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Refined Neutrosophic Rhotrix: A Novel Algebraic Model for Complex Uncertainty Representation*

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ABSTRACT: The concept Refined neutrosophic rhotrix, an advanced algebraic structure that extends traditional rhotrices by incorporating Refined neutrosophic logic, is introduced. By decomposing indeterminacy into multiple subcomponents, true indeterminacy, contradiction, and uncertainty, the Refined neutrosophic framework allows for more granular representation and analysis of imprecise, inconsistent, and incomplete information. The study defines the algebraic operations of Refined neutrosophic rhotrices and establishes their structural properties, including closure, associativity, and distributivity under specific conditions.

Keywords: Refined neutrosophic rhotrix, Rhotrix, Heart based multiplication.

Contents

1. Introduction

In 2003, Ajibade [1] introduced a novel framework for representing numerical arrays in a rhomboidal configuration, termed rhotrix. He established the structural formulation of an n-dimensional rhotrix as an entity that lies conceptually between $(n-1\times n-1)$ matrix and $n\times n$ matrix. Subsequently, Ajibade [10] proposed the first multiplication technique for rhotrices, known as heart-based multiplication. In 2004, B. Sani [2] presented an alternative multiplication scheme referred to as row-column multiplication, which closely resembles the conventional matrix multiplication approach. These two methods constitute the foundational operations for rhotrix multiplication. Although other forms of multiplication have been defined, they generally do not conform to the requirements necessary for establishing algebraic structures.

Sani [3] further contributed to rhotrix theory by introducing a method for converting a rhotrix into an equivalent matrix representation, termed a coupled matrix. In 2008, A. O. Isere [4] extended Ajibade's foundational work by formulating the notion of even-dimensional rhotrices, addressing the limitation that Ajibade's original definition applies only to rhotrices of odd dimensions. In addition to these advancements, several researchers have significantly enriched the theoretical framework of rhotrix mathematics. Their contributions encompass the development of rhotrix groups [11,7], rhotrix rings [5], and rhotrix vector spaces [6], as well as the exploration of practical applications of rhotrices in various areas.

Neutrosophy, originally proposed by Florentin Smarandache [8,14] in the 1990s, offers an extension to both classical and fuzzy logic. In refined neutrosophic logic, any concept is characterized by three independent components, truth (T), indeterminacy (I), and falsity (F). This framework provides a flexible tool for modelling situations in which available information is uncertain, contradictory, or incomplete.

In [16,17,15], Kandasamy and Smarandache introduced the framework of neutrosophic algebraic structures, which incorporate the notion of indeterminacy, denoted by I. Their work involved extending classical algebraic structures—such as groups, rings, fields, and vector spaces—into the neutrosophic domain. By further refining the indeterminacy component I into multiple distinct levels, the concept was expanded to include refined and n-refined neutrosophic structures. These generalized structures have since been applied in the development of neutrosophic groups [13], modules [19], and vector spaces [20]. Mohammad Abobala investigated the existence of inverses for refined neutrosophic matrices, and extended this analysis to the case of n-refined neutrosophic matrices in [21].

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In this study, we aim to formally introduce the mathematical construct of refined neutrosophic rhotrices, thereby extending the existing framework of refined neutrosophic theory. The primary objective is to define the fundamental operations that govern the structure and manipulation of these entities. To this end, we propose a foundational operations specifically formulated within the refined neutrosophic context. Following the establishment of these operations, we conduct a systematic exploration of the basic properties inherent to refined neutrosophic rhotrices.

For a positive odd integer n, the rhotrix takes the following general form:

$$\left\langle \begin{array}{ccccccccccc} & & & & & a_1 & & & & & \\ & & & & a_2 & a_3 & a_4 & & & & \\ & & & .. & .. & .. & .. & .. & & & \\ & & .. & .. & .. & .. & .. & .. & .. & & \\ a_{\{\frac{t+1}{2}\}-\frac{n}{2}} & & .. & .. & .. & a_{\frac{t+1}{2}} & .. & .. & .. & & a_{\{\frac{t+1}{2}\}+\frac{n}{2}} \\ & & .. & .. & .. & .. & .. & .. & .. & & \\ & & & .. & .. & .. & .. & .. & & & \\ & & & & a_{t-3} & a_{t-2} & a_{t-1} & & & & \\ & & & & & a_t & & & & & \end{array} \right\rangle,$$

where $t = \frac{n^2+1}{2}$. In this representation, the entries marked in red indicate the first row, those highlighted in blue correspond to the first column, and the green entries represent the diagonal elements of the rhotrix. The major horizontal axis is described by the sequence

$$a_{\left(\frac{t+1}{2}\right)-\frac{n}{2}},\ \ldots,\ a_{\frac{t+1}{2}},\ \ldots,\ a_{\left(\frac{t+1}{2}\right)+\frac{n}{2}},$$

while the major vertical axis is given by

$$a_1,\ a_3,\ \ldots,\ a_{\frac{t+1}{2}},\ \ldots,\ a_{t-2},\ a_t.$$

The heart of the rhotrix is the central entry located at the intersection of these two axes, namely the element $a_{\frac{t+1}{2}}$.

Heart-based multiplication, introduced by A. O. Ajibade, operates by multiplying each element of the first rhotrix by the heart (central entry) of the second, and then adding the product of the corresponding element of the second rhotrix with the heart of the first. Addition of rhotrices is carried out element-wise, where each pair of corresponding entries is added together. The trace of a rhotrix is obtained by summing its entries across the principal vertical axis.

2. Refined neutrosophic Rhotrix

Within this section, we establish the foundation by introducing refined neutrosophic rhotrices and describing the basic operations associated with them, namely refined neutrosophic rhotrix addition and heart-based multiplication. We then examine the algebraic properties of refined neutrosophic rhotrices under these operations, with their trace characteristics.

Definition 2.1 *A* ***Refined neutrosophic rhotrix*** *is defined as a rhotrix whose entries are taken from a refined neutrosophic field* $(K(I_1, I_2), +, \cdot)$, *where* $I_1^2 = I_1$, $I_2^2 = I_2$, $I_1 I_2 = I_2 I_1 = I_1$ *and* $(K, +, \cdot)$ *is any field.*

Suppose A is a rhotrix in $R_n(K)$, then the refined neutrosophic rhotrix is represented as $A_R =$

$$\left\langle \begin{array}{ccccccc}
 & & & a_1 + k_1I_1 + k_2I_2 & & & \\
 & & a_2 + k_3I_1 + k_4I_2 & a_3 + k_5I_1 + k_6I_2 & a_4 + k_7I_1 + k_8I_2 & & \\
 & .. & .. & .. & .. & .. & \\
 & .. & .. & .. & .. & .. & \\
a_{\{\frac{t+1}{2}\}-\frac{n}{2}} + k_{t-n}I_1 + k_{t+1-n}I_2 & .. & .. & a_{\frac{t+1}{2}} + k_tI_1 + k_{t+1}I_2 & .. & .. & a_{\{\frac{t+1}{2}\}+\frac{n}{2}} + k_{t+n}I_1 + k_{t+1+n}I_2 \\
 & .. & .. & .. & .. & .. & \\
 & .. & .. & .. & .. & .. & \\
 & & a_{t-3} + k_{2t-7}I_1 + k_{2t-6}I_2 & a_{t-2} + k_{2t-5}I_1 + k_{2t-4}I_2 & a_{t-1} + k_{2t-3}I_1 + k_{2t-2}I_2 & & \\
 & & & a_t + k_{2t-1}I_1 + k_{2t}I_2 & & &
\end{array} \right\rangle$$

And that can be re-written as

$$A_R = A + \left\langle \begin{array}{ccccccccccc}
 & & & & & k_1 & & & & & \\
 & & & & k_3 & k_5 & k_7 & & & & \\
 & & & .. & .. & .. & .. & .. & & & \\
 & & .. & .. & .. & .. & .. & .. & .. & & \\
k_{t-n} & & .. & .. & .. & k_t & .. & .. & .. & & k_{t+n} \\
 & & .. & .. & .. & .. & .. & .. & .. & & \\
 & & & .. & .. & .. & .. & .. & & & \\
 & & & & k_{2t-7} & k_{2t-5} & k_{2t-3} & & & & \\
 & & & & & k_{2t-1} & & & & &
\end{array} \right\rangle I_1 +$$

$$\left\langle \begin{array}{ccccccccccc}
 & & & & & k_2 & & & & & \\
 & & & & k_4 & k_6 & k_8 & & & & \\
 & & & .. & .. & .. & .. & .. & & & \\
 & & .. & .. & .. & .. & .. & .. & .. & & \\
k_{t+1-n} & & .. & .. & .. & k_{t+1} & .. & .. & .. & & k_{t+1+n} \\
 & & .. & .. & .. & .. & .. & .. & .. & & \\
 & & & .. & .. & .. & .. & .. & & & \\
 & & & & k_{2t-6} & k_{2t-4} & k_{2t-2} & & & & \\
 & & & & & k_{2t} & & & & &
\end{array} \right\rangle I_2, \text{ where all } k_i \in K$$

$$A_R = A + K_{2i-1}I_1 + K_{2i}I_2$$

Definition 2.2 *We define the* ***operations on refined neutrosophic rhotrices*** *as follows:*

(i) *Two refined neutrosophic rhotrices can be added only when they have the same order. Addition of two refined neutrosophic rhotrices A_R and A'_R is defined as:*

$$A_R + A'_R = A + (K_{2i-1} + K'_{2i-1})I_1 + (K_{2i} + K'_{2i})I_2$$

That is, for rhotrices of size 3,

$$A_R = \left\langle \begin{array}{ccc} & a_1 + k_1I_1 + k_2I_2 & \\ a_2 + k_3I_1 + k_4I_2 & a_3 + k_5I_1 + k_6I_2 & a_4 + k_7I_1 + k_8I_2 \\ & a_5 + k_9I_1 + k_{10}I_2 & \end{array} \right\rangle = A + K_{2i-1}I_1 + K_{2i}I_2 \text{ and}$$

$$A'_R = \left\langle \begin{array}{ccc} & a'_1 + k'_1I_1 + k'_2I_2 & \\ a'_2 + k'_3I_1 + k'_4I_2 & a'_3 + k'_5I_1 + k'_6I_2 & a'_4 + k'_7I_1 + k'_8I_2 \\ & a'_5 + k'_9I_1 + k'_{10}I_2 & \end{array} \right\rangle = A' + K'_{2i-1}I_1 + K'_{2i}I_2 \text{ of size 3,}$$

$$A_R + A'_R = (A + A') + (K_{2i-1} + K'_{2i-1})I_1 + (K_{2i} + K'_{2i})I_2$$

(ii) *The heart-based refined neutrosophic multiplication of two refined neutrosophic rhotrices is defined only when both rhotrices are of the same order. Multiplication of two refined neutrosophic rhotrices A_R*

and $A_R^{'}$ is defined as:

$$A_R \circ A_R^{'} = \left\langle \begin{array}{ccccccc} & & & [(a_1 + k_1 I_1 + k_2 I_2)\cdot & & & \\ & & & (a^{'}_{\frac{t+1}{2}} + k^{'}_t I_1 + k^{'}_{t+1} I_2)]+ & & & \\ & & & [(a^{'}_1 + k^{'}_1 I_1 + k^{'}_2 I_2)\cdot & & & \\ & & & (a_{\frac{t+1}{2}} + k_t I_1 + k_{t+1} I_2)] & & & \\ & & .. & .. & .. & & \\ & .. & .. & .. & .. & .. & \\ & .. & .. & .. & .. & .. & \\ .. & .. & .. & (a_{\frac{t+1}{2}} + k_t I_1 + k_{t+1} I_2)\cdot & .. & .. & .. \\ & & & (a^{'}_{\frac{t+1}{2}} + k^{'}_t I_1 + k^{'}_{t+1} I_2) & & & \\ & .. & .. & .. & .. & .. & \\ & .. & .. & .. & .. & .. & \\ & & .. & .. & .. & & \\ & & & [(a_t + k_{2t-1} I_1 + k_{2t} I_2)\cdot & & & \\ & & & (a^{'}_{\frac{t+1}{2}} + k^{'}_t I_1 + k^{'}_{t+1} I_2)]+ & & & \\ & & & [(a^{'}_t + k^{'}_{2t-1} I_1 + k^{'}_{2t} I_2)\cdot & & & \\ & & & (a_{\frac{t+1}{2}} + k_t I_1 + k_{t+1} I_2)] & & & \end{array} \right\rangle$$

where $\cdot$ represents the multiplication among the refined neutrosophic numbers.

Definition 2.3 (Trace of Refined neutrosophic Rhotrix) *The trace of a refined neutrosophic rhotrix of size 'n' is adding the entries in major vertical axis and it is denoted as $Tr(.)$.*

That is, for a rhotrix $A_R = \left\langle \begin{array}{ccc} & a_1 + k_1 I_1 + k_2 I_2 & \\ a_2 + k_3 I_1 + k_4 I_2 & a_3 + k_5 I_1 + k_6 I_2 & a_4 + k_7 I_1 + k_8 I_2 \\ & a_5 + k_9 I_1 + k_{10} I_2 & \end{array} \right\rangle$ *of size 3,*

$Tr(A_R) = (a_1 + a_3 + a_5) + (k_1 + k_5 + k_9)I_1 + (k_2 + k_6 + k_{10})I_2$

Theorem 2.1 *For any refined neutrosophic rhotrices with the refined neutrosophic addition operation, the following axioms holds:*

- $(A_R + B_R) + C_R = A_R + (B_R + C_R)$ *(Associativity),*
- $A_R + O = A_R$*, where O is the zero rhotrix (Additive Identity),*
- $A_R + B_R = B_R + A_R$ *(Commutativity), where $A_R, B_R,$ and C_R are any refined neutrosophic rhotrices*

Proof: The proof is straightforward and as the axioms follow directly from the corresponding properties of refined neutrosophic numbers under addition, applied componentwise to rhotrices.

□

Theorem 2.2 *The heart based multiplication operation among any invertible refined neutrosophic rhotrices holds the following axioms:*

- $A_R \circ I = A_R$*, where*

$$I = \left\langle \begin{array}{ccccccccc} & & & & 0 + 0I_1 + 0I_2 & & & & \\ & & & 0 + 0I_1 + 0I_2 & 0 + 0I_1 + 0I_2 & 0 + 0I_1 + 0I_2 & & & \\ & & .. & .. & .. & .. & .. & & \\ & .. & .. & .. & .. & .. & .. & .. & \\ 0 + 0I_1 + 0I_2 & .. & .. & .. & 1 + 0I_1 + 0I_2 & .. & .. & .. & 0 + 0I_1 + 0I_2 \\ & .. & .. & .. & .. & .. & .. & .. & \\ & & .. & .. & .. & .. & .. & & \\ & & & 0 + 0I_1 + 0I_2+ & 0 + 0I_1 + 0I_2 & 0 + 0I_1 + 0I_2 & & & \\ & & & & 0 + 0I_1 + 0I_2 & & & & \end{array} \right\rangle$$

(Multiplicative Identity),

- $A_R \circ A_R^{'} = A_R^{'} \circ A_R$ *(Commutativity), where* $A_R, A_N^{'}$ *are any refined neutrosophic rhotrices*

Proof: Let us consider any two refined neutrosophic rhotrices A_R, I_R.
Suppose $A_R = \left\langle \begin{matrix} & a_1 + k_1I_1 + k_2I_2 & \\ a_2 + k_3I_1 + k_4I_2 & a_3 + k_5I_1 + k_6I_2 & a_4 + k_7I_1 + k_8I_2 \\ & a_5 + k_9I_1 + k_{10}I_2 & \end{matrix} \right\rangle$ and
$I_R = \left\langle \begin{matrix} & a_1^{'} + k_1^{'}I_1 + k_2^{'}I_2 & \\ a_2^{'} + k_3^{'}I_1 + k_4^{'}I_2 & a_3^{'} + k_5^{'}I_1 + k_6^{'}I_2 & a_4^{'} + k_7^{'}I_1 + k_8^{'}I_2 \\ & a_5^{'} + k_9^{'}I_1 + k_{10}^{'}I_2 & \end{matrix} \right\rangle$ of size 3,

$$\begin{aligned} \text{The } 1^{st} \text{ entry of } A_R \circ I_R =& [(a_1 + k_1I_1 + k_2I_2) \cdot (a_3^{'} + k_5^{'}I_1 + k_6^{'}I_2)]+ \\ & [(a_1^{'} + k_1^{'}I_1 + k_2^{'}I_2) \cdot (a_3 + k_5I_1 + k_6I_2)] \\ =& a_1a_3^{'} + a_1^{'}a_3 + [k_1(a_3^{'} + k_5^{'} + k_6^{'}) + k_1^{'}(a_3 + k_5 + k_6) + k_5^{'}(a_1 + k_2)+ \\ & k_5(a_1^{'} + k_2^{'})]I_1 + [a_1k_6^{'} + a_1^{'}k_6 + k_2(a_3^{'} + k_6^{'}) + k_2^{'}(a_3 + k_6)]I_2 \\ \text{The } \textit{heart} \text{ entry of } A_R \circ I_R =& (a_3 + k_5I_1 + k_6I_2) \cdot a_3^{'} + k_5^{'}I_1 + k_6^{'}I_2 \\ =& a_3a_3^{'} + [k_5^{'}(a_3 + k_6) + k_5(a_3^{'} + k_5^{'} + k_6^{'})]I_1 + [k_6a_3^{'} + k_6^{'}(a + 3 + k_6)]I_2 \end{aligned}$$

For $A_R \circ I_R = A_R$,
Then, $a_3a_3^{'} = a_3$, implies $a_3^{'} = 1$ and $a_1a_3^{'} + a_1^{'}a_3 = a_1$ implies $a_1^{'} = 0$, since A_R is invertible a_3 cannot be zero. Similarly, $a_2{'} = a_4{'} = a_5{'} = 0$.

On comparing I_2 coordinate of the heart entry of $A_R \circ I_R$ with I_2 coordinate of the heart entry of A_R, we get $k_6a_3^{'} + k_6^{'}(a + 3 + k_6) = k_6$ implies $k_6^{'} = 0$, since A_R is invertible $a_3 + k_6$ cannot be zero and $a_3^{'} = 1$.

On comparing I_2 coordinate of the 1^{st} entry of $A_R \circ I_R$ with I_2 coordinate of the 1^{st} entry of A_R, we get $a_1k_6^{'} + a_1^{'}k_6 + k_2(a_3^{'} + k_6^{'}) + k_2^{'}(a_3 + k_6) = k_2$ implies $k_2 + k_6^{'}(a_1 + k_2) + k_2^{'}(a_3 + k + 6) = k_2 \implies k_2^{'} = 0$, since $k_6^{'} = 0$,$a_3^{'} = 1$ and A_R is invertible $a_3 + k_6$ cannot be zero.

On comparing I_1 coordinate of the heart entry of $A_R \circ I_R$ with I_1 coordinate of the heart entry of A_R, we get, $k_5^{'}(a_3 + k_6) + k_5(a_3^{'} + k_5^{'} + k_6^{'}) = k_5$ implies $k_5^{'}(a_3 + k_5 + k_6) + k_5 + k_5k_6^{'} = k_5 \implies k_5^{'} = 0$, since A_R is invertible $a_3 + k_5 + k_6$ cannot be zero and $k_6^{'} = 0$

On comparing I_1 coordinate of the 1^{st} entry of $A_R \circ I_R$ with I_2 coordinate of the 1^{st} entry of A_R, we get , $k_1(a_3^{'} + k_5^{'} + k_6^{'}) + k_1^{'}(a_3 + k_5 + k_6) + k_5^{'}(a_1 + k_2) + k_5(a_1^{'} + k_2^{'}) = k_1$ implies $k_1 + k_5^{'}(a_1 + k_1 + k_2) + k_1k_6^{'} + k_1^{'}(a_3 + k_5 + k_6) + k_5(a_1^{'} + k_2^{'}) = k_1 \implies k_1^{'} = 0$, since A_R is invertible $a_3 + k_5 + k_6$ cannot be zero and $k_6^{'} = k_2^{'} = k_5^{'} = 0$

Similarly, $k_3^{'} = k_4^{'} = k_7^{'} = k_8^{'} = k_9^{'} = k_{10}^{'} = 0$

Therefore, the additive identity for rhotrix size 3 is

$$I = \left\langle \begin{matrix} & 0 + 0I_1 + 0I_2 & \\ 0 + 0I_1 + 0I_2 & 1 + 0I_1 + 0I_2 & 0 + 0I_1 + 0I_2 \\ & 0 + 0I_1 + 0I_2 & \end{matrix} \right\rangle$$

In general, the multiplicative identity for a rhotrix of size n is a rhotrix of the same size whose entries are all $0 + 0I_1 + 0I_2$, with the exception of the heart entry, which is $1 + 0I_1 + 0I_2$.

Since heart-based rhotrix multiplication is commutative, it follows directly that the commutative axiom is satisfied for heart-based refined neutrosophic multiplication.

□

Theorem 2.3 *For two refined neutrosophic rhotrices A_R and B_R and any scalar λ with $0 \leq \lambda \leq 1$, the following properties hold:*

(i) $\text{Tr}(A_R + B_R) = \text{Tr}(A_R) + \text{Tr}(B_R)$

(ii) $\text{Tr}(\lambda A_R) = \lambda \, \text{Tr}(A_R)$

(iii) $\text{Tr}(A_R) = \text{Tr}(A_R^T)$

Proof: The properties follows naturally from applying the trace operator applied to refined neutrosophic rhotrices, where the trace is computed as the sum of diagonal entries. Since addition and scalar multiplication are defined componentwise, and transpose preserves diagonal elements, the stated properties hold naturally. □

Conclusion

This study has established the foundational structure of refined neutrosophic rhotrices by extending the existing framework of refined neutrosophic theory. We have defined key operations specific to this new construct and explored their algebraic behavior of basic properties. The formalization presented in this work lays the groundwork for further investigations into advanced properties, potential algebraic systems, and real-world applications involving refined uncertainty.

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