I. Introduction

The fuzzy logic was introduced in 1965 by Professor Lotfi A. Zadeh[1]. In a series of papers[2-5], Rosenfeld introduced certain ideas in fuzzy plane geometry, area, height, width, diameter, and perimeter of a fuzzy subset of a plane. The results developed in these papers have applications to pattern recognition. In [6], Gupta and Ray introduced fuzzy plane projective geometry. Their approach was axiomatic and involved fuzzy singletons. In this paper, we experiment with developing fuzzy geometry by limiting process of the notion of fuzzy sphere whose degree of circularity function is measured by a fuzzy set. The concept of a circularity function is also used in defining the union, intersection, and complement of fuzzy spheres. The circularity function of a fuzzy sphere converges to one of a crisp sphere as the fuzzy sphere shapes itself like a crisp sphere.

We recall some definitions and results used in this paper. Let \( X \) be a nonempty crisp set. A fuzzy subset \( \mu \) of \( X \) is a function from \( X \) into the closed unit interval \([0, 1]\), that is, \( \mu : X \rightarrow [0, 1] \). In the literature, a fuzzy set may also be written as a set of ordered pairs: \( \{(x, \mu(x)) : x \in X\} \), where \( \mu(x) \) is referred to as the membership function or grade of membership. If the range of the fuzzy set \( \mu \) contains only two values 0 or 1, then \( \mu \) is identical to the characteristic function of a subset of \( X \).

Motivated by the concept of equations of motion we can specify surfaces in the three-dimensional \( xyz \)-space by using equations,
\[
x = x(s, t), y = y(s, t), z = z(s, t),
\]
to express the coordinates of a point \((x, y, z)\) on the surface as functions of auxiliary variables \(s\) and \(t\). These are called parametric equations for the surface, and the variables \(s\) and \(t\) are called parameters. The parameters \(s\) and \(t\) should be viewed as independent variables the ordered pairs of which vary over a two dimensional rectangular region. Let \( S \) be the surface consisting of all ordered triplets \((x(s, t), y(s, t), z(s, t))\) on the \( xyz\)-
space, where \( x(s, t), y(s, t), \) and \( z(s, t) \) are continuous real valued functions defined on a closed two dimensional rectangular region \( R \).

Let \( P(s, t) = (x(s, t), y(s, t), z(s, t)) \) for \( (s, t) \in R \). The surface \( S \) is called a closed surface if for any two points on \( S \), there exists a space curve \( C \) that connects the two points such that \( C \subseteq S \). If a closed surface \( S \) does not intersect itself at any other point on the \( xyz \)-space, then \( S \) is called a simple closed surface. Spheres and ellipsoids are typical examples of simple closed surfaces.

II. Fuzzy Spheres

Let \( S \) be a simple closed surface that is given parametrically by \((x(s, t), y(s, t), z(s, t))\) for \((s, t) \in R\), where \(x(s, t), y(s, t),\) and \(z(s, t)\) are real valued continuous functions on a closed two dimensional rectangular region \( R \). And let \( R \) denote the set of all real numbers.

Definition 2.1. A function \( \mu \gamma: R \rightarrow [0, 1] \) is called a circularity function of \( S \) if

1. there exists a function \( f: R^3 \rightarrow [0, 1] \) such that \( \mu \gamma(s, t) = f(x(s, t), y(s, t), z(s, t)) \) for all \((s, t) \in R\),
2. \( \mu \gamma(s, t) = 1 \) for all \((s, t) \in R \) when \( S \) is a sphere.

Clearly, \( \mu \gamma(s, t) \) is a fuzzy subset of \( R \). Intuitively, the circularity function \( \mu \gamma(s, t) \) can be thought of as a numerical measure of the degree of circularity for simple closed surface on the \( xyz \)-space.

Definition 2.2. Let \( S \) be a simple closed surface on the \( xyz \)-space defined as above. A fuzzy sphere on the \( xyz \)-space is given by

\[ S = \{(x(s, t), y(s, t), z(s, t), \mu \gamma(s, t)) | (s, t) \in R \} \]

where

1. \( x(s, t), y(s, t), \) and \( z(s, t) \) are continuous parametric functions on \( R \) that define \( S \).
2. \( \mu \gamma(s, t) \) is a circularity function on \( S \).

Roughly speaking, a fuzzy sphere is formed by a simple closed surface \( S \) together with a circularity function \( \mu \gamma(s, t) \), for all \((s, t) \in R\). For the sake of simplicity, we shall use the symbol \( S = \langle (x(s, t), y(s, t), z(s, t)) , \mu \gamma(s, t) \rangle \) for a fuzzy sphere

\[ S = \{(x(s, t), y(s, t), z(s, t), \mu \gamma(s, t)) | (s, t) \in R \}. \]

If \( S \) is a crisp sphere, then the corresponding fuzzy sphere must have the maximum degree of circularity, that is, \( \mu \gamma(s, t) = 1 \), for \((s, t) \in R \). So we can write

\[ S = \langle (x(s, t), y(s, t), z(s, t)) , 1 \rangle. \]

The following example shows various fuzzy spheres.

Example 2.3.

Let \( S = \{(x(s, t), y(s, t), z(s, t)) | (s, t) \in R \} \) be a simple closed sphere on \( R^3 \). Then we can take \( C \) the smallest closed cuboid including \( S \). Let \( P_0 \) be the center point of \( C \). Define the function \( \mu \gamma(s, t) \) as follows:

\[ \mu \gamma(s, t) = \begin{cases} \frac{|P(s, t) - P_0|}{\text{Max}(|P(s, t) - P_0| : P \in S)} & \text{if } P_0 \in I(S) \\ 0 & \text{otherwise} \end{cases} \]

, where \(|P(s, t) - P_0|\) is the distance from \( P_0 \) to \( P(s, t) \), and \( I(S) \) is the set of all interior points of \( S \). Then \( \mu \gamma(s, t) \) is a circularity function of \( S \).

So we can take \( \mu \gamma(s, t) \)-fuzzy sphere \( S \) such that

\[ S = \langle (x(s, t), y(s, t), z(s, t)) , \mu \gamma(s, t) \rangle \]

We can consider geometrically the above Example 2.3. If \( S \) is a crisp sphere, then the parametric equations for the surface, \( S \), is given by

\[ x(s, t) = r \cos s \sin t, \]

\[ y(s, t) = r \sin s \sin t, \]

\[ z(s, t) = r \cos t, \]
\[ y(s, t) = r \sin s \sin t \quad \text{and} \quad z(s, t) = r \cos t, \]
\[(s, t) \in [0, 2\pi] \times [0, \pi].\]

Since \( S \) is a crisp sphere, it is clear that for all \((s, t) \in [0, 2\pi] \times [0, \pi],\)
\[ |P(s, t) - P_0| = \max \{|P(s, t) - P_0|: P \in S\}. \]
So, the calculated \( \mu_S(s, t) \) is 1. Hence the fuzzy sphere
\( \hat{S} \)
\[ \hat{S} = \langle (x(s, t), y(s, t), z(s, t)), 1 \rangle \]
\[ = \langle r \cos s \sin t, r \sin s \sin t, r \cos t, 1 \rangle. \]

![Fig. 1. 1- fuzzy sphere](image)

\[ \Rightarrow \mu_S = \frac{r}{r} = 1 \]

Similarly, if \( S \) is an ellipsoid, then the parametric equations for the surface, \( S \), is given by
\[ x(s, t) = a \cos s \sin t, \quad y(s, t) = b \sin s \sin t \]
and \[ z(s, t) = c \cos t, \quad (s, t) \in [0, 2\pi] \times [0, \pi] \]
then we can calculate the circularity function of \( S \) as follows
\[ \mu_S(s, t) = \frac{|P(s, t) - P_0|}{\max \{|P(s, t) - P_0|: P \in S\}}. \]

In particular, if \( |P(s, t) - P_0| = l(s, t) \) and
\[ \max \{|P(s, t) - P_0|: P \in S\} = |P_2 - P_0| = m, \]
then the ellipsoid is \( \frac{l(s, t)}{m} \)-fuzzy sphere, such that
\[ S = \langle (x(s, t), y(s, t), z(s, t)), \mu_S(s, t) \rangle \]
\[ = \langle a \cos s \sin t, b \sin s \sin t, c \cos t, \frac{l(s, t)}{m} \rangle. \]

And also the circularity function \( \mu_S(s, t) \) can also be used as a measure in comparing two fuzzy spheres. Let \( S_1 \) and \( S_2 \) be two fuzzy spheres with circularity functions \( \mu_S(s, t) \) and \( \mu_{S_2}(s, t) \), respectively. Then \( S_1 \) is called a fuzzy subsphere of \( S_2 \), written as \( S_1 \approx S_2 \), if \( \mu_S(s, t) \leq \mu_{S_2}(s, t) \) for all \((s, t) \in R\). \( S_1 \) is said to be equal to \( S_2 \), written as \( S_1 = S_2 \), if \( S_1 \approx S_2 \) and \( S_2 \approx S_1 \), that is, \( \mu_S(s, t) \leq \mu_{S_2}(s, t) \) and \( \mu_{S_2}(s, t) \leq \mu_S(s, t) \) for all \((s, t) \in R\). From the definition of equal relation, we can see that the relation \( \approx \) is an equivalence relation[7].

III. Convergence of Fuzzy Spheres

In this section, we discuss several convergent theorems of fuzzy sphere sequence. First of all we introduce concepts of the union, the intersection, and the complement of fuzzy spheres.

For \( n = 1, 2, \cdots \), let \( S_n \) be a simple closed surface given parametrically in terms of ordered triplets \((x_n(s, t), y_n(s, t), z_n(s, t))\) for \((s, t) \in R\), where \( x_n(s, t), y_n(s, t), \) and \( z_n(s, t) \) are real valued continuous functions on \( R \), and let \( \hat{S}_n \) be the fuzzy sphere that is formed by \( S_n \) with the circularity function \( \mu_{S_n}(s, t) \) such that
\[ S_n^* = \langle (x_n(s, t), y_n(s, t), z_n(s, t)), \mu_{\gamma_n}(s, t) \rangle \]

Also, let
\[ S = \langle (x(s, t), y(s, t), z(s, t)), \mu_{\gamma}(s, t) \rangle \]
be a fuzzy sphere with the circularity function \( \mu_{\gamma}(s, t) \).

For two fuzzy spheres
\[ S_1 = \langle (x_1(s, t), y_1(s, t), z_1(s, t)), \mu_{\gamma_1}(s, t) \rangle \]
\[ S_2 = \langle (x_2(s, t), y_2(s, t), z_2(s, t)), \mu_{\gamma_2}(s, t) \rangle \],
the union of \( S_1 \) and \( S_2 \), denoted by \( S_1 \cup S_2 \), is defined as follows:

Let
\[
\mu_{\gamma_1 \cup \gamma_2}(s, t) = (\mu_{\gamma_1} \vee \mu_{\gamma_2})(s, t).
\]

and
\[
S_2^* = \langle (x_2(s, t), y_2(s, t), z_2(s, t)), \mu_{\gamma_2}(s, t) \rangle \subseteq S_2
\]
If we can construct a simple closed sphere
\[ S_2' = S_2^1 \cup S_2^2, \]
where
\[ S_2^1 = \langle (x_1(s, t), y_1(s, t), z_1(s, t)), \mu_{\gamma_1 \cup \gamma_1}(s, t) \rangle \]
then we define
\[ \overline{S}_1 \cup \overline{S}_2 = \overline{S}_2^* \]
\[ = \langle (x^*(s, t), y^*(s, t), z^*(s, t)), \mu_{\gamma \cup \gamma}(s, t) \rangle \]
Roughly speaking, the simple closed sphere \( \overline{S}_2^* \) is reconstructed by \( S_2 \) with the circularity function
\[
\mu_{\gamma \cup \gamma}(s, t) = \mu_{\gamma_1}(s, t) \vee \mu_{\gamma_2}(s, t).
\]

We can consider that the geometric significance of \( \overline{S}_1 \cup \overline{S}_2 \) is given Fig. 3

For a given sequence \( \{S_n^*\} \) of fuzzy spheres, the fuzzy sphere \( \bigcup_{n=1}^{\infty} S_n^* \) is given by
\[ \bigcup_{n=1}^{\infty} S_n^* = \{((x^*(s, t), y^*(s, t), z^*(s, t)), \mu_{\bigcup \gamma_1}(s, t) | (s, t) \in \mathbb{R}) \}
\]
with the circularity function
\[
\mu_{\bigcup \gamma_1}(s, t) = (\bigvee_{n=1}^{\infty} \mu_{\gamma_1})(s, t)
\]
if we can construct a simple closed sphere
\[ \{((x^*(s, t), y^*(s, t), z^*(s, t)), \mu_{\bigcup \gamma_1}(s, t) | (s, t) \in \mathbb{R}) \}
\]
by \( \bigcup_{n=1}^{\infty} S_n \) satisfying
\[
\mu_{\bigcup \gamma_1}(s, t) = \bigvee_{n=1}^{\infty} \mu_{\gamma_n}(s, t).
\]
From now on we assume that \( \bigcup_{n=1}^{\infty} S_n \) exists for a fuzzy sequence \( \{S_n^*\} \).

Remark. In the problem of drawing a sphere by computer, we first consider a sequence of fuzzy spheres with their circularity functions in a non-decreasing order. As the circularity function gets closer and closer to 1, we would expect that the fuzzy sphere gets closer and closer to a crisp sphere.

Also the intersection of the fuzzy spheres \( \overline{S}_1 \) and \( \overline{S}_2 \),
denoted by $S_1 \cap S_2$, and the intersection of a sequence $(S_n)$ of fuzzy spheres, denoted by $\bigcap_{n=1}^{\infty} S_n$, are defined as the fuzzy spheres similarly defined to the union of the fuzzy sphere exchanging the symbols of union ($\cup$), join ($\vee$), and meet ($\wedge$) for intersection ($\cap$), meet ($\wedge$) and join ($\vee$), respectively.

The complement of $S$, denoted by $S^c$, is defined to be the fuzzy sphere

$$S^c = \langle x(s, t), y(s, t), z(s, t) \rangle$$

with the circularity function $\mu_S(s, t)$ given by $\mu_S(s, t) = 1 - \mu_S^c(s, t)$.

The following proposition gives the most elementary properties of the fuzzy spheres.

Proposition 3.1

1. $S_1 \leq S_1 \cup S_2$
2. $S_1 \leq \bigcup_{n=1}^{\infty} S_n$
3. $S_1 \geq S_1 \cup S_2$
4. $S_1 \geq \bigcup_{n=1}^{\infty} S_n$
5. $S \leq S \cup S^c$, $S^c \leq S \cup S^c$
6. $S \cup S^c \leq S$, $S \cup S^c \leq S^c$
7. $S \cup S^c \neq S_0$, where $S_0$ is formed by a crisp simple closed surface $S_0$ together with a circularity function $\mu_{S_0}(s, t) = 1$, $(s, t) \in R$.
8. $S \cap S^c \neq \emptyset$

Properties (1)-(6) are similar to those of the classical set theory, but (7) and (8) are somewhat different from the classical ones.

Since the fuzzy sphere has been defined with the circularity function, we can introduce a concept of the convergence in the sense of circularity function for fuzzy spheres.

**Definition 3.2** The sequence $(S_n)$ of fuzzy spheres is said to converge in the sense of circularity function to the fuzzy sphere $S$ if $\mu_{S_n}(s, t)$ converges to $\mu_S(s, t)$ for all $(s, t) \in R$.

The following theorem may be called the "Convergence Theorem of fuzzy sphere sequence for the sequence of monotone circularity functions," or the monotone convergence theorem.

**Theorem 3.3**[7] Let $S_1 \leq S_2 \leq \cdots \leq S_n \leq \cdots$ be a nondecreasing sequence of fuzzy spheres. Then $(S_n)$ converges in the sense of circularity to the fuzzy sphere $\bigcup_{n=1}^{\infty} S_n$.

**Proof.** For each $(s, t) \in R$, it is easily seen that $\{\mu_{S_n}(s, t)\}$ is a nondecreasing sequence of real numbers bounded above and

$$\sup_{n=1}^{\infty} \mu_{S_n}(s, t) = \bigvee_{n=1}^{\infty} \mu_{S_n}(s, t).$$

Thus, it follows from Theorem 2.5 of [8] that

$$\lim_{n \to \infty} \mu_{S_n}(s, t) = \bigvee_{n=1}^{\infty} \mu_{S_n}(s, t)$$

for all $(s, t) \in R$. Since the circularity function of $\bigcup_{n=1}^{\infty} S_n$ is given by $\bigvee_{n=1}^{\infty} \mu_{S_n}(s, t)$, the theorem follows.$\square$

The following property can be obtained in the same way as in Theorem 3.2.

**Corollary 3.4** Let $S_1 \geq S_2 \geq \cdots \geq S_n \geq \cdots$ be a nonincreasing sequence of fuzzy spheres. Then $(S_n)$ converges in the sense of circularity to the fuzzy sphere $S$. 
\[
\bigcap_{n=1}^{\infty} S_n^-, \text{ that is, } \lim_{n \to \infty} S_n^- = \bigcap_{n=1}^{\infty} S_n^- \text{ in the sense of circularity function.}
\]

**Lemma 3.5** Let \( R \) is a two-dimensional rectangular region, and \( \{ \mu_{\gamma}(s, t) \} \), \( \{ \mu_{\tau}(s, t) \} \) are sequences of real-valued functions defined on \( R \). Let \( \mu_{\gamma}(s, t) \to \mu_{\gamma}(s, t) \) and \( \mu_{\tau}(s, t) \to \mu_{\tau}(s, t) \) on \( R \).

Then \( \mu_{\gamma}(s, t) \lor \mu_{\tau}(s, t) \) converges to \( \mu_{\gamma}(s, t) \lor \mu_{\tau}(s, t) \) on \( R \).

**Proof.** Let \( \varepsilon > 0 \) be given, and \( (s, t) \in R \) be fixed.

Since \( \mu_{\gamma}(s, t) \to \mu_{\gamma}(s, t) \) and \( \mu_{\tau}(s, t) \to \mu_{\tau}(s, t) \) there exist \( N \) such that

\[
k, l \geq N \Rightarrow |\mu_{\gamma}(s, t) - \mu_{\gamma}(s, t)| < \varepsilon
\]

and

\[
|\mu_{\tau}(s, t) - \mu_{\tau}(s, t)| < \varepsilon.
\]

Let \( M = \max\{k, l\} \). Then there exist \( m \geq M \) such that

\[
|\mu_{\gamma}(s, t) - \mu_{\gamma}(s, t)| < \varepsilon
\]

and

\[
|\mu_{\tau}(s, t) - \mu_{\tau}(s, t)| < \varepsilon.
\]

And then

\[
\mu_{\gamma}(s, t) - \varepsilon < \mu_{\gamma}(s, t) < \mu_{\gamma}(s, t) + \varepsilon
\]

and

\[
\mu_{\tau}(s, t) - \varepsilon < \mu_{\tau}(s, t) < \mu_{\tau}(s, t) + \varepsilon.
\]

Hence

\[
(\mu_{\gamma}(s, t) - \varepsilon) \lor (\mu_{\tau}(s, t) - \varepsilon) < \mu_{\gamma}(s, t) \lor \mu_{\tau}(s, t) \lor (\mu_{\gamma}(s, t) + \varepsilon) \lor (\mu_{\tau}(s, t) + \varepsilon).
\]

(1)

Consider

\[
|(\mu_{\gamma}(s, t) \lor \mu_{\tau}(s, t)) - (\mu_{\gamma}(s, t) \lor \mu_{\tau}(s, t))|.
\]

I. The case \( \mu_{\gamma}(s, t) = \mu_{\tau}(s, t) \).

By (1), we obtain

\[
(\mu_{\gamma}(s, t) - \varepsilon) \lor (\mu_{\gamma}(s, t) - \varepsilon) < \mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t) \lor (\mu_{\gamma}(s, t) + \varepsilon) \lor (\mu_{\gamma}(s, t) + \varepsilon).
\]

Since \( \mu_{\gamma}(s, t) = \mu_{\tau}(s, t) \), we can get

\[
\mu_{\gamma}(s, t) - \varepsilon < \mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t)
\]

\[
< \mu_{\gamma}(s, t) + \varepsilon.
\]

From

\[
|\mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t) - \mu_{\gamma}(s, t)| < \varepsilon
\]

We have the conclusion

\[
|\mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t) - (\mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t))| < \varepsilon.
\]

II. The case \( \mu_{\gamma}(s, t) < \mu_{\tau}(s, t) \).

By (1) we can get

\[
(\mu_{\gamma}(s, t) - \varepsilon) \lor (\mu_{\gamma}(s, t) - \varepsilon) < \mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t) \lor (\mu_{\gamma}(s, t) + \varepsilon) \lor (\mu_{\gamma}(s, t) + \varepsilon).
\]

Since \( \mu_{\gamma}(s, t) < \mu_{\tau}(s, t) \), it follows that

\[
\mu_{\gamma}(s, t) - \varepsilon < \mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t)
\]

\[
< \mu_{\gamma}(s, t) + \varepsilon.
\]

Therefore,

\[
(\mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t)) - \varepsilon < \mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t) \lor (\mu_{\gamma}(s, t) + \varepsilon).
\]

Consequently, we have

\[
|\mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t) - (\mu_{\gamma}(s, t) \lor \mu_{\gamma}(s, t))| < \varepsilon.
\]
III. The case \( \mu_S(s, t) > \mu_T(s, t) \).

In a similar way, we can prove that the case of
\( \mu_S(s, t) > \mu_T(s, t) \). Therefore, the proof is now
complete by the case I, II, III.

When the symbol of \( \vee \) and \( \wedge \) are exchanged, we
can get the following result similar to Lemma 3.4, and the
proof is similar to the above.

Lemma 3.6. Let \( R \) is a two-dimensional rectangular region,
and \( \{ \mu_S(s, t) \}, \{ \mu_T(s, t) \} \) be a sequence of real
-valued functions defined on \( R \). Let \( \mu_S(s, t), \mu_T(s, t) : R \rightarrow \mathbb{R} \)
be a real-valued functions such that
\[
\lim_{n \to \infty} \mu_S(s, t) = \mu_S(s, t)
\]
\[
\lim_{n \to \infty} \mu_T(s, t) = \mu_T(s, t)
\]
on \( R \).
Then \( \mu_S(s, t) \wedge \mu_T(s, t) \) converges to
\( \mu_S(s, t) \wedge \mu_T(s, t) \) on \( R \).

The scalar multiple of \( S \), denoted by \( aS \), is defined to be the fuzzy sphere
\[
aS = \langle (x(s, t), y(s, t), z(s, t), \mu_S(s, t)) \rangle
\]
with the circularity function
\[
\mu_{aS}(s, t) = (a, \mu_S)(s, t)
\]
\[
= a \cdot \mu_S(s, t).
\]

Theorem 3.7. Let \( \{ S_n \} \) and \( \{ T_n \} \) converge in the
sense of circularity to the fuzzy sphere \( S \), \( T \) respectively.
Then
1. \( \{ S_n \cup T_n \} \) converges in the sense of circularity to
the fuzzy sphere \( S \cup T \).
2. \( \{ S_n \cap T_n \} \) converges in the sense of circularity to
the fuzzy sphere \( S \cap T \).
3. \( \{ aS_n \} \) converges in the sense of circularity to the
fuzzy sphere \( aS \).

Proof. We need to prove (3); the remaing properties can
be obtained directly from the Lemma 3.5 and Lemma 3.6.
For (3), since \( \{ S_n \} \) converges in the sense of circularity
to \( S \), for each \( (s, t) \in R \)
\[
\lim_{n \to \infty} \mu_{aS_n}(s, t) = a \lim_{n \to \infty} \mu_{S_n}(s, t)
\]
\[
= a \mu_S(s, t)
\]

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