Power linear Keller maps with ditto triangularizations

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Abstract

We show that power linear Keller maps $F = (x_1+(A_1x)^d, x_2+(A_2x)^d, \ldots, x_n+(A_nx)^d)$ are linearly triangularizable if (1) $\text{rk}A \le 2$ or (2) $\text{cork}A \le 2$ and $d \ge 3$ or (3) $\text{cork}A = 3$, $d \ge 5$ and the diagonal of A is nonzero. Furthermore, we show that the triangularizations can be chosen power linear as well.

1 Introduction

The famous Jacobian Conjecture, which was first formulated by O.H. Keller in 1939, for short JC, asserts that for every $n \ge 1$ the following holds:

If $F = (F_1, F_2, \ldots, F_n)$ is a polynomial map over $\mathbb{C}$ with constant nontrivial Jacobian determinant, then F is invertible.

In the 1980's, there are two famous reduction results. At first, it is shown that in order to prove the JC, it suffices to verify the JC for polynomial maps F over $\mathbb{C}$ of special cubic homogeneous form:

$$F = x + H = (x_1 + H_1, x_2 + H_2, \ldots, x_n + H_n)$$

where each component H_i of H is either zero or homogeneous of degree 3, see [1]. Later, Ludwik Drużkowski showed in [8] that in addition, one may assume that each component H_i of H is a third power of a linear form:

$$F = x + (Ax)^{*3} = (x_1 + (A_1x)^3, x_2 + (A_2x)^3, \ldots, x_n + (A_nx)^3)$$

where $x = (x_1, x_2, \ldots, x_n)$, A_i is the i-th row of an $(n \times n)$-matrix A, and A_ix is the matrix product

$$(A_{i1}\ A_{i1}\ \cdots\ A_{in}) \cdot \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

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For the case $\deg F \leq 2$, S. Wang had already proved in 1980 that the JC is true over any field of characteristic $\neq 2$, see [17] and [1].
In 1993, David Wright showed that in case $n = 3$, the JC holds for maps F having special cubic homogeneous form, see [18]. In particular F is so called 'linearly triangularizable', see definition 2.5. In 1994, the result of Wright was extended to the case $n = 4$ by Engelbert Hubbers, see [13], but for $n = 4$, maps of special cubic homogeneous form are not always linearly triangularizable. Hubbers used a (for those days) strong computer to get these results.
More than 10 jears later, the result of Wright was extended in another direction: Arno van den Essen and the second author showed that in case $n = 3$ the JC holds for maps F having special homogeneous form in general (not just cubic) in [2]. The main theorem of [2] asserts that F is even linearly triangularizable, just as in the cubic case.
But let us focus on special cubic linear maps $x + (Ax)^{*3}$ and, more generally, special power linear maps $x + (Ax)^{*d}$, from now on. At the same time that Wright showed the case $n = 3$ for special homogeneous cubic maps, Drużkowski showed that for special cubic linear maps $F = x + (Ax)^{*3}$ with $\mathrm{rk} A \leq 2$ or $\mathrm{cork} A \leq 2$, F is invertible, see [9]. In particular, F is tame.
Although the results of Drużkowski for degree $d = 3$ generalize to degree $d \geq 3$ in a straightforward manner, we have chosen to rewrite these results. The main reason for this is that the proofs of Drużkowski are very sketchy; at some points, one can better speak of 'guidelines of how to prove'.
Furthermore, Drużkowski only proved tameness in [9], which is weaker than linear triangularizability, but for the case $\mathrm{cork} A \leq 2$, his proof is powerful enough for linear triangularizability, as Charles Ching-An Cheng observes in [4]. In the same article, Cheng proves linear triangularizability for the case $\mathrm{rk} A = 2$ and $d = 3$.
But this proof is quite long. Cheng presents a much shorter proof for the case $\mathrm{rk} A = 2$ and d arbitrary in [6], by showing the following result (Theorem 2 in [6]):

Theorem 1.1. *Let $F = x + (Ax)^{*d}$ be a power linear Keller map, $r = \mathrm{rk} A$, and assume that all special homogeneous Keller maps of degree d in dimension r are linearly triangularizable. Then F is linearly triangularizable as well.*

Since it is a classical result that for $r = 2$, the conditions of this theorem are fulfilled (see [1], [2] or [6]), the case $\mathrm{rk} A = 2$ and d arbitrary follows. As mentioned above, the main result of [2] was exactly the case $r = 3$ of the conditions of the above theorem for all d, so the case $\mathrm{rk} A = 3$ and d arbitrary follows as well, as mentioned in [2].
We shall show that power linear Keller maps $F = (x_1 + (A_1 x)^d, x_2 + (A_2 x)^d, \ldots, x_n + (A_n x)^d)$ are linearly triangularizable in each of the following cases:

(1) $\mathrm{rk} A \leq 2$,

(2) $\mathrm{cork} A \leq 2$ and $d \geq 3$,

(3) $\mathrm{cork} A = 3$, $d \geq 5$ and the diagonal of A is nonzero.

Furthermore, we show that in all of the above cases, the triangularizations can be chosen power linear as well. For a significant part, our results are based on the work of Drużkowski in [9].
Although the results for $\mathrm{rk} A \leq 2$ are valid for any d, those for $\mathrm{cork} A \leq 2$ apply only to the case $d \geq 3$. This restriction is not important for the JC, since it has already been proved for any polynomial map over $\mathbb{C}$ with degree $d \leq 2$. On the other hand, the invertibility statement of the JC is weaker than linear triangularizability, so it is worth mentioning that in 2002, Cheng proved that quadratic linear Keller maps $x + (Ax)^{*2}$ with $\mathrm{cork} A = 1$ are linearly triangularizable, see [5].
In the last section, we present a quadratic linear map in dimension 6 with $\mathrm{rk} A = \mathrm{cork} A = 3$, which is, as observed above, linearly triangularizable, but without a linear triangularization that is quadratic linear as well. So in our result for $\mathrm{cork} A = 3$, the assumption $d \geq 5$ or at least some assumption on d, is necessary.

2 Definitions and preliminaries

Definition 2.1. Write A^{t} for the transpose of a matrix A. Now let A be an $(n \times n)$-matrix. We write e_i for the i-th standard basis vector over $\mathbb{C}^n$. Viewing vectors as column matrices, the matrix product Ae_i evaluates to the i-th column of A and $e_i^{\mathrm{t}} A$ evaluates to the i-th row of A. But we will just write A_i for the i-th row of A.

Definition 2.2. We call a map H *power linear (of degree d)* if H is of the form

$$H = (Ax)^{*d} := ((A_1 x)^d, (A_2 x)^d, \ldots, (A_n x)^d)$$

and a map F *special power linear (of degree d)* if F is of the form

$$F = x + (Ax)^{*d} = (x_1 + (A_1 x)^d, x_2 + (A_2 x)^d, \ldots, x_n + (A_n x)^d)$$

So H is power linear if and only if $x + H$ is special power linear.

Definition 2.3. Let F be a polynomial map. We say that F is *upper/lower triangular* if its Jacobian $\mathcal{J}F$ is upper/lower triangular. We call F *triangular* if it is either upper or lower triangular.

A triangular Keller map is tame and hence invertible.

Definition 2.4. Let $F = x + H$ be a polynomial map. We call F *special homogeneous (of degree d)* if H is homogeneous (of degree d).

In [1, lemma 4.1], it is shown that a special homogeneous map of degree $d \geq 2$ is a Keller map, if and only if $\mathcal{J}H$ is nilpotent.

Definition 2.5. Let F be a polynomial map over $\mathbb{C}$. We call F *linearly triangularizable* if there exists a $T \in \mathrm{GL}_n(\mathbb{C})$ such $T^{-1} \circ F \circ T$ is triangular.

A linear triangularizable map can be triangularized to both an upper and a lower triangular map: take $T = (x_n, x_{n-1}, \ldots, x_1)$ to get from lower to upper and vice versa.

Proposition 2.6. *If $F = x + H$ is a linearly triangularizable Keller map and the components of H do not have linear parts, then $\mathcal{J}H$ is nilpotent.*

Proof. The proof is left as an exercise to the reader. A stronger result can be found in [10, Th. 1.6]. □

Proposition 2.7. *If $F = x + H$ is a triangular Keller map and the components of H do not have linear parts, then $\mathcal{J}H$ has only zeros on its diagonal.*

Proof. From proposition 2.6, it follows that $\mathcal{J}H$ is nilpotent. Since a nilpotent matrix over a reduced ring has only eigenvalue zero and the diagonal of a triangular matrix is formed by its eigenvalues, it follows that $\mathcal{J}H$ has only zeros on its diagonal. □

Definition 2.8. Let $f \in \mathbb{C}[x] = \mathbb{C}[x_1, x_2, \ldots, x_n]$. We write $\deg f$ for the total degree of f. We write $\deg_{x_i}$ for the degree of f, seen as a polynomial in x_i over $\mathbb{C}[x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_n]$. We write $\deg_{x_i,x_j,x_k}$ for the (total) degree of f, seen as polynomial in x_i, x_j, x_k.

3 Some results on linear dependence

Lemma 3.1. *Let $H := (Ax)^{*d}$ such that $\mathcal{J}H$ is nilpotent. Assume that the first r rows of $A_1, A_2, \ldots, A_r$ of A are independent and the last $n - r$ rows of A are dependent of A_{r-1} and A_r only. Assume a similar condition on the columns of A, i.e. the last $n - r$ columns of A are dependent of Ae_{r-1} and Ae_r only. Then the components of $H := (Ax)^{*d}$ are linearly dependent.*

Proof. Write $Ae_{r+i} = \lambda_{r+i}Ae_{r-1} + \mu_{r+i}Ae_r$. Put

$$L = \begin{pmatrix} x_1 \\ \vdots \\ x_{r-2} \\ x_{r-1} - \lambda_{r+1}x_{r+1} - \cdots - \lambda_n x_n \\ x_r - \mu_{r+1}x_{r+1} - \cdots - \mu_n x_n \\ x_{r+1} \\ \vdots \\ x_n \end{pmatrix}$$

and let $B := A \cdot \mathcal{J}L$. Then the last $n - r$ columns of B and hence those of $\mathcal{J}\tilde{H}$

are zero, where

$$\tilde{H} := L^{-1} \circ H \circ L = \begin{pmatrix} (B_1x)^d \\ \vdots \\ (B_{r-2}x)^d \\ (B_{r-1}x)^d + \lambda_{r+1}(B_{r+1}x)^d + \cdots + \lambda_n(B_nx)^d \\ (B_rx)^d \ + \mu_{r+1}(B_{r+1}x)^d + \cdots + \mu_n(B_nx)^d \\ (B_{r+1}x)^d \\ \vdots \\ (B_nx)^d \end{pmatrix}$$

Each row B_{r+i} with $i \geq 1$ is a linear combination of B_{r-1} and B_r, for a similar statement holds for the rows of A. So $\hat{H} := (\tilde{H}_1, \ldots, \tilde{H}_{r-2}, \tilde{H}_{r-1}, \tilde{H}_r)$ is of the form

$$\hat{H} = \begin{pmatrix} (B_1x)^d \\ \vdots \\ (B_{r-2}x)^d \\ p(B_{r-1}x, B_rx) \\ q(B_{r-1}x, B_rx) \end{pmatrix}$$

Furthermore, since the last $n - r$ columns of $\mathcal{J}\tilde{H}$ are zero, the $(r \times r)$-matrix $\mathcal{J}\hat{H}$ is nilpotent as well. In particular, $\det \mathcal{J}\hat{H} = 0$. If $p(B_{r-1}x, B_rx)$ and $q(B_{r-1}x, B_rx)$ are algebraically independent, then all linear forms B_ix with $i \leq r$ are algebraically dependent of the components of $\hat{H}$. So

$$\operatorname{trdeg}_{\mathbb{C}}\hat{H} = \operatorname{trdeg}_{\mathbb{C}}(B_1x, \ldots, B_rx) = \operatorname{trdeg}_{\mathbb{C}}(A_1x, \ldots, A_rx) = r$$

for the first r rows of A are linearly independent. This contradicts $\det \mathcal{J}\hat{H} = 0$, so $p(B_{r-1}x, B_rx)$ and $q(B_{r-1}x, B_rx)$ are algebraically dependent. But with p and q homogeneous of the same degree d, this dependence relation refines to a linear relation, say that $\nu_1 p + \nu_2 q = 0$ with $\nu \neq 0$. Then

$$\begin{aligned} \nu_1((B_{r-1}x)^d + \lambda_{r+1}(B_{r+1}x)^d + \cdots + \lambda_n(B_nx)^d) + & \\ \nu_2((B_rx)^d + \mu_{r+1}(B_{r+1}x)^d + \cdots + \mu_n(B_nx)^d) &= 0 \end{aligned}$$

So the components of $(Bx)^{*d}$, and hence those of $H = (Ax)^{*d}$ also, are linearly dependent. □

The preceding lemma is a special case of the following theorem:

Theorem 3.2. *Let $H := (Ax)^{*d}$ such that $\mathcal{J}H$ is nilpotent. Assume that the first r rows of $A_1, A_2, \ldots, A_r$ of A are independent and the last $n - r$ rows of A are dependent of A_{r-1} and A_r only. Then the components of $H := (Ax)^{*d}$ are linearly dependent.*

Proof. Since the rows of A are dependent, the columns are dependent as well. We distinguish two cases:

- There is an $i \leq r-2$ such that column Ae_i of A is dependent of the other columns of A.

  Then there is a vector λ with $\lambda_i \neq 0$ for some $i \leq r-2$ such that $A\lambda = 0$. Replacing H by $P^{-1} \circ H \circ P$ for a suitable permutation P within $x_1, x_2, \ldots, x_{r-2}$, we may assume that $\lambda_1 \neq 0$. Since

$$\mathcal{J}H = d \begin{pmatrix} A_{11}(A_1x)^{d-1} & A_{12}(A_1x)^{d-1} & \cdots & A_{1n}(A_1x)^{d-1} \\ A_{21}(A_2x)^{d-1} & A_{22}(A_2x)^{d-1} & \cdots & A_{2n}(A_2x)^{d-1} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1}(A_nx)^{d-1} & A_{n2}(A_nx)^{d-1} & \cdots & A_{nn}(A_nx)^{d-1} \end{pmatrix} \tag{1}$$

  the expression $\det(TI_n + \mathcal{J}H)$, which is T^n on account of the nilpotence of $\mathcal{J}H$, can be seen as a polynomial in the transcendent 'variables' $A_1x, A_2x, \ldots, A_rx$. Since $r-2 \geq 1$, 'variable' A_1x only appears in the first row of (1). So substituting $A_1x = 0$ in $\mathcal{J}H$ just makes the first row of $\mathcal{J}H$ zero. This substitution does not affect the condition $\det(TI_n+\mathcal{J}H) = T^n$. So $\mathcal{J}\tilde{H}$ is nilpotent, where $\tilde{H} := (0, H_2, \ldots, H_n)$. Next, let

$$\hat{H} := L^{-1} \circ \tilde{H} \circ L = \tilde{H} \circ L$$

  where $L = x + \lambda_1^{-1}(0, \lambda_2 x_1, \ldots, \lambda_n x_1)$. Now $x + \hat{H}$ is power linear of degree d as well, but both the first row and the first column of $\mathcal{J}\hat{H}$ are zero. Hence $x + \hat{H}$ is essentially a power linear map in dimension $n-1$, and the result follows by induction.

- For each $i \leq r-2$, column Ae_i of A is independent of the other columns of A.

  Since in particular the first $r-2$ columns of A are independent, there exists a basis of the column space of A of the form $Ae_1, Ae_2, \ldots, Ae_{r-2}, Ae_{i_1}, Ae_{i_2}$. Furthermore, for each $j \geq r-1$, column Ae_j is a linear combination of Ae_{i_1} and Ae_{i_2} only. We shall show that we may assume that $i_1 = r-1$ and $i_2 = r$, in order to be able to apply lemma 3.1.

  For that purpose let us look at the *rows* A_{i_1} and A_{i_2} of A. If both rows are dependent, then H_{i_1} and H_{i_2} are linearly dependent and we are done. So assume that A_{i_1} and A_{i_2} are independent. Since the last $n-r$ rows of A are linear combinations of A_{r-1} and A_r and $i_1, i_2 \geq r-1$, both A_{i_1} and A_{i_2} are linear combinations of A_{r-1} and A_r. Hence the spaces $\mathbb{C}A_{i_1} + \mathbb{C}A_{i_2}$ and $\mathbb{C}A_{r-1} + \mathbb{C}A_r$ are equal.

  Hence A_{i_1} and A_{i_2} can take the role of A_{r-1} and A_r, i.e. the rows $A_1, A_2, \ldots, A_{r-2}, A_{i_1}, A_{i_2}$ are independent and each row A_j with $j \geq r-1$ is a linear combination of A_{i_1} and A_{i_2} only.

  Replacing H by $P^{-1} \circ H \circ P$ for a suitable permutation P within $x_{r-1}, x_r, \ldots, x_n$, we may assume that H satisfies the conditions of lemma 3.1. So the components of H are linearly dependent. $\square$

The proof of theorem 3.2 and its preceding lemma was essentially given by Druzkowski in [9], where he proved the case $r = n-2$ of theorem 3.2. The remaining theorems in this section show that under certain conditions, the components of H are not only linearly dependent, but the linear dependence even restricts to two components of H, i.e. $H_i = sH_j$ for some $i \neq j$ and an $s \in \mathbb{C}$.

Lemma 3.3. *Let $L_1, L_2, \ldots, L_r \in \mathbb{C}[x]$ be linear such that $2 \le r \le d+1$ and*

$$\lambda_1 L_1^d + \lambda_2 L_2^d + \ldots + \lambda_r L_r^d = 0 \tag{2}$$

for some $\lambda = (\lambda_1, \ldots, \lambda_r) \neq 0$. Then there are $i \neq j$ and an $s \in \mathbb{C}$ such that $L_i = sL_j$.

Proof. Assume the opposite. In particular, $L_1 \neq sL_r$ and $L_r \neq sL_1$ for all $s \in \mathbb{C}$, whence L_1 and L_r are independent. There exists a linear basis $y_1, y_2, \ldots, y_n$ of $\mathbb{C}[x]$ with $y_1 = L_1$ and $y_2 = L_r$.
The case $d = 1$ is easy, so assume $d \ge 2$. Differentiating (2) with respect to y_1 gives

$$\mu_1 L_1^{d-1} + \mu_2 L_2^{d-1} + \ldots + \mu_{r-1} L_{r-1}^{d-1} = 0$$

for certain $\mu_i \in \mathbb{C}$. In particular, $\mu_1 = d\lambda_1$, whence not all μ_i are zero. Hence, the result follows by induction on d. □

The following theorem generalizes Theorem 3.1 of [16] (the case $\text{cork}A = 3$ of this theorem). [16] is a co-production of Song Shuang and the first author.

Theorem 3.4. *Assume H is of the form $(Ax)^{*d}$ such that $\text{cork}A \le d-2$, $\text{tr}\mathcal{J}H = 0$, and the diagonal of A is nonzero. Then there are $i \neq j$ and an $s \in \mathbb{C}$ such that $A_i = sA_j \neq 0$.*

Proof. Since the diagonal of $\mathcal{J}H$ is nonzero, we can replace H by $P^{-1} \circ H \circ P$ to get $A_{11} \neq 0$, where P is a permutation. Similarly, we can make the first r rows of A independent in addition, where $r = \text{rk}A \ge n - (d-2)$. Since $\text{tr}\mathcal{J}H = 0$, we have

$$dA_{11}(A_1 x)^{d-1} + dA_{22}(A_2 x)^{d-1} + \cdots + dA_{nn}(A_n x)^{d-1} = 0 \tag{3}$$

Since the first r rows of A are independent, there exists a basis y of $\mathbb{C}x_1 + \mathbb{C}x_2 + \cdots + \mathbb{C}x_n$ such that $A_i x = y_i$ for all $i \le r$. Differentiating (3) with respect to y_1 gives

$$d(d-1)A_{11}(A_1 x)^{d-2} + \lambda_{r+1}(A_{r+1}x)^{d-2} + \cdots + \lambda_n (A_n x)^{d-2} = 0$$

for certain $\lambda_i \in \mathbb{C}$. These are $n - r + 1 \le d - 1$ linear powers (powers of linear forms). Now apply lemma 3.3 to get $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$ with $i, j \in \{1, r+1, r+2, \ldots, n\}$. □

Theorem 3.5. *Assume H is as in theorem 3.2 and $\text{cork}A \le d-1$. Then there are $i \neq j$ and an $s \in \mathbb{C}$ such that $A_i = sA_j$.*

Proof. From theorem 3.2, it follows that there is a linear relation between the components of H. Similar to the proof of theorem 3.4 (but with d instead of $d-1$), one can show that this relation is of the form $H_i = \alpha H_j$ for some $i \neq j$. So $A_i = sA_j$ for some $s \in \mathbb{C}$. □

We will use the above theorems in the next section.

4 Linear triangularization to power linear maps

The following lemma is crucial in both [9] and our study of power linear maps $(Ax)^{*d}$ where A has a small corank. It can be found at the beginning of page 238 in [9].

Lemma 4.1. *Let $H = (Ax)^{*d}$ such that $\mathcal{J}H$ is nilpotent. If A has a principal minor of any size which determinant is nonzero, then there exists a relation $R \neq 0$ such that*

$$R((A_1x)^{d-1}, (A_2x)^{d-1}, \dots, (A_nx)^{d-1}) = 0$$

and $\deg_{y_i} R(y) \leq 1$ *for all* $i \leq n$. *Furthermore, if* $A_k = 0$ *for some* k, *then* $\deg_{y_k} R = 0$ *as well.*

Proof. Write

$$\begin{aligned} &\det\left(TI_n + d\begin{pmatrix} A_{11}y_1 & A_{12}y_1 & \cdots & A_{1n}y_1 \\ A_{21}y_2 & A_{22}y_2 & \cdots & A_{2n}y_2 \\ \vdots & \vdots & & \vdots \\ A_{n1}y_n & A_{n2}y_n & \cdots & A_{nn}y_n \end{pmatrix}\right) \\ &= \quad T^n + R_1(y)T^{n-1} + R_2(y)T^{n-2} + \cdots + R_{n-2}(y)T^2 + R_{n-1}(y)T + R_n(y) \end{aligned}$$

Since $\mathcal{J}H$ is nilpotent, $\det(TI_n + \mathcal{J}H) = T^n$. It follows from (1) that the coefficient of T^{n-j} of $\det(TI_n + \mathcal{J}H)$ equals

$$R_j((A_1x)^{d-1}, (A_2x)^{d-1}, \dots, (A_nx)^{d-1}) = 0$$

for all $j \geq 1$. Furthermore, it follows from the definition of determinant that $\deg_{y_i} R_j \leq 1$ for all i, j. For some j, A has a principal minor of size j which determinant is $\alpha \neq 0$, say with rows and columns $i_1, i_2, \dots, i_j$. Then the coefficient of $y_{i_1}y_{i_2}\cdots y_{i_j}$ of R_j equals $d\alpha$, whence $R_j \neq 0$.
If $A_k = 0$, then all minors with row k of A have determinant zero, whence $\deg_{y_k} R_j = 0$. □

In all remaining lemmas in this section, relations R between linear powers $L_1^d, L_2^d, \dots, L_m^d$ with $\deg_{y_i} R \leq 1$ for all $i \leq m$ are studied. For such relations, conditions are formulated that imply $L_i = sL_j$ for some $i \neq j$ and an $s \in \mathbb{C}$,

Lemma 4.2. *Let $d \geq 2$ and R be a nonzero relation with $\deg_{y_i} R \leq 1$ such that*

$$R(x_1^d, x_2^d, \ldots, x_r^d, (\lambda_1 x_1 + \lambda_2 x_1 + \cdots + \lambda_r x_r)^d) = 0 \tag{4}$$

Then $\lambda = \lambda_i e_i$ for some i.

Proof. Since $x_1^d, x_2^d, \ldots, x_r^d$ are algebraically independent, it follows that R has a term of the form

$$\alpha \cdot y_1^{t_1} \cdots y_r^{t_r} \cdot y_{r+1}$$

with $\alpha \neq 0$ and $0 \leq t_i \leq 1$ for all i. The coefficient of $x_1^{dt_1} x_2^{dt_2} \cdots x_r^{dt_r} x_j^{d-1} x_k$ in (4) equals $(d-1)\alpha\lambda_j\lambda_k = 0$, so $\lambda_j\lambda_k = 0$ for all $j \neq k$. It follows that λ has at most one nonzero coordinate, i.e. $\lambda = \lambda_i e_i$ for some i. □

Lemma 4.3. *Let $d \geq 2$ and R be a nonzero relation with $\deg_{y_i} R \leq 1$ such that*

$$R(x_1^d, x_2^d, \ldots, x_r^d, (\lambda_1 x_1 + \lambda_2 x_2 + \cdots + \lambda_r x_r)^d, (\mu_1 x_1 + \mu_2 x_2 + \cdots + \mu_r x_r)^d) = 0 \tag{5}$$

Assume further that $\lambda_i = \mu_i = 0$ for at most $r-3$ i's. Then either $\lambda = \lambda_i e_i$ for some i or $\mu = \mu_i e_i$ for some i or λ and μ are dependent.

Proof. Assume that λ and μ are independent. Without loss of generality, we assume that (λ_1, λ_2) and (μ_1, μ_2) are independent. The cases $\deg_{y_{r+1}} R = 0$ and $\deg_{y_{r+2}} R = 0$ follow from lemma 4.2. So assume the opposite.

i) Suppose first that $\lambda_1 = \mu_2 = 0$. Then $\lambda_2\mu_1 \neq 0$. Since $\deg_{y_{r+2}} R = 1$, R has a term of the form

$$\alpha y_1^{t_1} y_2^{t_2} \cdots y_r^{t_r} \cdot y_{r+1}^{t_{r+1}} y_{r+2}$$

with $0 \leq t_i \leq 1$ for all i. If $t_{r+1} = 0$, then by looking at the term

$$x_1^{dt_1} x_2^{dt_2} \cdots x_r^{dt_r} \cdot (x_1^{d-1} x_m)$$

of (5), we see that $\mu_m = 0$ for all $m \neq 1$, i.e. $\mu = \mu_1 e_1$. So assume $t_{r+1} = 1$. Looking at the term

$$x_1^{dt_1} x_2^{dt_2} \cdots x_r^{dt_r} \cdot x_2^{d-1} x_l^2 x_1^{d-1}$$

of (5), we see that $\lambda_l \mu_l = 0$ for all $l \geq 3$. Assume $\lambda \neq \lambda_2 e_2$. Then there is an $l \geq 3$ such that $\lambda_l \neq 0$. So $\mu_l = 0$. Looking at the term

$$x_1^{dt_1} x_2^{dt_2} \cdots x_r^{dt_r} \cdot x_2^{d-1} x_l x_m x_1^{d-1}$$

gives $\mu_m = 0$ for all $m \geq 3$. So $\mu = \mu_1 e_1$.

So assume $(\lambda_i, \mu_{3-i}) \neq 0$ for $i = 1, 2$. Since (λ_1, λ_2) and (μ_1, μ_2) are independent, at least three of their four coordinates are nonzero. Assume without loss of generality that $\lambda_1\lambda_2\mu_1 \neq 0$. If $\mu_2 = 0$, then we may assume that $\mu_3 \neq 0$ on account of the assumption $\mu \neq \mu_1 e_1$.

If $\mu_2 \neq 0$, then $\lambda_1\lambda_2\mu_1\mu_2 \neq 0$. From the assumption $\lambda_i = \mu_i = 0$ for at most $r-3$ i's, it follows that $\lambda_i \neq 0$ or $\mu_i \neq 0$ for some $i \geq 3$. So without loss of generality, we may assume $\mu_3 \neq 0$. So assume $\mu_3 \neq 0$ regardless of whether $\mu_2 = 0$ or not.

Assume that (λ_2, λ_3) and (μ_2, μ_3) are dependent. Then $\mu_2 \mid \lambda_2\mu_3 \neq 0$, so $\lambda_2\mu_2 \neq 0$. If we interchange (λ_1, μ_1) and (λ_2, μ_2), which can be realized by flipping x_1 and x_2, (λ_2, λ_3) and (μ_2, μ_3) get independent but the condition $\lambda_1\mu_1 \neq 1$ is not affected. So we may assume that (λ_2, λ_3) and (μ_2, μ_3) are independent and in addition $\lambda_1\mu_1 \neq 0$.

ii) We show that the above assumptions lead to a contradiction. Replacing R by $R(y_1, y_2, \dots, y_r, \lambda_1^d y_{r+1}, \mu_1^d y_{r+2})$, we may assume that $\lambda_1 = \mu_1 = 1$. Write $\lambda_1 x_1 + \lambda_2 x_2 + \cdots + \lambda_r x_r = x_1 + L$ and similarly $\mu_1 x_1 + \mu_2 x_2 + \cdots + \mu_r x_r = x_1 + M$.

Let $s := \deg_{y_1, y_{r+1}, y_{r+2}} R$. Notice that $\deg_{y_i} R \leq 1$ for all i. If $s \geq 3$, then $s = 3$ and the left hand side of (5) has degree $3d$ with respect to x_1; contradiction. Since $\deg_{y_{r+1}} R \neq 0$, $s \geq 1$. So two cases remain:

- $s = 1$:
  We can write

$$R = R_1 y_1 + R_2 y_{r+1} + R_3 y_{r+2} + R_4$$

  with $R_i \in \mathbb{C}[y_2, \dots, y_r]$. Looking at the coefficient of x_1^{d-1} in (5) gives

$$R_2(x_2^d, \dots, x_r^d)L = -R_3(x_2^d, \dots, x_r^d)M$$

  Assume $R_2 \neq 0$. Notice that $d \geq 2$. Reduction modulo $x_i^d - y_i$ for all i gives $R_2 L = -R_3 M$. Next, a generic substitution into the y_i's gives $L = \alpha M$ for some $\alpha \in \mathbb{C}$. So L and M are linearly dependent. This contradicts the independence of (λ_2, λ_3) and (μ_2, μ_3), so $R_2 = R_3 = 0$. Looking at the coefficient of x_1^d in (5) gives $R_1 = 0$. So $R = R_4$. This contradicts $s = 1$.
- $s = 2$:
  We can write

$$R = R_1 y_{r+1} y_{r+2} + R_2 y_1 y_{r+2} + R_3 y_1 y_{r+1} + R_4$$

  with $R_i \in \mathbb{C}[y_2, \dots, y_r]$ for all $i \leq 3$ and $\deg_{y_1, y_{r+1}, y_{r+2}} R_4 \leq 1$. Looking at the coefficient of x_1^{2d-1} in (5) gives

$$(R_1 + R_3)(x_2^d, \dots, x_r^d)L = -(R_1 + R_2)(x_2^d, \dots, x_r^d)M$$

  and $(R_1 + R_3) = (R_1 + R_2) = 0$ follows similar as $R_2 = R_3 = 0$ in the case $s = 1$. Looking at the coefficient of x_1^{2d} in (5) gives $R_1 + R_2 + R_3 = 0$, so $R_2 = R_3 = 0$ and also $R_1 = 0$. So $R = R_4$. This contradicts $s = 2$. □

Theorem 4.4. *Assume A is a matrix of corank 2 at most, $d \geq 3$ and $H = (Ax)^{*d}$ such that $\mathcal{J}H$ is nilpotent. Then there exists a $T \in \mathrm{GL}_n(\mathbb{C})$ and a lower triangular matrix B such that*

$$T^{-1} \circ (Ax)^{*d} \circ T = (Bx)^{*d}$$

Proof. Assume first that every principal minor of A has determinant zero. From [9, lemma 1.2] (see also [12, prop. 6.3.9]), it follows that there is a permutation P such that $P^{-1}AP$ is lower triangular. So take $T = P$.
Assume next that A has an invertible principal minor. From lemma 4.1, it follows that there exists a nonzero relation R such that

$$R((A_1x)^{d-1}, (A_2x)^{d-1}, \ldots, (A_nx)^{d-1}) = 0$$

Let $r := \mathrm{rk}A \geq n - 2$. After a suitable permutation, we have that the rows $A_1, A_2, \ldots, A_r$ are independent,

$$A_{r+1} = \lambda_1 A_1 + \lambda_2 A_2 + \cdots + \lambda_r A_r$$

and, in case $r = n - 2$,

$$A_{r+2} = \mu_1 A_1 + \lambda_2 A_2 + \cdots + \mu_r A_r$$

We first show that $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$. The case $r = n - 1$ follows from lemma 4.2, so assume that $r = n - 2$. The case $\lambda_i = \mu_i = 0$ for at most $r - 3$ i's follows from lemma 4.3, so assume $\lambda_i = \mu_i = 0$ for at least $r - 2$ i's. Replacing A by $P^{-1}AP$ for a suitable permutation P, we get that $\lambda_i = \mu_i = 0$ for all $i \leq r - 2$, and theorem 3.5 applies. So $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$.
So the components of H are linearly dependent. Replacing H by $T^{-1} \circ H \circ T$ for a suitable linear transformation T, we get $H_1 = 0$ and hence $A_1 = 0$. This transformation may make all principal minor determinants zero, but then, again by [9, lemma 1.2], there is a permutation matrix P such that $P^{-1}AP$ is lower triangular. So we may assume that there is still a nonzero principal minor determinant in A. From lemma 4.1 it follows that there exists a nonzero relation R_1 such that

$$R_1((A_2x)^{d-1}, \ldots, (A_nx)^{d-1}) = 0$$

After a suitable permutation, we have that the rows $A_2, A_3, \ldots, A_{r+1}$ are independent and

$$A_{r+2} = \lambda_2 A_2 + \lambda_3 A_3 + \cdots + \lambda_{r+1} A_{r+1}$$

Applying lemma 4.2 again gives $A_i = sA_j$ for some $i \neq j$ with $i, j \neq 1$ and $s \in \mathbb{C}$, i.e. a linear relation between $(A_2x)^d, \ldots, (A_nx)^d$. So after a suitable linear transformation, we have $A_2 = 0$ as well.
Since $\mathrm{cork}A \leq 2$, $(A_3x)^{d-1}, \ldots, (A_nx)^{d-1}$ are algebraically independent. It follows from lemma 4.1 that all principal minor determinants of A are zero. So again we can take for T a suitable permutation matrix P. □

The proof of the above theorem was essentially given by Drużkowski in [9]. Drużkowski observed something more or less similar to lemma 4.3, but found it unnecessary to prove that in full detail.

Lemma 4.5. *Let $d \geq 3$ and R be a nonzero relation with $\deg_{y_i} R \leq 1$ such that*

$$R(x_1^d, x_2^d, \ldots, x_r^d, (\lambda_1 x_1 + \lambda_2 x_1 + \cdots + \lambda_r x_r)^d, (\mu_1 x_1 + \mu_2 x_1 + \cdots + \mu_r x_r)^d) = 0 \quad (6)$$

Then either $\lambda = \lambda_i e_i$ for some i or $\mu = \mu_i e_i$ for some i or λ and μ are dependent.

Proof. The cases $\deg_{y_{r+1}} R = 0$ and $\deg_{y_{r+2}} R = 0$ follow from lemma 4.2, so assume the opposite. The case $\lambda_i = \mu_i = 0$ for at most $r - 3$ i's follows from lemma 4.3, so assume without loss of generality that $\lambda_i = \mu_i = 0$ for all $i \geq 3$. Similar as in the proof of lemma 4.3, we assume that $\lambda_1 = \mu_1 = 1$ and write $\lambda_1 x_1 + \lambda_2 x_2 + \cdots + \lambda_r x_r = x_1 + L$ and $\mu_1 x_1 + \mu_2 x_2 + \cdots + \mu_r x_r = x_1 + M$. Put $s := \deg_{y_1, y_{r+1}, y_{r+2}} R$. If $s \geq 3$, then $s = 3$ and the left hand side of (6) has degree $3d$ in x_1; contradiction. Since $\deg_{y_{r+1}} R \neq 0$, $s \geq 1$. So two cases remain:

- $s = 1$:
  Since $\lambda_i = \mu_i = 0$ for all $i \geq 3$, R is in fact a relation between x_1^d, x_2^d, $(x_1 + L)^d$ and $(x_1 + M)^d$, say

  $$R_0(x_1^d, x_2^d, (x_1 + L)^d, (x_1 + M)^d) = 0$$

  for some *homogeneous* $R_0 \neq 0$ with $\deg_{y_1, y_3, y_4} R_0 \leq s$ and $\deg_{y_2} R_0 \leq 1$. If R_0 is linear, then it follows from lemma 3.3 and $d \geq 3$ that $L = 0$, $M = 0$ or $L = M$. If R_0 is not linear, then it follows from $s = 1$ that R_0 is quadratic and $y_2 \mid R_0$, for R_0 is homogeneous. Hence, R_0 decomposes into linear factors and can be chosen linear instead.

- $s = 2$:
  Write

  $$R = R_1 y_{r+1} y_{r+2} + R_2 y_1 y_{r+2} + R_3 y_1 y_{r+1} + R_4$$

  with $R_i \in \mathbb{C}[y_2, \ldots, y_r]$ for all $i \leq 3$ and $\deg_{y_1, y_{r+1}, y_{r+2}} R_4 \leq 1$. Looking at the coefficient of x_1^{2d-1} in (6) gives

  $$(R_1 + R_3)(x_2^d, \ldots, y_r^d) L = -(R_1 + R_2)(x_2^d, \ldots, y_r^d) M$$

  Looking at the coefficient of x_1^{2d} in (6), gives $R_1 + R_2 + R_3 = 0$, which implies $-R_2 L = R_3 M$.

  At last, the coefficient of x_1^{2d-2} in (6) implies that the following is zero:

  $$\begin{aligned} & 2dR_1 LM + (d-1)(R_1 + R_3)L^2 + (d-1)(R_1 + R_2)M^2 \\ = \; & 2dR_1 LM - (d-1)R_2 L^2 - (d-1)R_3 M^2 \\ = \; & 2dR_1 LM + (d-1)R_3 LM + (d-1)R_2 LM \\ = \; & (d+1)R_1 LM \end{aligned}$$

So $LM = 0$ or $R_1 = 0$. So assume $R_1 = 0$. Then $-R_2 = R_3$ due to $R_1 + R_2 + R_3 = 0$. From $-R_2 = R_3$ and $-R_2 L = R_3 M$, it follows that either $R = R_4$, which contradicts $s = 2$, or $L = M$. □

Theorem 4.6. *If H is as in theorem 3.4 and* $\mathrm{cork} A = 3$*, then there exists a $T \in \mathrm{GL}_n(\mathbb{C})$ and a lower triangular matrix B such that*

$$T^{-1} \circ (Ax)^{*d} \circ T = (Bx)^{*d}$$

Proof. Since the proof of theorem 4.6 is more or less similar to that of theorem 4.4, we only give a sketch of it.
From theorem 3.4 or [16, Th. 3.1], it follows that $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$, i.e. the components of H are linearly dependent. So we may assume that the first row of A is zero. Assume A has a nonzero principal minor determinant. The conditions of theorem 3.4 imply that $3 = \mathrm{cork} A \leq d - 2$, so $d \geq 5$. So it follows from lemmas 4.1 and 4.5 that we may assume that the first two rows of A are zero. Next, it follows from lemmas 4.1 and 4.2 that we may assume that the first three rows of A are zero. Since $\mathrm{cork} A = 3$, all principal minors of A have determinant zero. So B as above exists. □

Observe that in the proofs of theorems 4.4 and 4.6, the process of triangularization is as follows: first, all occurences of $A_i = sA_j$ with $i \neq j$ and $s \in \mathbb{C}^*$ are eliminated by linear transformations 'within $\mathbb{C}[x_i, x_j]$'. After that, A is made triangular by a permutation transformation. This result does not follow from the methods of Drużkowski.
The above observation does not hold for power linear maps $(Ax)^{*d}$ with $\mathrm{rk} A = 2$, but still there exist a triangularization of $(Ax)^{*d}$ that is power linear as well. The following theorem, which is in fact a closer look on what happens in the proof of Theorem 1 of [6], shows this result not only for $d \geq 3$, but for any $d \geq 1$.

Theorem 4.7. *Assume A is a matrix of rank* 2 *at most and $\mathcal{J}(Ax)^{*d}$ is nilpotent. Then there exists a $T \in \mathrm{GL}_n(\mathbb{C})$ and a lower triangular matrix B such that*

$$T^{-1} \circ (Ax)^{*d} \circ T = (Bx)^{*d}$$

Proof. The case $\mathrm{rk} A = 1$ was already done by Drużkowski in [9]. So assume that $\mathrm{rk} A = 2$. Then there are two rows A_{i_1} and A_{i_2} of A such that all other rows of A are linear combinations of A_{i_1} and A_{i_2}. There are $n - 2$ distinct unit vectors $e_{k_3}, \dots, e_{k_n}$ such that the rows $A_{i_1}, A_{i_2}, e_{k_3}^{\mathrm{t}}, \dots, e_{k_n}^{\mathrm{t}}$ are independent. Replacing A by $P^{-1}AP$ for a suitable permutation P makes that the rows $A_{j_1}, A_{j_2}, e_3^{\mathrm{t}}, \dots, e_n^{\mathrm{t}}$ are independent.
Hence the matrix with those n rows is invertible. So set

$$T := \begin{pmatrix} A_{j_1} \\ A_{j_2} \\ e_3^{\mathrm{t}} \\ \dots \\ e_n^{\mathrm{t}} \end{pmatrix}^{-1}$$

Then the last $n-2$ rows of T are $e_3^{\mathrm{t}}, \dots, e_n^{\mathrm{t}}$ as well. Put $\tilde{H} = T^{-1} \circ H \circ T$, where $H = (Ax)^d$. The components $\tilde{H}_3, \dots, \tilde{H}_n$ of $\tilde{H}$ are clearly linear powers. Write $A_i = \lambda_i A_{j_1} + \mu_i A_{j_2}$ for all i. Then

$$A = \begin{pmatrix} \lambda_1 & \mu_1 & 0 & \cdots & 0 \\ \lambda_2 & \mu_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ \lambda_n & \mu_n & 0 & \cdots & 0 \end{pmatrix} \cdot T^{-1}$$

So the last $n-2$ columns of $A \cdot T$ are zero. It follows that $\tilde{H}_i \in \mathbb{C}[x_1, x_2]$ for each i. Hence $(x_1, x_2) + (\tilde{H}_1, \tilde{H}_2)$ is a homogeneous Keller map in dimension 2. Such maps are classified in e.g. [1]: we have either $\tilde{H}_1 = \tilde{H}_2 = 0$, in which case $\tilde{H}$ is already of the form $(Bx)^{*d}$ with B triangular, or

$$\begin{pmatrix} \tilde{H}_1 \\ \tilde{H}_2 \end{pmatrix} = S^{-1} \circ \begin{pmatrix} 0 \\ x_1^d \end{pmatrix} \circ S$$

Now $(S, x_3, \dots, x_n)^{-1} \circ \tilde{H} \circ (S, x_3, \dots, x_n)$ is of the form $(Bx)^{*d}$ with B triangular. □

In case $\mathrm{rk} A = 1$, Drużkowski found a matrix B with $n-1$ zero rows, but an argument similar as above would give a matrix B with $n-1$ zero columns.

5 Some final remarks

At first, we like to mention that in [5], Cheng proves that in case $\mathrm{cork} A = 1$, $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$, also in the quadratic case. So the conclusion of theorem 4.4 holds for this case as well: see the proof of theorem 4.4.
The following quadratic linear map $(Ax)^{*2}$ in dimension 6 with $\mathrm{rk} A = \mathrm{cork} A = 3$, which is, as observed in the introduction, linearly triangularizable, but without a linear triangularization that is quadratic linear as well:

$$H = \begin{pmatrix} 0 \\ 0 \\ (x_1 + x_2 + x_3 - x_4 - x_5 + x_6)^2 \\ (x_1 - x_2 + x_3 - x_4 - x_5 + x_6)^2 \\ (x_1 - x_2 - x_3 + x_4 + x_5 - x_6)^2 \\ (x_1 + x_2 - x_3 + x_4 + x_5 - x_6)^2 \end{pmatrix}$$

In order to prove that the above quadratic linear H has no ditto linear triangularization, we need the following normalization principle for triangular power linear maps.

Proposition 5.1. *Let $H = (Ax)^{*d}$ be lower triangular. Then there exists an r and a $G = (Bx)^{*d}$ which is lower triangular as well, such that $G_1 = G_2 = \cdots = G_r = 0$ and $G_{r+1}, G_{r+2}, \dots, G_n$ are linearly independent over $\mathbb{C}$.*

Proof. Assume

$$\lambda_1 H_1 + \lambda_2 H_2 + \cdots + \lambda_s H_s$$

is a linear dependence relation between the components of H with $\lambda_s \neq 0$. After a suitable linear transformation that does not affect the fact that H is lower triangular, we have $H_s = 0$. Repeating this argument, we get that all linear relations between the components of H are determined by zero components of H.

Next, if $H_s = 0$, but $H_i = 0$ does not hold for all $i \le s$, then the map $P^{-1} \circ H \circ P$ with $P = (x_2, \ldots, x_s, x_1, x_{s+1}, \ldots, x_n)$, which is lower triangular as well, has more zero components at the beginning than H has, and the result follows by induction. □

Now let $E = (x_1, x_2, x_3 + x_4 + x_5 - x_6, x_4, x_5, x_6)$, then

$$G := E^{-1} \circ H \circ E = \begin{pmatrix} 0 \\ 0 \\ 8x_1x_2 \\ (x_1 - x_2 + x_3)^2 \\ (x_1 - x_2 - x_3)^2 \\ (x_1 + x_2 - x_3)^2 \end{pmatrix}$$

is a triangularization of H. In order to prove that H has no triangularization that is quadratic linear as well, we show that $\tilde{G} = T^{-1} \circ G \circ T$ cannot be both lower triangular just as G and quadratic linear just as H.

Assume $\lambda^{\mathrm{t}} G = 0$. Looking at $(\frac{\partial}{\partial x_1})^2 G_i$ for all i, we see that $\lambda_4 + \lambda_5 + \lambda_6 = 0$. Looking at $(\frac{\partial}{\partial x_2})^2 G_i$ and $(\frac{\partial}{\partial x_3})^2 G_i$ for all i as well, we see that $\lambda_4 = \lambda_5 = \lambda_6 = 0$. Since $G_1 = G_2 = 0$, $\lambda_3 = 0$ and the last four components of G are linearly independent.

Assume that $\tilde{G}$ is lower triangular. From proposition 5.1, it follows that we may assume that $\tilde{G}_1 = \tilde{G}_2 = 0$. Since the last four components of G, and hence those of $G(Tx)$ as well, are linearly independent, it follows from $0 = \tilde{G}_1 = (T^{-1})_1 G(Tx)$ that the last four coordinates of $(T^{-1})_1$ are zero. Similarly, the last four coordinates of $(T^{-1})_2$ are zero. Since $\tilde{G}$ is lower triangular, we have $\tilde{G}_3 \in \mathbb{C}[x_1, x_2]$, whence $(T^{-1}G)_3 = \tilde{G}_3(T^{-1}x) \in \mathbb{C}[x_1, x_2]$ as well.

Looking at $\frac{\partial}{\partial x_3} G_i$ for all i, it follows that $(T^{-1}G)_3 \in \mathbb{C}[x_1, x_2]$, if and only if $(T^{-1})_3$ is of the form

$$T_3^{-1} = (\mu_1 \; \mu_2 \; \mu_3 \; 0 \; 0 \; 0)$$

Assume $\tilde{G}_3$ is the square of a linear form. Then $(T^{-1}G)_3$ is such a square as well. This requires $\mu_3 = 0$, so the first three rows of T^{-1} are dependent. Contradiction, so $\tilde{G}_3$ is not the square of a linear form.

In [12, Th. 8.4.2], a special cubic linear map is given that is not linearly triangularizable; the proof follows from [12, Th 7.4.4] and [12, Th 8.3.2]. Another power linear map that is not linearly triangularizable is

$$H = \begin{pmatrix} 0 \\ 0 \\ (x_1 + x_5 - x_6 + x_7 - x_9)^2 \\ (x_2 + x_5 - x_6 + x_7 - x_9)^2 \\ (x_2 + x_3 - x_8)^2 \\ (x_3 - x_8)^2 \\ (x_4 - x_8)^2 \\ (x_5 - x_6 + x_7 - x_9)^2 \\ (x_1 + x_4 - x_8)^2 \end{pmatrix}$$

The proof that this quadratic linear map cannot linearly be triangularized at all uses the same techniques as above, and is left as an exercise to the reader. Since for a triangular special homogeneous map $x + H$, either the first or the last component of H is zero, triangularizability of a power linear map H implies that its components are linearly dependent over $\mathbb{C}$. So one can ask whether the components of H need to be linearly dependent. This is not the case: in [3], the second author shows that there exists a cubic linear counterexample to this linear dependence problem in dimension 53.

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