Uniqueness Polynomials for Holomorphic Curves into the Complex Projective Space

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Abstract. In this paper, by making use of uniqueness polynomials for meromorphic functions, we obtain a class of uniqueness polynomials for holomorphic curves from the complex plane into complex projective space. The related uniqueness problems are also considered.

1. Introduction and Results

We first recall the definitions of sharing values and sets which play an important role in the development of uniqueness theory of meromorphic functions. Let \( f \) and \( g \) be two non-constant meromorphic functions in the complex plane \( \mathbb{C} \) and let \( a \) be a finite complex number. We say that \( f \) and \( g \) share the value \( a \) \( \text{CM} \) (counting multiplicities), provided that \( f - a \) and \( g - a \) have the same zeros with the same multiplicities. Similarly, we say that \( f \) and \( g \) share the value \( a \) \( \text{IM} \) (ignoring multiplicities), provided that \( f - a \) and \( g - a \) have the same set of zeros, where the multiplicities are not taken into account. In addition we say that \( f \) and \( g \) share \( \infty \) \( \text{CM} \) \( \text{IM} \), if \( 1/f \) and \( 1/g \) share \( 0 \) \( \text{CM} \) \( \text{IM} \).

Let \( S \) be a set of distinct elements of \( \mathbb{C} \cup \{\infty\} \) and \( E_f(S) = \bigcup_{a \in S} \{z; f(z) - a = 0\} \), where each zero is counted according to its multiplicity. If multiplicities are not counted, then the set is denoted by \( E_f(S) \). If \( E_f(S) = E_g(S) \), we say that \( f \) and \( g \) share the set \( S \) \( \text{CM} \). On the other hand, if \( E_f(S) = E_g(S) \), we say that \( f \) and \( g \) share the set \( S \) \( \text{IM} \).

In [1], F. Gross proposed the following problem (known as “Gross-problem”) which has a significant influence on uniqueness theory of meromorphic functions: Whether there exist two (even one) finite sets \( S_j \) (\( j = 1, 2 \)) such that \( E_f(S_j) = E_g(S_j) \) (\( j = 1, 2 \)) can imply \( f \equiv g \) for any pair of nonconstant entire functions \( f \) and \( g \) ? Since then many authors have found such two finite sets (called unique range sets) with as small cardinalities as possible. See [2–4, 6].

P. Li and C. C. Yang [13] seem to have been the first to draw a connection between unique range sets and zeros of polynomials.
A polynomial \( P \in \mathbb{C}[T] \) is called a **uniqueness polynomials for meromorphic functions** (UPM) if

\[
P(f) = P(g) \Rightarrow f = g
\]

for all nonconstant meromorphic functions \( f \) and \( g \) on \( \mathbb{C} \).

In the last years, much attention has been given to find uniqueness polynomials for meromorphic functions. For instance, Yi [7], Yang and Hua [8] proved

**Theorem 1.1.** [7, 8] For \( m, n \in \mathbb{N}^* \), let \( P(z) = z^n - az^{n-m} + b \), \( a, b \in \mathbb{C} \). Then \( P(z) \) is a UPM if \((m, n) = 1, n > m + 1, m \geq 2 \).

Recall that the \( N \)-dimensional complex projective space

\[
P^N(\mathbb{C}) = \mathbb{C}^{N+1} - \{0\}/\sim,
\]

where

\[
(a_0, \ldots, a_N) \sim (b_0, \ldots, b_N) \quad \text{if and only if} \quad (a_0, \ldots, a_N) = \lambda(b_0, \ldots, b_N)
\]

for some \( \lambda \in \mathbb{C} \). We denote by \([a_0 : \cdots : a_N]\) the equivalence class of \((a_0, \ldots, a_N)\). Throughout this paper, we fix homogeneous coordinates \([x_0 : \cdots : x_N]\) on \(P^N(\mathbb{C})\). Let \( H \) be a hypersurface of degree \( d \) in \(P^N(\mathbb{C})\) defined by the equation

\[
\sum_{i \in I_d} a_i x_i^d = 0
\]

where \( T_d = \{(i_0, \ldots, i_N) \in \mathbb{N}^{N+1}; i_0 + \cdots + i_N = d\}, X^l = x_0^{i_0} \cdots x_N^{i_N} \) for \( l = (i_0, \ldots, i_N) \). Sometimes, we identify the hypersurface \( H \) with its defining polynomial, i.e., we will write

\[
H(x_0, \ldots, x_N) = \sum_{i \in I_d} a_i x_i^d.
\]

Since a meromorphic function on \( \mathbb{C} \) is also a holomorphic curve from \( \mathbb{C} \) into the complex projective with dimension 1, it is natural to generalize the results about UPM to the case of holomorphic curves from \( \mathbb{C} \) into \(P^N(\mathbb{C})\). Now we recall the following definition

**Definition 1.2.** A homogeneous polynomial \( P \) of variables \( x_0, \ldots, x_N \) is called a uniqueness polynomials for holomorphic curves (UPC) if

\[
P(\tilde{f}) = P(\tilde{g}) \Rightarrow \tilde{f} = \tilde{g}
\]

for all algebraically nondegenerate holomorphic curves \( f \) and \( g \) from \( \mathbb{C} \) into \(P^N(\mathbb{C})\).

In 1997, Shirosaki [9] proved the homogeneous polynomial

\[
H(x_0, x_1) = x_0^d + x_0^m x_1^{n-m} + x_1^n
\]

is a uniqueness polynomial for holomorphic curves from \( \mathbb{C} \) into \(P^1(\mathbb{C})\) if \((m, n) = 1, n > 2m + 8, m \geq 2 \). Afterwards, he constructed inductively uniqueness polynomials for algebraically nondegenerate holomorphic curves into \(P^N(\mathbb{C})\). In 2005, T. V. Tan [10] improved Shirosaki’s result to more general cases and hence obtained a larger class of UPCs.

In 2011, V. H. An and T. D. Duc [11] obtained a UPC related to Theorem 1.1.

**Theorem 1.3.** [11] Suppose that \( m, n \in \mathbb{N}^* \) with \((m, n) = 1, m \geq 2, n \geq 2m + 9 \). Let

\[
P_i(x_i, x_N) = x_i^d - a_i x_i^{n-m} x_N^m + b_i x_N^d, \quad (0 \leq i \leq N - 1),
\]

where \( a_i, b_i \in \mathbb{C}, 0 \leq i \leq N - 1 \) and \( b_i \neq b_j b_l \) with \( i \neq j, i \neq l \). Then \( P_{N,d} := \sum_{i=0}^{N-1} P_i(x_i, x_N) \) is a UPC if \( d \geq (2N - 1)^2 \).
Note that the homogeneous polynomial $P_i(x_i, x_N) = x_i^n - a_i x_i^{r-m} x_N^m + b_i x_N^n$ is the homogeneous equation of the polynomial $\tilde{P}_i(x) = x^n - a_i x^{r-m} + b_i$ as in Theorem 1.1, that is $P_i(x_i, x_N) = x_N^n \tilde{P}_i(x)$. Inspired by this heuristic, we present, in this article, a connection between the UPCs and the UPMs, which provides a class of uniqueness polynomials for holomorphic curves from $\mathbb{C}$ into complex projective space.

**Theorem 1.4.** (Main Result) Suppose that $m, n, d \in \mathbb{N}^*$ with $n \geq 2m + 9, d \geq (2N - 1)^2$. Let $$P_i(x) = \sum_{\mu=0}^{m} a^i_{n-\mu} x^{n-\mu} + b_i$$ be a UPM, where $a^i_{n}, b_i \in \mathbb{C}, 0 \leq \mu \leq m, a^i_{n} \neq 0, b_i \neq 0, a^i_{n-\mu_0} \neq 0$ for some $\mu_0 \in \{1, \ldots, m\}$ (0 $\leq i \leq N - 1$). Set $$P_i(x_i, x_N) = \sum_{\mu=0}^{m} a^i_{n-\mu} x_i^{n-\mu} x_N^{\mu} + b_i x_N^n,$$ (0 $\leq i \leq N - 1$).

If $b_i^2 \neq b_j^2$ with $i \neq j, i \neq k$, then $P_{N,d} := \sum_{i=0}^{N-1} P_i(x_i, x_N)$ is a UPC.

In particular, Theorem 1.4 generalizes Theorem 1.3 in the case of $\tilde{P}_i(x) = x^n - a_i x^{r-m} + b_i$ (0 $\leq i \leq N - 1$). In addition, Theorem 1.4 can yield some new UPCs. For example, as a corollary of the result of G. Frank and M. Reinders [12], we have the polynomial $P(x) = \frac{(n-1)(n-2)}{2} x^n - (n-1)(n-2)x^{n-1} + \frac{n(n-1)}{2} x^{n-2} - c$ is a UPM, where $n(\geq 11)$ is a positive integer and $c(\neq 0, 1)$ is a constant. Thus, Theorem 1.4 implies the following

**Corollary 1.5.** Suppose that $n \in \mathbb{N}^*$ with $n \geq 11$. For 0 $\leq i \leq N - 1$, let $$P_i(x_i, x_N) = \frac{(n-1)(n-2)}{2} x_i^n - (n-1)(n-2)x_i^{n-1} x_N^n + \frac{n(n-1)}{2} x_i^{n-2} x_N^2 + b_i x_N^n,$$ where $b_i^2 \neq b_j^2$ with $i \neq j, i \neq k$. Then $P_{N,d} := \sum_{i=1}^{N-1} P_i(x_i, x_N)$ is a UPC if $d \geq (2N - 1)^2$.

Let $P_{N,d}$ be the homogeneous polynomial defined in Theorem 1.4. Now consider the hypersurface $S$ in $\mathbb{P}^N(\mathbb{C})$, which is defined by the equation $P_{N,d}(x_0, \ldots, x_N) = 0$. For a holomorphic curve $f: \mathbb{C} \to \mathbb{P}^N(\mathbb{C})$, we denote by $f^*S$ the pull-back of the divisor $S$ in $\mathbb{C}$ by $f$. By Theorem 1.4, we have the following uniqueness theorem.

**Corollary 1.6.** Suppose that $m, n, d \in \mathbb{N}^*$ with $n \geq 2m + 9, d \geq (2N - 1)^2$. Let $f$ and $g$ be two algebraically nondegenerate holomorphic curves from $\mathbb{C}$ into $\mathbb{P}^N(\mathbb{C})$. Let $S$ be the hypersurface defined as above. Assume that $b_i^2 \neq b_j^2$ with $i \neq j, i \neq k$. If $f^*S = g^*S$, then $f = g$.

### 2. Preliminaries

We start with relevant notions and definitions. For details see [13–15]. Let $D$ be a domain in $\mathbb{C}$, $f: D \to \mathbb{P}^N(\mathbb{C})$ be a holomorphic curve and $U$ be an open set in $D$. Any holomorphic curve $\tilde{f}: U \to \mathbb{C}^{N+1}$ such that $P(\tilde{f}(z)) = f(z)$ in $U$ is called a representation of $f$ on $U$, where $P: \mathbb{C}^{N+1} - \{0\} \to \mathbb{P}^N(\mathbb{C})$ is the standard projective map.

**Definition 2.1.** For an open subset $U$ of $D$ we call a representation $\tilde{f} = (f_0, \ldots, f_N)$ a reduced representation of $f$ on $U$ if $f_0, \ldots, f_N$ are holomorphic functions on $U$ without common zeros.
Remark 2.2. As is easily seen, if both \( f_j : U_j \to \mathbb{C}^{N+1} \) are reduced representations of \( f \) for \( j = 1, 2 \) with \( U_1 \cap U_2 \neq \emptyset \), then there is a holomorphic function \( h \neq 0 \) : \( U_1 \cap U_2 \to \mathbb{C} \) such that \( f_2 = hf_1 \) on \( U_1 \cap U_2 \).

Remark 2.3. As is easily seen, if both \( \hat{f} \) and \( \tilde{f} \) are homogeneous polynomials, then \( \hat{f} = \tilde{f} \).

Definition 2.4. Let \( f : \mathbb{C} \to \mathbb{P}^N(\mathbb{C}) \) be a holomorphic curve with a representation \( \hat{f} \). If there exists no nonzero homogeneous polynomial \( H(x_0, \ldots, x_N) \) such that \( H(\hat{f}) \equiv 0 \), then it is said that \( f \) is algebraically nondegenerate.

Obviously, for holomorphic curves from \( \mathbb{C} \) to \( \mathbb{P}^N(\mathbb{C}) \), i.e., meromorphic functions, algebraically nondegeneracy coincides with nonconstantness.

To prove our main result, we need the following lemmas.

Lemma 2.5. [16] Let \( F, f \neq 0, 0 \leq j \leq N \) be holomorphic functions on \( \mathbb{C} \), and let \( d \in \mathbb{N}^* \). Assume that

\[
F^d_0 + \cdots + F^d_N = 0.
\]

If \( d > (N + 1)(N - 1) \), there is a partition of indices, \( \{0, 1, \ldots, N\} = \bigcup I_i \) such that

(i) the cardinality \( |I_i| \geq 2 \) for every \( I_i \),
(ii) \( F_i/F_j = c_{ij} \in \mathbb{C} \) for all \( i, j \in I_i \),
(iii) \( \sum_{i \in I} P^d_i = 0 \).

Lemma 2.6. [17] Let \( g(x_0, \ldots, x_N) \) be homogeneous polynomial of degree \( \delta_j \) for \( 0 \leq j \leq N \). Suppose there exists a holomorphic curve \( f : \mathbb{C} \to \mathbb{P}^N(\mathbb{C}) \) so that its images lies in

\[
\sum_{j=0}^{N} x^d_j g_j(x_0, \ldots, x_N) = 0.
\]

and \( d > (N+1)(N-1)+\sum_{j=0}^{N} \delta_j \). Then there is a nontrivial linear relation among \( x^d_0 g_0(x_0, \ldots, x_N), \ldots, x^d_N g_N(x_0, \ldots, x_N) \) on the image of \( f \).

3. Proofs

3.1. Proof of Theorem 1.4

Proof. Suppose that \( f \) and \( g \) be two holomorphic curves from \( \mathbb{C} \) into \( \mathbb{P}^N(\mathbb{C}) \) with reduced representations \( f = (f_0, \ldots, f_N), g = (g_0, \ldots, g_N) \), respectively, such that \( P_{\alpha}(\hat{f}) = P_{\alpha}(\hat{g}) \). Then we get

\[
P_d(f_0, f_N) + \cdots + P_{d-1}(f_{N-1}, f_N) - P_{d}(g_0, g_N) - \cdots - P_{d}(g_{N-1}, g_N) = 0.
\]

Since \( d \geq (2N-1)^2 \), \( f \) and \( g \) are algebraically nondegenerate holomorphic curves, from Lemma 2.5 it follows that there exists some permutation, says \( \sigma, \sigma : \{0, 1, \ldots, N-1\} \to \{0, 1, \ldots, N-1\} \) such that

\[
P_i(f_i, f_N) = A_i P_{\sigma(i)}(g_{\sigma(i)}, g_N),
\]

where \( A_i^\sigma = 1, 0 \leq i \leq N-1 \). Fix \( B_i \) such that \( B_i^\sigma = A_i, 0 \leq i \leq N - 1 \). Then

\[
\hat{g} = (g_0, \ldots, g_N) \Rightarrow (B_i g_0, \ldots, B_i g_N)
\]

is also a reduced representation of \( g \) and

\[
P_i(f_i, f_N) = P_{\sigma(i)}(g_{\sigma(i)}, g_N),
\]

for \( 0 \leq i \leq N - 1 \).

Claim 1 \( b_{ij}f_i^q = b_{ij}f_N^q \) for \( 0 \leq i \leq N - 1 \).
We have from (3.3) that
\[ g_{\alpha(0)}^{\nu} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(0)} g_{\alpha(0)}^{\nu \mu} g_{N}^{\mu} \right) - f_{i}^{n-m} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(i)} f_{j}^{n-\mu} f_{N}^{\mu} \right) - b_{i} f_{N}^{n} + b_{\alpha(0)} g_{N}^{n} = 0. \] (3.4)

for \( 0 \leq i \leq N-1 \). We now define the holomorphic curve \( F_{1} \) from \( C \) into \( \mathbb{P}^{2}(C) \) induced by the mapping \( F_{1}(z) = (g_{\alpha(0)}, f_{i}, f_{N}, \tilde{g}_{N}) \). By (3.4), we see that the images of \( F \) lies in
\[ x_{0}^{n-m} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(0)}^{x_{0}^{\mu}} x_{3}^{\mu} \right) - x_{1}^{n-m} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(i)} x_{1}^{n-\mu} x_{2}^{\mu} \right) - b_{i} x_{2}^{n} + b_{\alpha(0)} x_{3}^{n} = 0. \]

Since \( n > 2m + 8 \), it follows from Lemma 2.6 that the homogeneous polynomials
\[ x_{1}^{n-m} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(i)} x_{1}^{n-\mu} x_{2}^{\mu} \right) b_{i} x_{2}^{n}, b_{\alpha(0)} x_{3}^{n} \]
are linearly dependent on the image of \( F_{1} \). Hence, there exist constants \( C_{1}, C_{2}, C_{3} \) with \((C_{1}, C_{2}, C_{3}) \neq (0, 0, 0)\), such that
\[ C_{1} b_{\alpha(0)} \tilde{g}_{N}^{n} + C_{2} b_{i} f_{N}^{n} + C_{3} f_{i}^{n-m} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(i)} f_{j}^{n-\mu} f_{N}^{\mu} \right) = 0. \] (3.5)

Note that the holomorphic curve \( f \) is algebraically nondegenerate, we then have \( C_{1} \neq 0 \). If \( C_{1}, C_{2}, C_{3} \neq 0 \), we can define the holomorphic curve \( F_{2} \) from \( C \) into \( \mathbb{P}^{2}(C) \) induced by the mapping \( F_{2}(z) = (\tilde{g}_{N}, f_{i}, f_{1}) \). Similarly, by (3.5) and Lemma 2.6, we obtain
\[ D_{1} b_{i} f_{N}^{n} + D_{2} f_{i}^{n-m} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(i)} f_{j}^{n-\mu} f_{N}^{\mu} \right) = 0 \]
for some constants \( D_{1}, D_{2} \) with \((D_{1}, D_{2}) \neq 0\). Which is a contradiction to the assumption that \( f \) is algebraically nondegenerate. Therefore, we have \( C_{1} \neq 0 \) and one of \( C_{2}, C_{3} \) is 0. We next consider the following two possible cases.

If \( C_{2} = 0 \), then \( C_{3} \neq 0 \). By the assumption of the theorem that \( a_{n-\mu}^{(i)} \neq 0 \) for some \( \mu_{0} \in [1, \ldots, m] \), we can rewrite (3.5) as the following
\[ C_{1} b_{\alpha(0)} \tilde{g}_{N}^{n} + C_{3} a_{n-\mu_{0}}^{(i)} f_{j}^{n-\mu_{0}} f_{N}^{\mu_{0}} + C_{3} f_{i}^{n-m} \left( \sum_{\mu_{0} \in [0, \ldots, m], \mu_{0} \neq \mu_{0}} a_{n-\mu_{0}}^{(i)} f_{j}^{n-\mu_{0}} f_{N}^{\mu_{0}} \right) = 0. \]

In the exactly same way, we obtain \( f \) is algebraically degenerate by Lemma 2.6. Again, we get a contradiction.

If \( C_{3} = 0 \), then \( C_{2} \neq 0 \). Thus, we deduce by (3.5) that
\[ b_{\alpha(0)} \tilde{g}_{N}^{n} = - \frac{C_{2}}{C_{1}} b_{i} f_{N}^{n}. \] (3.6)

Then \( \tilde{g}_{N} = c f_{N} \) holds for some constant \( c \neq 0 \). Combing this with (3.4) and (3.6) yields that
\[ g_{\alpha(0)}^{\nu} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(0)} \tilde{g}_{\alpha(0)}^{\nu \mu} \tilde{g}_{N}^{\mu} \right) - f_{i}^{n-m} \left( \sum_{\mu=0}^{m} a_{n-\mu}^{(i)} f_{j}^{n-\mu} f_{N}^{\mu} \right) - b_{i} \left( 1 + \frac{C_{2}}{C_{1}} \right) f_{N}^{n} = 0. \]

Suppose that \( 1 + \frac{C_{2}}{C_{1}} \neq 0 \). By the similar arguments above for the holomorphic curve \( F_{3} \) from \( C \) into \( \mathbb{P}^{2}(C) \) induced by the mapping \( F_{3}(z) = (\tilde{g}_{\alpha(0)}, f_{N}, f_{1}) \) we obtain a contradiction. Hence, \( 1 + \frac{C_{2}}{C_{1}} = 0 \) and Claim 1 holds.
Claim 2 The map $\sigma$ is an identity, that is $\sigma(i) = i$ for $0 \leq i \leq N - 1$.

Suppose that there exists $i_0 \in \{0, 1, \ldots, N - 1\}$ such that $\sigma(i_0) \neq i_0$. We will arrive at a contradiction below.

By Claim 1, we have $b_i f_N^i = A_i b_{\sigma(i)} g_N^\sigma$ for $0 \leq i \leq N - 1$. Recall that $A_i^d = 1$, we deduce $b_i^d f_N^{\sigma d} = b_{\sigma(i)}^d g_N^d$ for $0 \leq i \leq N - 1$. We thus obtain
\begin{equation*}
\frac{b_i^d}{(b_{\sigma(i)})^d} = \frac{g_N^d}{f_N^{\sigma d}} = \frac{(b_{\sigma(i)})^d}{b_i^d}.
\end{equation*}

However, this contradicts the assumption that for $i \neq j, i \neq k, b_i^d b_j^d \neq b_i^d b_k^d$. And hence, The map $\sigma$ is an identity.

We are now ready to get back to our original task of showing that $f = g$. Claims 1,2 imply that $f_N^1 = g_N^1$. This clearly implies, together with (3.3), that
\begin{equation*}
P_i\left(\frac{f_i}{f_N}, 1\right) = P_i\left(\frac{g_i}{g_N}, 1\right),
\end{equation*}
for $0 \leq i \leq N - 1$. Note the definition of $\overline{P}_i(z)$, we then have
\begin{equation*}
\overline{P}_i\left(\frac{f_i}{f_N}\right) = \overline{P}_i\left(\frac{g_i}{g_N}\right) = \overline{P}_i\left(\frac{\hat{g}_i}{\hat{g}_N}\right),
\end{equation*}
for $0 \leq i \leq N - 1$. Since $\overline{P}_i(z), 0 \leq i \leq N - 1$, are UPMs, we have $\frac{\hat{f}}{\hat{f}_N} = \frac{\hat{g}}{\hat{g}_N}$ holds for $0 \leq i \leq N - 1$. Thus, $f = g$.

This completes the proof. \qed

3.2. Proof of Corollary 1.6

Proof. Suppose that $f$ and $g$ be two holomorphic curves from $C$ into $\mathbb{P}^N(C)$ with reduced representations $f = (f_0, \ldots, f_N), g = (g_0, \ldots, g_N)$, respectively. Since $f^* S = g^* S, P_{N,d}(f, g) \neq 0$ is an entire function without zeros, denote by $h(z)$. Thus $P_{N,d}(\hat{f}) = P_{N,d}(\hat{h})$, where $h\hat{g} = (h g_0, \ldots, h g_N)$ is also a reduced representation of $g$. By the definition of $P_{N,d}$ and Theorem 1.4, $f = g$. \qed

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