above, the equality \([x, g_-] = 0 \) implies that \( x = 0 \).

**Proposition 4.6.** Consider a transitive graded algebra \( g \) as above. For each integer \( t \geq 0 \), if \( g_t = g_{t+1} = \cdots = g_{t+\rho-1} \equiv 0 \) then we have \( g_{t+\rho} = 0 \). Moreover, if \( g \) is also fundamental then the equality \( g_0 = 0 \) implies independently that \( g_{t+1} = 0 \).

**Proof.** Assume the following gradation for the transitive algebra \( g \):

\[
g := g_- \oplus g_0 \oplus g_1 \oplus \cdots \oplus g_t \oplus \bigoplus_{g_{t+1}} \oplus \bigoplus_{g_{t+2}} \oplus \cdots \oplus \bigoplus_{g_{t+\rho}} \oplus \cdots
\]

and let \( x \in g_{t+\rho} \). According to the inequality \([g_t, g_j] \subset g_{i+j} \), we have:

\[
[x, g_{-1}] \subset g_{t+\rho-1} = 0,
\]

\[
[x, g_{-2}] \subset g_{t+\rho-2} = 0,
\]

\[
\vdots
\]

\[
[x, g_{-\rho}] \subset g_{t+\rho-\rho} = 0,
\]

which implies that \([x, g_-] = 0 \). Now, the transitivity of \( g \) immediately implies that \( x = 0 \). For the second part of the assertion, similarly assume the following gradation for \( g \):

\[
g := g_- \oplus g_0 \oplus g_1 \oplus \cdots \oplus g_{t-1} \oplus g_t \oplus g_{t+1} \oplus \cdots,
\]

and let \( x \in g_{t+1} \). Consequently we have:

\[
[x, g_{-1}] \subset g_{t+1-1} = g_t = 0.
\]

Again, the definition of fundamental transitive algebras immediately implies that \( x = 0 \). This completes the proof.

Accordingly, for a homogeneous CR manifold \( M \) and to realize how much we have to compute the homogeneous components of \( g \) to arrive at the last weighted homogeneous component \( g_\rho \) we can apply the following plain strategy:

- **When \( g_- \) is fundamental.** Compute the homogeneous components \( g_t \) of \( g \) as much as it appears the first trivial component.
- **When \( g_- \) is not fundamental.** Compute the homogeneous components \( g_t \) of \( g \) as much as they appear \( \rho \) successive trivial components.

**Example 4.7.** In Example 4.3 we computed the negative part \( g_- = g_{-3} \oplus g_{-2} \oplus g_{-1} \) and also zeroth component \( g_0 \) of the graded algebra \( g := \text{aut}_{CR}(M) \) associated to the presented homogeneous CR manifold \( M \subset \mathbb{C}^{1+3} \). Here, let us finalize computation of the desired algebra. Proceeding further in this direction, now let us compute the next component \( g_1 \). In this case, we can set the following expressions...
for four desired coefficients \( Z(z, w) \) and \( W^l(z, w) \) \( l = 1, 2, 3 \), with their weighted homogeneities at their left hand sides (cf. 17).

\[
\begin{align*}
1+1: & \quad Z(z, w) := a_3 w_1 + a_2 z^2, \\
2+1: & \quad W^1(z, w) := a_3 w_2 + a_4 w_3 + a_5 z^3 + a_6 z w_1, \\
3+1: & \quad W^2(z, w) := a_7 w_1^2 + a_8 z^2 w_1 + a_9 z^4 + a_{10} z w_2 + a_{11} z w_3, \\
4+1: & \quad W^3(z, w) := a_{12} w_1^2 + a_{13} z^2 w_1 + a_{14} z^4 + a_{15} z w_2 + a_{16} z w_3.
\end{align*}
\]

Now, we should check these predefined expressions in the tangency equations (18). This gives us the total system \( \text{Sys}^1 = \bigcup_{j=1}^3 \text{Sys}^{1,j} \) as follows:

\[
\text{Sys}^1 = \left\{ \begin{array}{l}
a_5 = 0, \quad i(a_6 + a_3 - a_2 = 0) + a_4 = 0, \quad i(a_3 - \mathfrak{a}_2) - a_4 + 2 a_1 = 0, \quad -2 i \mathfrak{a}_1 + a_6 = 0, \\
\mathfrak{a}_5 = 0, \quad -2i a_1 - \mathfrak{a}_6 = 0, \quad a_3 - \mathfrak{a}_3 = 0, \quad a_4 - \mathfrak{a}_4 = 0, \quad a_9 = 0, \quad i(a_{10} - 2 a_2 + a_8) + a_{11} = 0, \\
i(a_{10} - a_2 - a_2) + 8a_1 - 2a_{11} - 4a_7 = 0, \quad -2i \mathfrak{a}_1 + a_8 = 0, \quad a_1 - i \mathfrak{a}_2 = 0, \quad a_{10} = 0, \\
a_{11} = 0, \quad i(a_7 - a_2 - a_2 = 0) = 0, \quad \mathfrak{a}_9 = 0, \quad -a_8 - 2i a_1 = 0, \quad \mathfrak{a}_{10} = 0, \quad \mathfrak{a}_{10} = 0, \quad a_{14} = 0, \\
a_1 a - \mathfrak{a}_2 = 0, \quad a_7 + a_1 a = 0, \quad a_1 a - a_2 + \mathfrak{a}_1 = 0, \quad i(a_{12} - 2 a_2 + a_8) + a_{11} = 0, \\
a_{13} + a_{12} + a_1 = 0, \quad a_{13} + a_{12} + a_1 = 0, \quad a_{15} = 0, \quad a_{16} = 0, \quad a_{14} = 0, \\
-2a_1 + a_2 = 0, \quad -\mathfrak{a}_1 = 0, \quad \mathfrak{a}_{16} = 0, \quad a_{12} - a_{12} = 0
\end{array} \right\}.
\]

This system has only the trivial solution \( a_1 = \cdots = a_{16} = 0 \) which means that we have \( g_1 = 0 \).

Furthermore as we know, the desired algebra \( g \) is fundamental which guarantees that the next components are trivial, too. Summing up the results of this example with those of Example 3.3, one finds the sought 7-dimensional Lie algebra of infinitesimal CR-automorphisms associated to \( M \) as the gradation:

\[
g = g_{-3} \oplus g_{-2} \oplus g_{-1} \oplus g_0,
\]

with \( g_{-3} = \langle X_4, X_5 \rangle \), with \( g_{-2} = \langle X_3 \rangle \), with \( g_{-1} = \langle X_1, X_2 \rangle \) and with \( g_0 = \langle X_6, X_7 \rangle \) with the Lie commutators displayed in the following table:

| \( X_5 \) | \( X_4 \) | \( X_3 \) | \( X_2 \) | \( X_1 \) | \( X_0 \) | \( X_7 \) |
|---|---|---|---|---|---|---|
| \( X_5 \) | 0 | 0 | 0 | 0 | 3X_5 | -X_4 |
| \( X_4 \) | * | 0 | 0 | 0 | 3X_4 | X_5 |
| \( X_3 \) | * | * | 0 | 4X_5 | 4X_4 | 2X_3 | 0 |
| \( X_2 \) | * | * | * | 0 | -4X_3 | X_2 | -X_1 |
| \( X_1 \) | * | * | * | * | 0 | X_1 | X_2 |
| \( X_6 \) | * | * | * | 0 | 0 | 0 | 0 |
| \( X_7 \) | * | * | * | * | * | 0 | 0 |

One observes that the achieved algebra is exactly that of Example 3.6.

One can find another computation of the Lie algebra achieved in the above example via the classical method of solving the arisen PDE system in [33]. Comparing the above process with that of this paper clarify the effectiveness of the prepared algorithm.

5. Summing up the results

Here, let us gather the results obtained so far to provide an algorithm for computing the sought Lie algebras of infinitesimal CR-automorphisms associated to the holomorphically nondegenerate homogeneous CR manifolds, represented as (17). The strategy introduced in subsection 4.1 enabled one to compute separately the homogeneous components \( g_t, t = -\rho, \ldots, \rho \) of the graded algebra \( g \) of infinitesimal CR-automorphisms of such CR manifolds as:

\[
g := g_{-\rho} \oplus \cdots \oplus g_1 \oplus g_0 \oplus \cdots \oplus g_\rho.
\]

One may follow the following two points for computing the desired algebras associated to the under consideration homogeneous CR manifolds:
Point 1 Executing three steps (s1) − (s2) − (s3) introduced in subsection 4.1 and finding homogeneous components $g_\ell$ successively. In particular if $g_-$ is fundamental then one can execute the step (ib).

**Point 2** In the above gradation, the minimum homogeneity $-\rho$ is equal to $[w_k]$ where $w_k$ has the maximum homogeneity among the complex variables appearing in $(11)$. Moreover, it suffices to compute successively the homogeneous components $g_0, g_1, \ldots$ as much as we find $\rho$ successive trivial algebras. In particular if $g_-$ is fundamental, we can terminate the computations as much as we find first trivial component.

**Remark 5.1.** In [7], Beloshapka called his introduced CR manifolds by nice universal CR-models. These manifolds have the ability of enjoying all properties, required for launching the presented algorithm. They are of finite type, holomorphically nondegenerate, generic and real analytic with the graded Lie algebras of infinitesimal CR-automorphisms their negative parts are fundamental. Having such properties, we shall confirm that these models are really deserved to be called by the phrase nice.

Let us conclude this paper by computing Lie algebras of infinitesimal CR-automorphisms associated to the following CR-manifold:

\begin{equation}
\mathcal{M} := \begin{cases} 
  w_1 - \overline{w}_1 = 2i \overline{z} \zeta, \\
  w_2 - \overline{w}_2 = 2i \overline{z} (z + \overline{z}), \\
  w_3 - \overline{w}_3 = 2i \overline{z} (z^2 + \frac{3}{2} \overline{z} + \overline{z}^2). 
\end{cases}
\end{equation}

It is worth noting that this CR-manifold — which admits some interesting features [26, 33] — does not belong to the class of CR-models introduced by Beloshapka [7]. Before computations, let us show that $\mathcal{M}$ is homogeneous.

**Proposition 5.2.** The already introduced CR-manifold $\mathcal{M} \subset \mathbb{C}^{1+3}$ is homogeneous.

**Proof.** To prove the assertion, we show that for each arbitrary point $(p, q_1, q_2, q_3)$ of $\mathcal{M}$, there is a CR-automorphism mapping the origin to it. For this aim, it suffices to prove that after applying the four replacements $z \mapsto z + p$ and $w_j \mapsto w_j + q_j$, $j = 1, 2, 3$, one can transform the model into its initial form by means of some certain changes of coordinates. At first, let us consider the effect of these transformations on the third equation. In fact, it gives:

\begin{equation}
w_3 - \overline{w}_3 + q_3 - \overline{q}_3 = 2i \overline{z} (z^2 - 3 \overline{z} + \overline{z}^2) + \\
  + 3i p^2 \overline{p}^2 + 2i p^2 \overline{p} + 2i \overline{p} p^2 + (6i \overline{p} p^2 + 2i \overline{p}^2 + 6i p \overline{p}) z + (6i \overline{p}^2 + 6i p^2 + 2i p^3) z + \\
  + (6i \overline{p}^2 + 6i p^2 + 12i p \overline{p}) z \overline{z} + (3i \overline{p}^2 + 6i p \overline{p}) z^2 + (6i p \overline{p} + 3i p^3) z^2 + \\
  + (6i p + 6i \overline{p}) z^2 \overline{z} + (6i \overline{p} + 6i p) z \overline{z}^2 + 2i \overline{p} z^3.
\end{equation}

It is possible to kill all pluriharmonic terms by the change of variables $w_3 \mapsto w_3 + P_3(z)$ with:

\[ P_3(z) = -q_3 + \frac{3}{2} i p^2 \overline{p}^2 + 2i p^2 \overline{p} + (6i p \overline{p}^2 + 2i \overline{p}^2 + 6i p^2 \overline{p}) z + (3i p^2 + 6i p \overline{p}) z^2 + 2i \overline{p} z^3. \]

After such change of variables we will have:

\[ w_3 - \overline{w}_3 = 2i \overline{z} (z^2 - 3 \overline{z} + \overline{z}^2) + \\
  + (6i \overline{p}^2 + 6i p^2 + 12i p \overline{p}) z \overline{z} + \\
  + (6i p + 6i \overline{p}) z^2 \overline{z} + (6i \overline{p} + 6i p) z \overline{z}^2. \]

Replacing the term $z \overline{z}$ by the equal expression $\frac{1}{2i} (w_1 - \overline{w}_1)$ at the second line, one plainly verifies that it is also possible to eliminate this line by the change of coordinates $w_3 \mapsto w_3 + (3 \overline{p}^2 + 3 p^2 + 6 p \overline{p}) w_1$ and obtain:

\[ w_3 - \overline{w}_3 = 2i \overline{z} (z^2 - 3 \overline{z} + \overline{z}^2) + \\
  + (6i p + 6i \overline{p}) z^2 \overline{z} + (6i \overline{p} + 6i p) z \overline{z}^2. \]
Now it remains to eliminate the second line of the above expression again by some holomorphic change of coordinates. First, one should notice that according to the defining equations of the model, the second line can be represented into the form:

\[(6i\overline{p} + 6i\overline{p})z^2\overline{z} + (6i\overline{p} + 6i\overline{p})z\overline{z}^2 = (3\overline{p} + 3p)(w_2 - \overline{w}_2)\,.

Hence, to eliminate this line from the last expression, it suffices to use the holomorphic change of coordinates \(w_3 \mapsto w_3 + (3p + 3\overline{p})w_2\). This convert the third expressions into the initial form:

\[w_3 - \overline{w}_3 = 2iz\overline{z} (z^2 - 3\overline{z} + \overline{z}^2),\]

as desired. Simpler procedure works in the cases of two first defining equations. 

**Example 5.3.** Now, let us compute the Lie algebra \(\mathfrak{g} := \text{aut}_{CR}(\mathcal{M})\) associated to the CR-manifold \(\mathcal{M}\) defined as (21). First, one notices that we have the following weights of the appearing complex variables:

\[\left\{ \begin{array}{c} |z| = 1, \quad |w_1| = 2, \quad |w_2| = 3, \quad |w_3| = 4. \end{array} \right.\]

Hence the minimum homogeneity of the homogeneous components will be \(-\rho = -4\). Here, an infinitesimal CR-automorphism is of the form:

\[X := Z(z, w) \partial_z + W^1(z, w) \partial_{w_1} + W^2(z, w) \partial_{w_2} + W^3(z, w) \partial_{w_3},\]

enjoying the following three fundamental tangency equations:

\[0 \equiv \left[ W^1 - \overline{W^1} - 2i \overline{p} Z - 2i \overline{z} \overline{Z} \right]_{\mathcal{M}},\]
\[0 \equiv \left[ W^2 - \overline{W^2} - 4i z \overline{p} Z - 2i \overline{z}^2 \overline{Z} - 2i z \overline{z} \overline{Z} - 4i z \overline{Z} \right]_{\mathcal{M}},\]
\[0 \equiv \left[ W^3 - \overline{W^3} - 6i z^2 \overline{p} Z - 6i \overline{z}^2 \overline{Z} - 2i \overline{z}^3 \overline{Z} - 2i z^3 \overline{Z} - 6i z \overline{Z}^2 Z - 6i z \overline{Z} \overline{Z} \right]_{\mathcal{M}}.\]

Let us start by computing the negative part \(\mathfrak{g}_{-}\). For the \((-1)\)-th component \(\mathfrak{g}_{-1}\), the sought coefficients are of the forms:

\[\left\{ \begin{array}{c} Z(z, w) := a_1, \quad W^1(z, w) := a_2 z, \quad W^3(z, w) := a_3 \overline{z}^2 + a_4 w_1, \quad W^4(z, w) := a_5 z^3 + a_6 z w_1 + a_7 w_2. \end{array} \right.\]

Checking these predefined polynomials into the tangency equations (23) gives the following system:

\[\text{Sys}^{-1} := \left\{ \begin{array}{c} a_2 - 2i \overline{a}_1 = 0, \quad -4i a_1 - 4i \overline{a}_1 + 2i \overline{a}_4 = 0, \quad a_3 - 2i a_4 = 0, \quad a_4 - a_6 = 0, \quad a_7 - \overline{a}_7 = 0. \end{array} \right.\]

which has the solution:

\[a_1 := a + i b, \quad a_2 = 2b + 2i a, \quad a_3 = 2b + 2i a, \quad a_4 = 4a, \quad a_5 = 2b + 2i a, \quad a_6 = 0, \quad a_7 = 6a, \quad (a, b \in \mathbb{R}).\]

Consequently, the sought homogeneous component \(\mathfrak{g}_{-1}\) is 2-dimensional with the generators:

\[X_1 = \partial_z + 2iz \partial_{w_1} + 2iz^2 \partial_{w_2} + 4wu_1 \partial_{w_2} + 2iz^3 \partial_{w_3} + 6w_2 \partial_{w_3}, \quad X_2 = i \partial_z + 2z \partial_{w_1} + 2z^2 \partial_{w_2} + 2z^3 \partial_{w_3}.\]

Similar (and even simpler) computations give three vector fields:

\[X_3 := \partial_{w_1}, \quad X_4 := \partial_{w_2}, \quad X_5 := \partial_{w_3},\]

of homogeneities \(-2, -3, -4\), respectively. So far, we have computed the negative component:

\[\mathfrak{g}_{-} := \mathfrak{g}_{-4} \oplus \mathfrak{g}_{-3} \oplus \mathfrak{g}_{-2} \oplus \mathfrak{g}_{-1}\]

with \(\mathfrak{g}_{-1} := \langle X_1, X_2 \rangle\), with \(\mathfrak{g}_{-2} := \langle X_3 \rangle\), with \(\mathfrak{g}_{-3} := \langle X_4 \rangle\) and with \(\mathfrak{g}_{-4} := \langle X_5 \rangle\). One can see all the possible Lie commutators of these generators in the table presented below. From this table, one easily verifies that the negative part \(\mathfrak{g}_{-}\) of \(\mathfrak{g}\) is in fact fundamental. Hence, we have to compute nonnegative
This nonnegative component was not trivial; hence we have to proceed by computing the next component
the sought graded algebra
Checking these predefined functions in the tangency equations (18) gives the following complex system:
\[ \text{Sys}^0 = \begin{cases} a_3 = 0, & -2ia_1 - 2ia_1 + 2ia_2 = 0, & -a_3 = 0, & -a_2 + a_2 = 0, & a_5 = 0, \\
-4i a_1 - 2i a_1 - 2i a_1 + 2ia_4 = 0, & a_6 - a_5 = 0, & -a_6 = 0, \\
a_{10} - 2i a_1 + 2i a_0 + 2i a_7 + 2ia_{11} - 6ia_1 = 0, & 3ia_7 + 2ia_{11} - 4a_8 - 6ia_3 - 6ia_1 = 0, \\
a_4 - a_4 = 0, & a_0 = 0, & 2ia_7 - 6ia_1 - 2ia_1 = 0, & 4ia_8 = 0, & a_{11} = 0, & -a_{10} = 0, \\
-ia_0 = 0, & -a_{11} = 0, & a_8 - a_8 = 0, & a_7 - a_7 = 0 & \end{cases} \]
This system has the solution:
\[ a_1 = a, \quad a_2 = 2a, \quad a_4 = 3a, \quad a_7 = 4a, \quad a_3 = a_5 = a_6 = a_8 = a_9 = a_{10} = a_{11} = 0 \]
for some real number \( a \). Therefore, \( g_0 \) is 1-dimensional with the generator:
\[ X_0 = z \partial_z + 2w_1 \partial_{w_1} + 3w_2 \partial_{w_2} + 4w_3 \partial_{w_3}. \]
This nonnegative component was not trivial; hence we have to proceed by computing the next component
\( g_1 \). Similar computations that we do not present them for saving space shows that this component
is trivial. Then, according to the fundamentality of \( g_- \) we can terminate the computations. Consequently,
the sought graded algebra \( g \) is of the form:
\[ g := g_{-4} \oplus g_{-3} \oplus g_{-2} \oplus g_{-1} \oplus g_0 \]
with the negative components as above, with \( g_0 = \langle X_0 \rangle \) and with the table of commutators displayed as follows:

|   | \( X_0 \) | \( X_1 \) | \( X_2 \) | \( X_3 \) | \( X_4 \) | \( X_5 \) |
|---|---|---|---|---|---|---|
| \( X_0 \) | 0 | -\( X_1 \) | -\( X_2 \) | -2\( X_3 \) | -3\( X_4 \) | -4\( X_5 \) |
| \( X_1 \) | * | 0 | -4\( X_3 \) | -4\( X_4 \) | 6\( X_5 \) | 0 |
| \( X_2 \) | * | * | 0 | 0 | 0 | 0 |
| \( X_3 \) | * | * | * | 0 | 0 | 0 |
| \( X_4 \) | * | * | * | * | 0 | 0 |
| \( X_5 \) | * | * | * | * | * | 0 |

6. PARAMETRIC DEFINING EQUATIONS
AND GRÖBNER SYSTEMS

Actually, one of the main — somehow hidden — obstacles appearing among the computations arises
when the set of defining equations includes some certain parametric polynomials. This case is quite usual as one observes in [7,10,24,36]. To treat such cases, we suggest the modern and effective concept of comprehensive
Gröbner systems [41,20,21,30,31] which enables us to consider and solve (linear) parametric systems appearing among the computations.

To begin, let \( \mathbb{K} \) be a field and let \( \alpha := \alpha_1, \ldots, \alpha_t \) and \( x := x_1, \ldots, x_n \) be two certain sequences of parameters and variables, respectively. Naturally, we call the ring:
\[ \mathbb{K}[\alpha][x] := \left\{ \sum_{i=1}^m p_{i,\alpha} x_1^{\alpha_{i1}} \cdots x_n^{\alpha_{in}} \mid p_{i,\alpha} \in \mathbb{K}[\alpha], \alpha_{ij} \in \mathbb{N} \cup \{0\} \right\} \]
the parametric polynomial ring over \( \mathbb{K} \) with parameters \( \alpha \) and variables \( x \). Let \( P \) be a set of parametric polynomials which generates the parametric ideal \( \mathcal{I} \). Obviously, the solutions of the parametric system
Example 6.2. Consider the following parametric polynomial system in $\mathbb{C}[a, b, c][x, y]$:

$$
\Sigma : \begin{cases}
    ax - b &= 0 \\
    by - a &= 0 \\
    cx^2 - y &= 0 \\
    cy^2 - x &= 0.
\end{cases}
$$
Choosing the graded reverse lexicographical ordering $y < x$ and computing the sought comprehensive Gröbner system using the algorithm PGB give the results displayed in the following table:

| $E_i$ | $N_i$ | $G_i$ |
|-------|-------|-------|
| $\{a, b, c\}$ | $\{\}$ | $\{x, y\}$ |
| $\{a, b\}$ | $\{x\}$ | $\{cx^2 - y, cy^2 - x\}$ |
| $\{a^o - b^o, a^o e - b^o, b^o e - a^o, ac^2 - a, bc^2 - b\}$ | $\{b\}$ | $\{bx - acy, by - a\}$ |
| $\{\}$ | $\{a^o - b^o, a^o e - b^o, b^o e - a^o, ac^2 - a, bc^2 - b\}$ | $\{1\}$ |

Accordingly, the algorithm divides the solution set of the system $\Sigma$ into four partitions, each of them corresponds to one of the above rows. Let us explain what each of these rows means. For the first row, we have the null conditions $E_1 = \{a, b, c\}$ and there is no any non-null condition. This means that if the elements of $E_1$ are null, namely if $a = b = c = 0$ then the system $\Sigma$ reduces to the system $G_4 = \{x = 0, y = 0\}$ which obviously has the single solution $(0, 0)$. For the second row, we have null conditions $E_2 = \{a, b\}$ and non-null condition $N_2 = \{c\}$. This means that if $a = b = 0$ and $c \neq 0$ then the system $\Sigma$ reduces to $G_2 = \{cx^2 - y = 0, cy^2 - x = 0\}$ which has the solution set $\{(1, \frac{1}{c}) \in C \cup \{(0, 0), (\frac{-1 + \sqrt{3}i}{2c}, \frac{-1 - \sqrt{3}i}{2c}), (\frac{-1 - \sqrt{3}i}{2c}, \frac{1 + \sqrt{3}i}{2c})\}$). Similar interpretation holds for the third row. Finally, the last row means that if none of the previous null conditions holds, namely if $E_1, E_2, E_3 \neq 0$, then the under consideration system $\Sigma$ reduces to $G_4 = \{1 = 0\}$ which of course its solution set is empty.

6.1. Implementation. In [35], we have implemented the designed algorithm in MAPLE 15 which is available online as a library entitled CRAUT (together with a sample file relevant to the following example). To do it, at first we implemented the recent algorithm PGB of Kapur, Sun and Wang [21]. By means of this auxiliary algorithm, we employ techniques of comprehensive Gröbner systems to consider and solve the appearing parametric linear systems $Sys$ in the parametric case. Our implementation CRAUT enables one to compute the desired algebras of infinitesimal CR-automorphisms associated to homogeneous and weighted homogeneous CR-manifolds in two non-parametric and parametric cases and also to evaluate the effectiveness of the algorithm designed in this paper.

Example 6.3. (reverification of the Beloshapka’s conjecture in the lengths $\rho = 1, \ldots, 5$, cf. [6] [24] [36]). Consider the following weighted homogeneous rigid defining equations:

\[
\begin{align*}
&w_1 - \overline{w}_1 = 2i z \overline{z}, \\
&w_2 - \overline{w}_2 = 2i (z^2 \overline{z} + \overline{z}^2 z), \\
&w_3 - \overline{w}_3 = 2 (z^2 \overline{z} - \overline{z}^2 z), \\
&w_4 - \overline{w}_4 = 2i (z^2 \overline{z} + \overline{z}^2 z) + 2i a z \overline{z}^2, \\
&w_5 - \overline{w}_5 = 2 (z^2 \overline{z} - \overline{z}^2 z) + 2i b z \overline{z}^2, \\
&w_6 - \overline{w}_6 = 2i z \overline{z}^2, \\
&w_7 - \overline{w}_7 = 2i (z^4 + \overline{z}^4) + 2i (w_1 + \overline{w}_1) \overline{z}^2, \\
&w_8 - \overline{w}_8 = 2i z^2 \overline{z}^2, \\
&w_9 - \overline{w}_9 = 2i (z^2 \overline{z}^2 + \overline{z}^2 z) + 2i (w_1 + \overline{w}_1) \overline{z}^2, \\
&w_{10} - \overline{w}_{10} = 2i (z^2 \overline{z}^2 + \overline{z}^2 z) + i \overline{w}_1 (w_1 + \overline{w}_1) \overline{z}^2, \\
&w_{11} - \overline{w}_{11} = (w_1 + \overline{w}_1) (z^2 \overline{z} - \overline{z}^2 z), \\
&w_{12} - \overline{w}_{12} = (w_1 + \overline{w}_1) (z^2 \overline{z} + \overline{z}^2 z), \\
\end{align*}
\]

and let $M_k$ be the Beloshapka’s CR-model of CR-dimension 1 and codimension $k = 1, \ldots, 12$, represented in coordinates $(z, w_1, \ldots, w_k)$ in $\mathbb{C}^{k+1}$. For $k = 1, \ldots, 5$, $M_k$ is represented as the graph of the above first $k$ equations. For $k = 6, \ldots, 11$, it is represented again by the first $k$ equations but with the assumption $a, b = 0$. Finally, $M_{12}$ is represented as the graph of the above 12 equations with the assumption that all the appearing six parameters $a, b, c, d, e, f$ are vanished — namely a non-parametric model as $M_1, M_2, M_3$ and $M_6$ are. These twelve CR-manifolds encompass all the Beloshapka’s models up to the length five and are constructed by Shanamia and Mamai [24] [36]. They also computed the associated Lie algebras of infinitesimal CR-automorphisms, thought Mamai did not present the outputs, perhaps because of the length of them. It is also known that these models are all homogeneous (71). By means of our implementation, we have computed the associated Lie algebras of infinitesimal CR-automorphisms. The following table displays some properties of the obtained results, where the timings were conducted on a personal laptop with Intel(R) Core(TM) i7 CPU@2.80 GHz and 6.00 GB of RAM.
The last row of the above table needs some explanation. In fact for some models, the dimension of the associated algebra is not unique and depends on the values of the extant parameters. Being more precise, in this table we observe two different values for the dimensions associated to some models. In such cases, the left number is the dimension of the desired Lie algebra associated to the model whereas all the appearing parameters vanish identically; otherwise the dimension is equal to the number at the right hand side. For example for $M_6$, we have $\dim(\aut_{CR}(M_6)) = 12$ if $c, d = 0$ and $= 10$, otherwise. More precisely, in the case that $c, d \neq 0$, we have the basis elements of the components of $\aut_{CR}(M_6)$ as:

\begin{equation}
\mathfrak{g}_{-5} = \langle \partial_{w_7}, \partial_{w_8} \rangle,
\mathfrak{g}_{-4} = \langle \partial_{w_6}, \partial_{w_5}, \partial_{w_4} \rangle,
\mathfrak{g}_{-3} = \langle \partial_{w_3}, \partial_{w_2} \rangle,
\mathfrak{g}_{-2} = \langle \partial_{w_1} + aw_2 \partial_{w_5} + bw_3 \partial_{w_8} \rangle,
\end{equation}

\begin{align*}
\mathfrak{g}_{-1} & = \langle -2w_5 \partial_{w_7} + 2w_4 \partial_{w_8} + z \partial_{w_1} + w_3 \partial_{w_6} + z^2 \partial_{w_4} + 2w_1 \partial_{w_3} + z^2 \partial_{w_2} + z^4 \partial_{w_7} - \frac{3}{2} w_3 \partial_{w_4} + \frac{3}{2} w_2 \partial_{w_5} + \\
& + cz^2 w_1 \partial_{w_7} + c w_6 \partial_{w_7} + d z^2 w_1 \partial_{w_8} + dw_6 \partial_{w_8} + i z \partial_{z} - 2z^2 \partial_{w_3} - 2z^3 \partial_{w_5} - 2z^4 \partial_{w_7},
\end{align*}

\begin{align*}
& \quad + cz^2 w_1 \partial_{w_7} + dx^2 w_1 \partial_{w_8} + dx z \partial_{w_3} + d x^2 \partial_{w_2} - c b w_1^2 \partial_{w_7} - \frac{3}{2} d w_3 \partial_{w_5} - \frac{3}{2} d w_2 \partial_{w_4} \\
& - d w_2 \partial_{w_5} - d x^4 \partial_{w_8} - d x^3 \partial_{w_5} - d x^2 \partial_{w_3} - \frac{1}{2} d \partial_{z} + d w_4 \partial_{w_7} - d w_1 \partial_{w_2} - d w_5 \partial_{w_8} - d w_1^2 \partial_{w_8},
\end{align*}

\begin{align*}
\mathfrak{g}_0 & = \langle -w_5 \partial_{w_7} + \frac{1}{3} w_2 \partial_{w_5} + w_7 \partial_{w_8} - \frac{1}{3} w_3 \partial_{w_5} + \frac{2}{3} w_4 \partial_{w_5} - \frac{2}{3} w_2 \partial_{w_4} - 2 \partial_{w_3} + \frac{1}{3} i z \partial_{z},
\end{align*}

\begin{align*}
& \quad + \frac{1}{5} z \partial_{z} + \frac{3}{5} w_3 \partial_{w_3} + \frac{3}{5} w_2 \partial_{w_2} + \frac{4}{5} w_5 \partial_{w_5} + \frac{4}{5} w_6 \partial_{w_6} + \frac{4}{5} w_4 \partial_{w_4} + w_7 \partial_{w_7} + w_8 \partial_{w_8} + \frac{2}{5} w_1 \partial_{w_1} \rangle.
\end{align*}

In the case that $c, d = 0$, the basis elements of $\mathfrak{g}_i, i = -1, \ldots, -5$ are as above with of course $c, d = 0$ while in this case $\mathfrak{g}_0$ has two basis elements as follows:

\begin{align*}
\mathfrak{g}_0 & = \langle -w_8 \partial_{w_7} + \frac{1}{3} w_2 \partial_{w_5} + w_7 \partial_{w_8} - \frac{1}{3} w_3 \partial_{w_5} + \frac{2}{3} w_4 \partial_{w_5} - \frac{2}{3} w_2 \partial_{w_4} - 2 \partial_{w_3} + i z \partial_{z},
\end{align*}

\begin{align*}
& \quad + \frac{1}{5} z \partial_{z} + \frac{3}{5} w_3 \partial_{w_3} + \frac{3}{5} w_2 \partial_{w_2} + \frac{4}{5} w_5 \partial_{w_5} + \frac{4}{5} w_6 \partial_{w_6} + \frac{4}{5} w_4 \partial_{w_4} + w_7 \partial_{w_7} + w_8 \partial_{w_8} + \frac{2}{5} w_1 \partial_{w_1} \rangle.
\end{align*}

One easily concludes from the results of the above table, all the above twelve models have rigidity, as is the main result of Mamai in [24]. Together with the library CRAUT, we also have put a sample file concerning the computations of this example.

According to the above table, it took just 13 minutes from the implementation to verify the Beloshapka’s conjecture in the lengths $\rho = 1, \ldots, 5$. This shows the effectiveness of the algorithm, designed in this paper.

Remark 6.4. A glance on the above timings shows how it increases mostly the complexity of computations as one passes from each model to the next by adding just one variable and one defining equation to the previous ones. The following diagram may be helpful to compare the appearing timings. Moreover, actually the computations in the case of parametric defining equations are more complicated in comparison to those of the non-parametric case. For example, compare the timings corresponding to the models $M_{11}$ and $M_{12}$ — notice that the defining equations of $M_{12}$ are non-parametric.
Example 6.5. Add the following rigid defining equations to the list (24):

\[
\begin{align*}
    w_{13} - \overline{w}_{13} &= 2i(z^5z + \overline{z}^5z), \\
    w_{14} - \overline{w}_{14} &= 2(z^5z - \overline{z}^4z), \\
    w_{15} - \overline{w}_{15} &= 2i(z^4z^2 + \overline{z}^4z^2), \\
    w_{16} - \overline{w}_{16} &= 2(z^4z^2 - z^4z^2), \\
    w_{17} - \overline{w}_{17} &= 2i z^3z^3,
\end{align*}
\]

and for \( k = 13, \ldots, 17 \) let \( M_k \) to be the CR-manifold of CR-dimension one and codimension \( k \) represented as the graph of the equations of (24) together the first \( k - 12 \) equations of the above list. These are the next five rigid Beloshapka’s models which are the very first models of the length six. Here, we also compute — for the first time — the desired Lie algebras associated to these models and the results are displayed in the following table:

| Model | Time (sec.) | \( M_{13} \) | \( M_{14} \) | \( M_{15} \) | \( M_{16} \) | \( M_{17} \) |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|
| \( \rho \) | 83.5 | 152 | 286 | 545 | 1157 |
| \( \rho \) | -1 | -1 | -1 | -1 | -1 |
| dim | 15 | 16 | 17 | 18 | 19 |

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