Fingerprint FIS Report

IMAT3406 - Fuzzy Logic & Knowledge Based Systems

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CONTENTS

ABSTRACT

Inspired by the challenge of interpreting the variable and imprecise biometric data, this research aims to enhance the accuracy and reliability of biometric security systems. Current systems often falter due to the inherent uncertainty that comes with biological data, thus leading to security vulnerabilities. The research addresses these challenges by integrating fuzzy logic into the biometric process. Fuzzy logic, which processes data on a spectrum rather than in binary, is particularly suited to manage the details of biometric data. The approach involved a comprehensive literature review, which helped contextualise the problem within the field of biometric security and underscored the potential of fuzzy logic to mitigate it. Membership functions, and rules were carefully selected to ensure they aligned with the intricacies of fingerprint data. The results from iterative testing indicated a significant enhancement in the system's capacity to analyse fingerprints with increased accuracy, handling the variability of the data effectively. In conclusion, the FIS represents a significant advancement in biometric technology. Future directions include validating the system with a larger, more diverse dataset and potentially integrating additional variables to further improve its applicability and robustness. The study highlights the importance of fuzzy logic in addressing the complexities of biometric data and opens avenues for more secure and reliable authentication systems.

Keywords

Fuzzy Logic, Biometric Data Preprocessing, Biometric Systems, Data Uncertainty Management, Fingerprint Analysis, Biometric Data Accuracy, Biometric Authentication, Secure Biometric Systems, Fuzzy Rules, Biometric Data Analysis.

INTRODUCTION

Biometric authentication is a security process that relies on the unique biological characteristics of individuals to verify their identity. While biometric systems do offer a higher level of security compared to traditional passwords or PINs, they do come with flaws. Factors such as poor image quality, physical changes in the user, and environmental conditions can result in inaccuracies, leading to either false rejections or acceptances.

This report presents a novel Fuzzy Inference System (FIS) designed to enhance the reliability of fingerprint analysis, a pillar in biometric authentication. Traditional systems operate on binary logic, where a scan either matches a stored template or does not, this can be problematic when dealing with variability and imperfections that occur in biometric data. Fuzzy Logic, by contrast, introduces the concept of partial truth. Fuzzy Logic mitigates the shortcomings of binary systems by accommodating the imprecision inherent in biometric data, providing a more robust and malleable framework for authentication. Fewer false rejections of uses and a lower likelihood of false acceptances are expected to arise once the implementation is complete.

The following sections in the report will explore the integration of the FIS into the current biometric systems, illustrating and testing how it enhances the accuracy and adaptability of fingerprint authentication and how damages can alter.

LITERATURE REVIEW

Background & Theory

Biometrics is the science of authenticating identity through physiological or behavioural characteristics. Fingerprints, in particular, are widely recognised for their uniqueness and practicality in identification processes (Rajasekar et al., 2022). The reliability of fingerprint recognition, however, can be compromised by factors such as quality and environmental conditions. Fuzzy logic is a method that operates on degrees of truth rather than binary true/false logic, and offers advantages in biometric applications. It provides a more adaptable approach to data analysis, crucial for handling the inherent variability of biological data (EURASIP Journal on Image and Video Processing, 2014). The integration of fuzzy logic into biometric systems, especially in fingerprint analysis, represents an advancement, enhancing accuracy and reliability of identification processes. This approach, particularly in multimodal biometric systems, demonstrates improved performance, including lower error rates and higher precision (Rajasekar et al., 2022).

Fuzzy Logic in Biometric Systems

The integration of fuzzy logic into biometric systems represents a significant advancement in enhancing security and accuracy. Biometric systems, particularly those using fingerprints, have advanced to become crucial in security structures. Fuzzy logic's capability to handle uncertain and imprecise information makes it ideal for biometric systems, where exact matchings are often challenging due to inherent variabilities in biometric data (Masoud Moradi, Masoud Moradkhani, and Mohammad Bagher Tavakoli, 2022).

Fingerprint-based biometric systems have seen increased applications in smart devices due to their ease of access and the potential for secure data encryption. In such systems, fuzzy logic enhances the process of encoding and encrypting biometric data, providing robust security against potential breaches. The implementation of fuzzy logic in these systems involves extracting key features from fingerprint scans and utilising them in complex encryption algorithms. This approach not only ensures the secure storage of biometric data but also optimises system performance by balancing security with efficient data compression (Masoud Moradi, Masoud Moradkhani, and Mohammad Bagher Tavakoli, 2022). The adaptation of fuzzy logic in biometric systems highlights its versatility and effectiveness in managing the complexities of the data. As biometric technology continues to grow, the role of fuzzy logic in ensuring the security and efficiency of these systems becomes increasingly imperative.

Challenges in Fingerprint Analysis

A main challenge is the occurrence of false negatives, where legitimate users are not recognised due to poor fingerprint quality, often resulting from skin conditions, injuries, or environmental conditions. To mitigate these issues, fingerprint enhancement algorithms are employed to improve the extraction of minutiae points for more accurate identification (Clark, How accurate are today's fingerprint scanners? 2023). False acceptances represent another significant concern, where unauthorised scans are

mistakenly accepted. These incidents typically occur due to matching of a sample with a stored template (Clark, How accurate are today's fingerprint scanners? 2023) Additionally, touch-based fingerprint recognition systems face problems such as low contrast signals and distortions due to elastic deformation of the finger, impacting the accuracy of the scans (Eurasip Journal on Image and Video Processing, 2022).

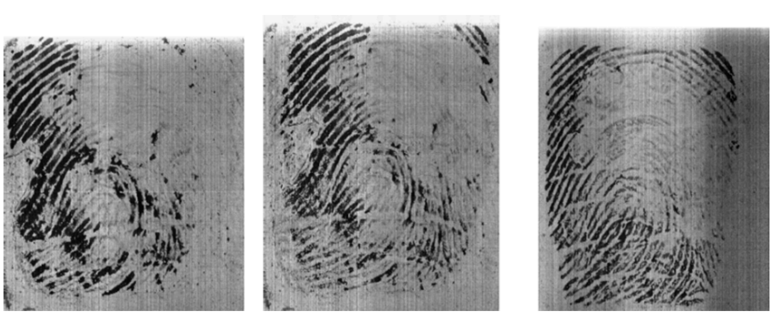

Figure 1. Imperfect and unideal acquisition of the sample due to ***"poor quality"*** *and* ***"extreme dryness"****. (Figure from Biometrics: a tool for information security).*

Some of these issues are resolved within modern touchless fingerprint systems, as they bypass issues like latent fingerprints or distortions from pressing fingers on sensors. However, they introduce new challenges like reliable finger detection and focusing (Eurasip Journal on Image and Video Processing, 2022).

Comparative Studies

In biometric systems, (particularly fingerprint recognition) the integration of fuzzy logic significantly differentiates touch-based from touchless technologies. Touch-based systems, widely used in security, face challenges like distortion and deformation, adversely affecting fingerprint accuracy (EURASIP Journal on Image and Video Processing, 2022). Fuzzy logic's ability to interpret imprecise data is key in these scenarios, enhancing system performance even with low-quality scans.

Touchless systems, addressing hygiene and distortion issues inherent in touch-based methods, also benefit from fuzzy logic, especially in image preprocessing and reliable biometric detection (EURASIP Journal on Image and Video Processing, 2022). With studies showing these systems achieving a high user acceptability and effective performance (Jannis Priesnitz Jannis Biometrics and InternetSecurity Research Group et al.).

Future Directions & Conclusion

In order to advance the application of fuzzy logic within biometric systems, particularly for fingerprints, it is critical to conduct future research. For example, studies like Chen et al. (Fuzzy-logic is precise-its application to biometric system 2011) highlights the potential for enhanced robustness and precision in biometric systems using fuzzy logic. Another example is the work done by Rajasekar et al (Enhanced multimodal biometric recognition approach for smart cities based on an optimised fuzzy genetic algorithm 2022) on multimodal biometric systems using optimised fuzzy genetic algorithms which point towards the importance of such integrations in the realm of smart cities. The key challenges such as false negatives and positives need to be addressed through innovative fingerprint enhancement methods using fuzzy logic and neural networks as suggested in recent research (Sarraju & Bein, 1970).

Throughout this literature review I have highlighted the transformative role that fuzzy logic can bring to fingerprint-based systems. The integration of fuzzy logic has not only allowed enhancement through increasing accuracy but also opened new pathways for secure data processing and encryption (Masoud Moradi, Masoud Moradkhani, and Mohammad Bagher Tavakoli, 2022). Continuous evolution of fuzzy logic in applications that include biometric systems is imperative, as this advancement is vital not only for maintaining robust security standards but also for fostering innovation in identity verification processes.

SYSTEM OVERVIEW

This system is designed to evaluate essential characteristics of fingerprints, mainly in systems that utilise biometric authentication; however, the system could still be applied to other areas such as forensics and identification systems. The design choices I have made, including the selection of the inputs, membership functions, and rules, have been carefully selected based on the unique requirements that fingerprint analysis needs.

System Layout

I have created the layout of my FIS system (fisQuality, See appendix Page 20) around three key input variables - MinutiaeMatch, RidgeDensity, and WhorlPattern - and an output variable, Fingerprint Damage. I have gone with these variables as they each have a direct impact on the quality and clarity of fingerprints

- MinutiaeMatch: This input will assess the level of detail in the fingerprint which is crucial for matching accuracy.
- RidgeDensity: This input will measure the concentration of ridges, impacting the fingerprints distinctiveness.
- WhorlPattern: This input evaluates the clarity of whorl patterns, which is an important aspect in terms of uniqueness.

Design Considerations

The system's main function being fingerprint analysis, gave me the initial idea to use the trapezoidal membership function (trapmf). This choice was made as the nature of biometric data, especially fingerprints, can often exhibit uncertain boundaries and gradual changes with its features. Due to this system having real-world useability, the decision to focus on trapmf was thought of as trapmf is known to enable smooth transitions between various membership levels. However, also recognising the diversity of fingerprint patterns and the need for the system to be adaptable to varying data distributions, the Gaussian membership function (Gaussmf) was also considered. The gaussmf would be more useful in scenarios where fingerprint features could display a more natural, continuous distribution, highlighting the systems adaptability and commitment to precision. (See appendix Page 22 & 23).

The rule base of the system developed in tandem with the membership functions. Beginning with 30 base rules to cover the main possibilities (See appendix Page 21) for the initial testing, These rules were carefully selected as the foundation as they cover a wide spectrum of conditions, ensuring that the system is robust and reliable. As I develop the system through rigorous testing and validation, there would be potential to theoretically expand the rule base to around 150 rules

(See appendix Page 21). Expanding the system in this way would allow me to enhance the accuracy and adaptability of the FIS, creating a broader range of fingerprint qualities with more precision. Each rule, from the initial set to additions, is thoughtfully chosen to combine the conditions in a way that provides control over the process.

TECHNICAL DESCRIPTION

Fuzzy Inference sub-Systems

Fingerprint Quality FIS:

The following figure demonstrates a simple diagram on the application of the system, with three inputs (Shown in the red boxes on the left) going into the Fingerprint FIS (Shown in the blue box in the middle) and finally outputting the fingerprint damage score (Shown by the green box on the right.

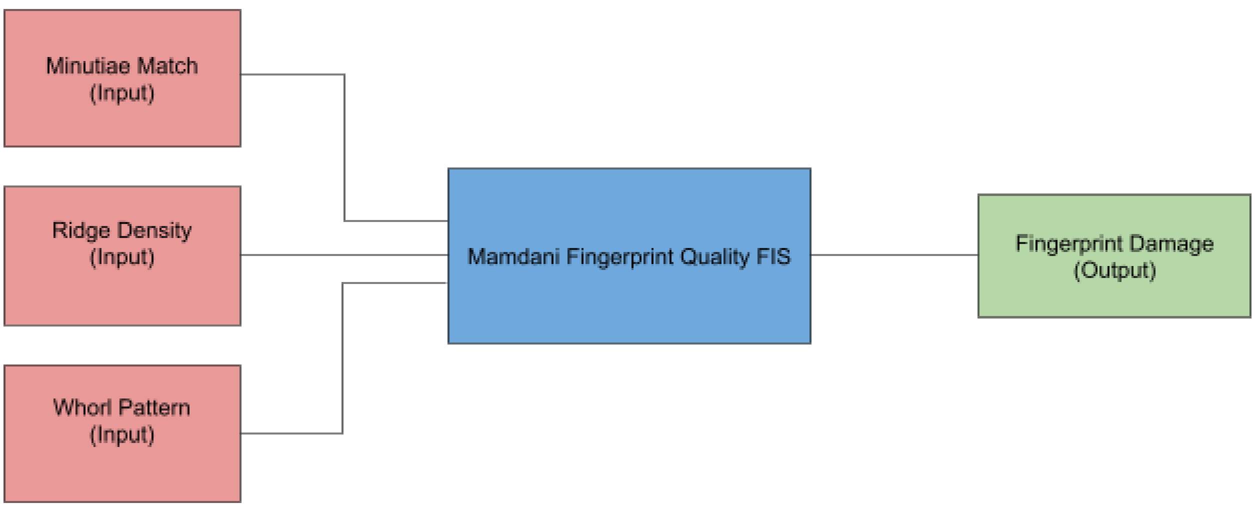

Figure 2: Diagram of the Fingerprint Quality FIS

Description of the Fingerprint Quality FIS

The Fingerprint Quality FIS will have three inputs (RedBox) and one output (GreenBox) which will be used to calculate the overall damage of the user's fingerprint. The inputs I have chosen for this FIS are best suited for calculating the overall well being of the fingerprint, as they capture all aspects of the fingerprints individual design.

Table 1: Breakdown of the inputs and output variables with their stated ranges and intervals.

Variable	Type of Variable	Range	Intervals
Minutiae Match	Input	0% - 100%	Very Low, Low, Medium, High, Very High
Ridge Density	Input	0 - 1	Sparse, Dense
Whorl Pattern	Input	0 - 1	Weak, Average, Strong
Fingerprint Damage	Output	0% - 100%	Poor, Decent, Average, Good, Excellent

Justification of the parameters chosen

For the Minutiae Match input variable, I have decided to choose a range of 0 - 100, as this variable will be conducted as a percentile (0% - 100%). When calculating the Minutiae on a fingerprint you take into consideration where ridge lines terminate. Having a degree of percentage allows me to give a complete spectrum ranging from no match (0%) to an exact match (100%).

The ridge density range is only between 0 and 1 as this variable refers to the ridges per unit area on a fingerprint. The scale 0 to 1 represents the normalised value and probability, with 0 outputting no ridges and 1 representing the highest density per area.

For Whorl patterns I have also gone with a 0 to 1 range scheme as this classification can be binary as the whorl patterns are either present or not present. The 0 to 1 range is used to indicate the clarity or prevalence of the pattern in the print, with 0 meaning no pattern and 1 indicating a clear and distinct one.

Similar to the Minutiae Match range I have chosen to use a percentile 0% - 100% range for the output (Fingerprint Damage). This is simply because the percentage score will determine how damaged the fingerprint is. Choosing this percentile scoring system over a more binary one like 0 to 1 allows for me to have a broader horizon when outputting the damage score.

Future Implementation Idea

The following figure demonstrates a simple example on a future iteration of the system, with a new total of five inputs (Shown in the red boxes on the left) going into the Fingerprint FIS and the new Environment FIS (Shown in the blue box in the middle) then outputting the fingerprint damage score and Fingerprint score (Shown by the green box on the right), these outputs then filter into a third FIS called Authorisation which finally sends out a final output called Authorisation.

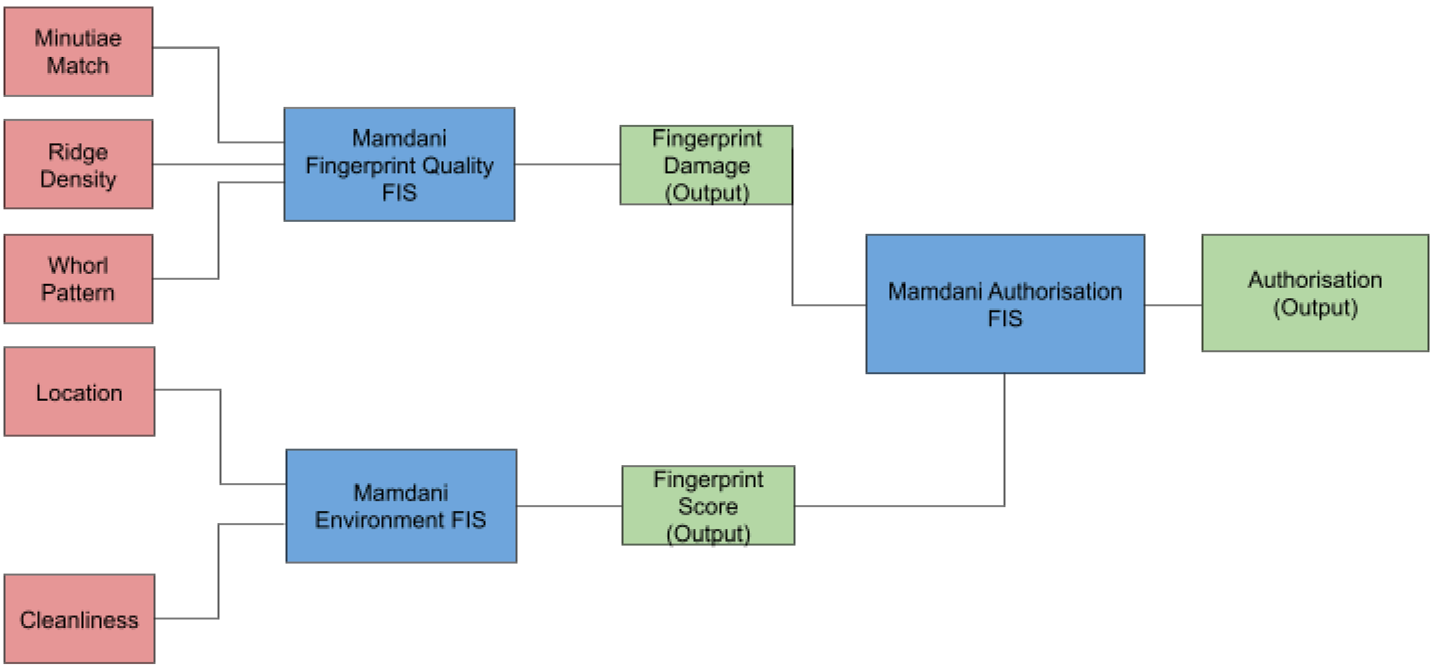

Figure 2: Diagram for the future iterations of the Fingerprint Quality FIS with extra variables.

Table 2: Breakdown of the new inputs and output variables with their stated ranges and intervals.

Variable	**Type of Variable**	**Range**	**Intervals**
Cleanliness	Input	0 - 100	Rotten, Dirty, Neutral, Clean, Spotless
Location	Input	0 - 1	Indoor, Outdoor
Fingerprint Score	Output	0 - 100	Poor, Decent, Average, Good, Excellent
Fingerprint Score	Input	0 - 100	Poor, Decent, Average, Good, Excellent
Fingerprint Damage	Input	0 - 100	Poor, Decent, Average, Good, Excellent
Authorisation	Output	0 - 1	Granted, Denied

Justification of the parameters chosen

If I were to add the Cleanliness input variable, I would go with a range of 0 - 100, as this would allow for a percentage scale. Having the range set as a percentile would give me the access to accurately change the interval locations (e.g. 0% = Rotten but 12% = Dirty) something that a more binary oriented scale would not allow.

The Location range would only be between 0 and 1 as this variable would refer to whether or not an individual is Outside or Inside, only having 2 intervals would allow for me to have a simpler range with the use of binary outputs (0 being outside and 1 being inside). If you wanted to make this variable more accurate you could create a bigger range that classifies what geographical location you are in rather than just indoors or outdoors.

Fingerprint Score would be similar to the fingerprint damage interval mentioned above, as once again it is a score pre determined by its inputs. Having the 0 - 100 range would allow for me to have a detailed gradation of the score, as the intervals translate the score into a more qualitative assessment.

Authorisations range would be similar to Location with it being more binary based, as you are either Granted or Denied access, due to this I would go with a 0 - 1 range with 0 being Denied and 1 being Granted.

EXPERIMENTAL DESIGN & EVALUATION

Data and Test Subjects

Focusing on three age-based groups, for the data for the FIS application. This strategy ensures a diverse and realistic representation of fingerprint variations influenced by age, health and lifestyle factors:

1. Group 1 (Age 71+): Individuals like a retired nurse with arthritis and ex-military personnel.
2. Group 2 (Age 41-70): Individuals like long-term smokers and construction workers.
3. Group 3 (Age 20-40): Younger individuals, like university students and a health-conscious yoga instructor.

The data for these subjects are estimated, considering the limited capabilities with acquiring biometric data. These estimated are informed by various sources like Marks (2007) in the impact of smoking on fingerprints, studies on age-related variations in fingerprint recognition, and research by Drahansky et al. (2012) and Dolezel et al (2012) on the influence of skin diseases and conditions on fingerprint quality and recognition. Using this approach ensures that the system is tested against a wide array of realistic conditions. (See Appendix 24 - 26 for full subject report).

General Notes

Prior to the testing, the FIS for fingerprint quality assessment underwent key refinements. A noticeable change was the consideration between the use of a Gaussian membership function alongside the trapezoidal ones in order to better represent the continuous nature of the fingerprints features. The rule base is initially set at 30, but was considered to be expanded up to 150 rules, depending on the insights I gain during my extensive tests. This potential expansion is aimed to help enhance the system's granularity and accuracy. The input data used within the system is an estimation due to equipment and time limitations, however, I have ensured that the test subjects data is reflected within a wide variety of realistic scenarios. System flexibility is also imperative, with future enhancements such as integrating advanced algorithms or adding new input variables (See figures 4 & 5), to adapt to evolving needs in fingerprint analysis.

Testing

Test 1

Results & Analysis of Test 1

Test 1 of the FIS for my system incorporated a diverse set of subject data, aimed at ensuring an unbiased and comprehensive evaluation. Upon applying the real-world inspired data, the system's outputs were closely marked against the expected outcomes. The results showed a notable error with the concentration of output values being within the 70-90 range (Average - Excellent), this suggested a potential bias towards the higher damage assessments. While this high range dominance indicated a level of consistency, it also pointed to a possible calibration requirement for a more diverse and balanced output.

The comparison between the actual and expected outcomes showed alignment in a couple instances, mainly within the middle-aged group when using Bisector and Centroid but not with LOM, SOM or MOM. This did allow for some confirmation with the system's capacity for accurate outputs, however, the young and elderly groups exhibited greater errors. The SOM defuzzification method particularly stood out, as it helped deliver the most accurate match to the expected outcomes, providing some lower scores for the elderly and throughout in general, also having the most connections to my predicted outcomes. For the next test, adjustments to the membership function parameters and rule base will be considered to try and address the observed output range errors and improve the overall accuracy. See page 29 -32 in Appendix for results.

The data subject profiles and tables can be found on pages 25 -28 in the Appendix

Defuzzification:

There were a total of 5 defuzzification methods that we used to help calculate various crisp outputs. The results for these methods can be found in the Appendix, on pages 29 & 30.

The comparison table between my chosen expected outcomes and the actual outcomes can be found on pages 31 & 32 in the Appendix.

Test 2

Changes

In order to change the output data from being heavily high-range based previously seen in the first test, significant refinements were made. The intervals for the three inputs were adjusted to better align with the observed data trends, aiming for a more sensitive and precise evaluation. The rule base was also expanded with additional rules.

Expected Outcomes

Test 2s expected outcomes tables were also adjusted to reflect the changes in the FIS configuration. See page 36 in the appendix.

Results & Analysis of Test 2

In test 2, the testing results were again not perfect. However, it demonstrated a discernible improvement over test 1 in terms of the distribution of the outputs, with these values spreading more evenly across the expected range, compared to clustering in the upper categories. THe actual outcomes did display better harmony with the modified expected results, particularly the middle-aged and young subject groups (with the elderly group still having a few anomalies). This suggests that the adjustments to the membership functions and rule base had effectively enhanced the systems ability between the subtle variations.

While some errors persisted, they were reduced compared to the data received in test 1, suggesting that the direction of the changes I had made were well-founded. The FISs' performance, especially when considering the Centroid method of defuzzification, is reflecting a much more accurate representation of the diverse data. See page 27 -40 in Appendix for results.

Test 3

Final Changes

In preparation for the final test, I decided to play around with the rule base and membership functions. After looking through the rule base for a final time I realised I had neglected to include various rules for the Poor and Decent outputs compared to the number of rules for the other three. I decided to add in some extra rules alongside lowering the weight of the rules that were outputting for the Excellent and Good sections in order to try and correct the high-range bias observed in the previous two tests. The membership functions were also given a final recalibration, narrowing down the ranges for Medium and High quality categories to reduce the overestimation and high-ranges. All of these changes were made after carefully observing all of the errors derived from the prior two tests as I wanted to ensure the system created more accurate and trustworthy outputs. Modifications to the rule base and membership functions can be found on pages 41-44 of the Appendix.

Results & Analysis of Test 3

The 3rd and final test demonstrated significant improvements in the accuracy and diversity of the output. I decided on using the Mean of Maximum (MOM) as my defuzzification option, as I had found that it provided a balance between the extremes of LOM and SOM. The outputs now exhibit a distribution that more closely mirrors the real-world data and my predictions. See Page 45 in the Appendix for a short test between the three. See page 46 - 48 in the appendix for results.

Final System Configuration

This can be found on pages 49 - 54 in the Appendix, includes the latest and final versions of the rule base, fuzzy sets, variables and membership functions.

CRITICAL REFLECTION

Reflecting on the development journey for the Fuzzy Inference System (FIS) of my fingerprint analysis. The primary challenge was the difficult balancing of the precision of biometric data with the inherent fuzziness that such data exhibits. My goal was to create a system that not only outputs the damage score of your fingerprint but also improves the accuracy of biometric authentication through fingerprints. I also hope that after further development this application can be seamlessly placed into existing security frameworks.

The literature review helped to reinforce the notion that the application of fuzzy logic could be a game-changer in handling the uncertainties of biometric data. As it provided a theoretical foundation for this project, highlighting the potential of fuzzy logic to help elevate the robustness and precision of biometric systems, especially in the most common use fingerprint recognition. This research phase was particularly informative as not only am I working with biometric data for this project but also in my Final Development project over the course of this year, being able to increase my knowledge and highlighting the adaptability of fuzzy logic in managing the complexities has allowed me to see various ways I can incorporate this into my own final project.

Each design choice, from the selection of inputs and membership functions to the formulation of rules, was a deliberate step towards developing a capable system for analysis and interpretation. The process of testing and refining the system was a critical step, as it helped reveal the need for significant changes and additions.

The adjustments made post-test 1 and test 2 helped paint the trajectory of the system, with each change getting closer to my main goal. The critical moment came with the development of Test 3, which showcased the final design of my FIS. The decision to utilise the MOM defuzzification method marked a turning point, where the system's outputs began to reflect the diversity of the fingerprint data. This choice was not made sporadically; it was the result of rigorous testing and critical understanding of the process's impact on the crisp values.

The knowledge and insight gained from this project extend beyond just technical proficiency as they have helped me gain a broader perspective into the role of fuzzy logic in biometric applications.

CONCLUSION

In conclusion, the development of the FIS system has been an amazing journey, blending the intricate biometric data with the capabilities of fuzzy logic. This report has documented the evolution of a theoretical concept into a practical and sophisticated tool, highlighted by a rigorous process of research, design, testing and refinement.

The system has proven to be adaptable and robust, with its final application displaying a marked improvement in its accuracy, as evidenced by the comprehensive testing process. The success of this FIS is not solely in its technological advancements but also in its understanding and application of fuzzy logic to enhance biometric authentication.

Although I am happy with how my design and system is, there is obviously room for future improvements and development. The next steps would involve obtaining real biometric data from a larger group of applicants to further validate and refine the FIS. The reliance on estimated data, while necessary due to constraints, is a limitation that future iterations must address to ensure an even more robust and accurate system performance. Acquiring actual biometric samples would allow for a more precise calibration of the system's variables and rules, enhancing the authenticity of the authentication process. Additionally, exploring the integration of new variables such as cleanliness and location, as outlined in the Further Implementations section, could create new directions for the application as it takes in more complex and varied environments.

The opportunity to delve into an area of personal interest has been exceptionally interesting. The process of being able to develop this FIS has deepened my understanding of not only the intricate details of biometrics but also the potential of Fuzzy Logic within this domain. This project creates an insight into the untapped potential of fuzzy logic in various applications that leaves me eager to explore its further applications.

Acknowledgements

I extend my gratitude to my lecturer, whose expertise and guidance have been the foundation for the development of this project. Their profound knowledge and insights have shaped my understanding and approach to this project. I would also like to acknowledge the support and advice from my lab tutor, whose patience and expertise in the practical aspects of development were instrumental in the realisation of this FIS.

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APPENDICES

Variable Declarations:

```
% Define input variables for Minutiae Match
fisQuality = addvar(fisQuality,'input','MinutiaeMatch',[0 100]);
% Define membership functions for Minutiae Match
fisQuality = addmf(fisQuality,'input',1,'Very Low','trapmf',[0 0 10 20]);
fisQuality = addmf(fisQuality,'input',1,'Low','trapmf',[10 20 30 40]);
fisQuality = addmf(fisQuality,'input',1,'Medium','trapmf',[30 50 70 90]);
fisQuality = addmf(fisQuality,'input',1,'High','trapmf',[80 100 100 100]);
fisQuality = addmf(fisQuality,'input',1,'Very High','trapmf',[90 100 100 100]);

% Define input variables for Ridge Density
fisQuality = addvar(fisQuality,'input','RidgeDensity',[0 1]);
% Define membership functions for Ridge Density
fisQuality = addmf(fisQuality,'input',2,'Sparse','trapmf',[0 0 0.3 0.5]);
fisQuality = addmf(fisQuality,'input',2,'Dense','trapmf',[0.4 0.7 1 1]);

% Define input variables for Whorl Pattern
fisQuality = addvar(fisQuality,'input','WhorlPattern',[0 1]);
% Define membership functions for Whorl Pattern
fisQuality = addmf(fisQuality,'input',3,'Weak','trapmf',[0 0 0.3 0.5]);
fisQuality = addmf(fisQuality,'input',3,'Average','trapmf',[0.4 0.5 0.6 0.7]);
fisQuality = addmf(fisQuality,'input',3,'Strong','trapmf',[0.5 0.7 1 1]);

% Define output variable for Fingerprint Quality
fisQuality = addvar(fisQuality,'output','Fingerprint Damage',[0 100]);
% Define membership functions for Fingerprint Damage
fisQuality = addmf(fisQuality,'output',1,'Poor','trapmf',[0 0 20 40]);
fisQuality = addmf(fisQuality,'output',1,'Decent','trapmf',[30 40 60 70]);
fisQuality = addmf(fisQuality,'output',1,'Average','trapmf',[60 70 80 90]);
fisQuality = addmf(fisQuality,'output',1,'Good','trapmf',[80 90 100 100]);
fisQuality = addmf(fisQuality,'output',1,'Excellent','trapmf',[90 100 100 100]);
```

Rule Bases

```
rule1 = [1 1 1 1 1 1];
rule2 = [1 1 2 1 1 1];
rule3 = [1 1 3 2 1 1];
rule4 = [1 2 1 2 1 1];
rule5 = [1 2 2 2 1 1];
rule6 = [1 2 3 3 1 1];
rule7 = [2 1 1 2 1 1];
rule8 = [2 1 2 2 1 1];
rule9 = [2 1 3 3 1 1];
rule10 = [2 2 1 3 1 1];
rule11 = [2 2 2 3 1 1];
rule12 = [2 2 3 4 1 1];
rule13 = [3 1 1 3 1 1];
rule14 = [3 1 2 3 1 1];
rule15 = [3 1 3 4 1 1];
rule16 = [3 2 1 4 1 1];
rule17 = [3 2 2 4 1 1];
rule18 = [3 2 3 5 1 1];
rule19 = [4 1 1 4 1 1];
rule20 = [4 1 2 4 1 1];
rule21 = [4 2 1 5 1 1];
rule22 = [4 2 2 5 1 1];
rule23 = [4 2 3 5 1 1];
rule24 = [5 1 1 5 1 1];
rule25 = [5 1 2 5 1 1];
rule26 = [5 1 3 5 1 1];
rule27 = [5 2 1 5 1 1];
rule28 = [5 2 2 5 1 1];
rule29 = [5 2 3 5 1 1];
rule30 = [1 2 3 2 1 1];
```

(MF) = Membership Function

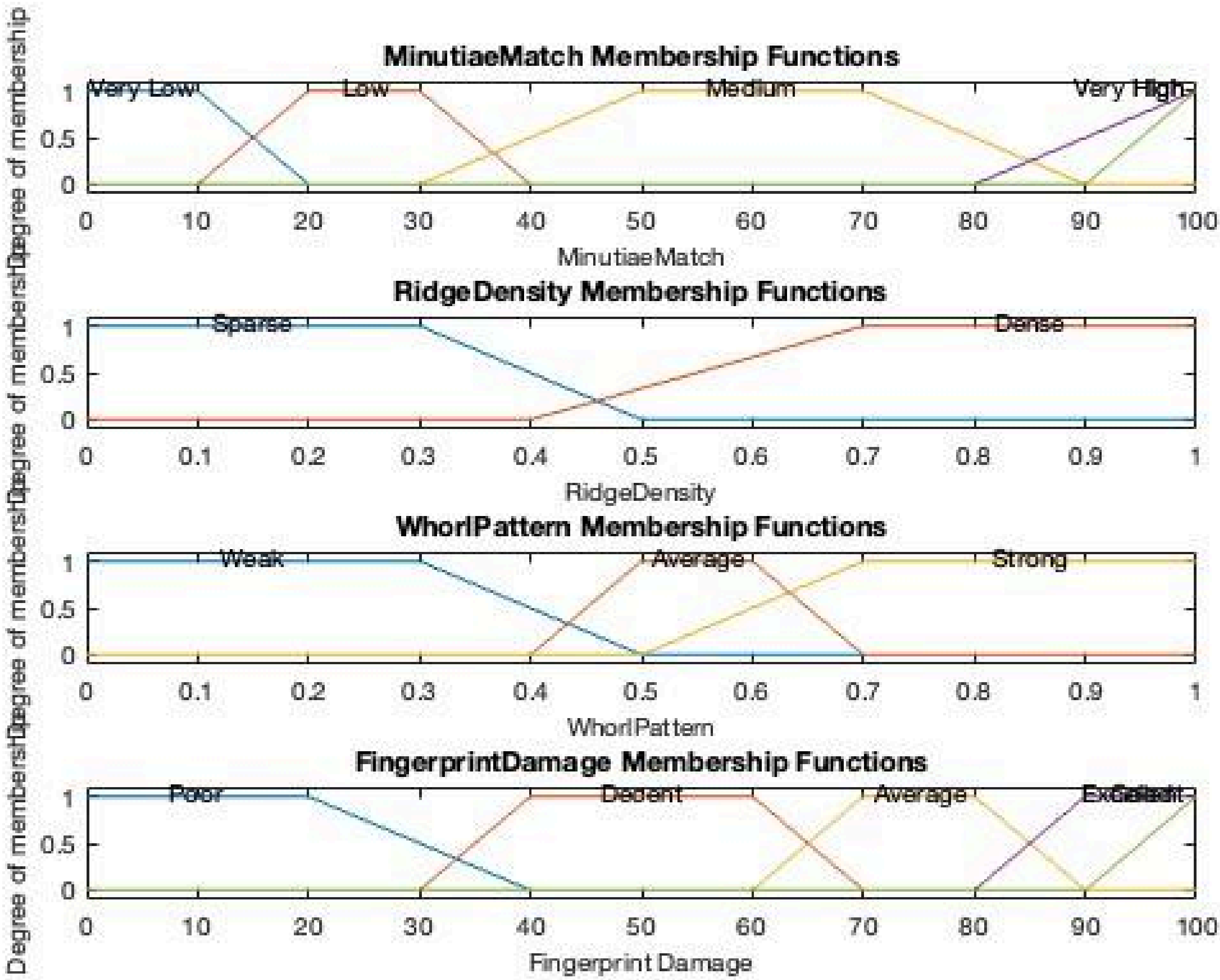
Base Rules: (MF)MinutaieMatch ⨉ (MF)RidgeDensity ⨉ (MF)WhorlPattern

Number of Base Rules: 5 ⨉ 2 ⨉ 3 = 30

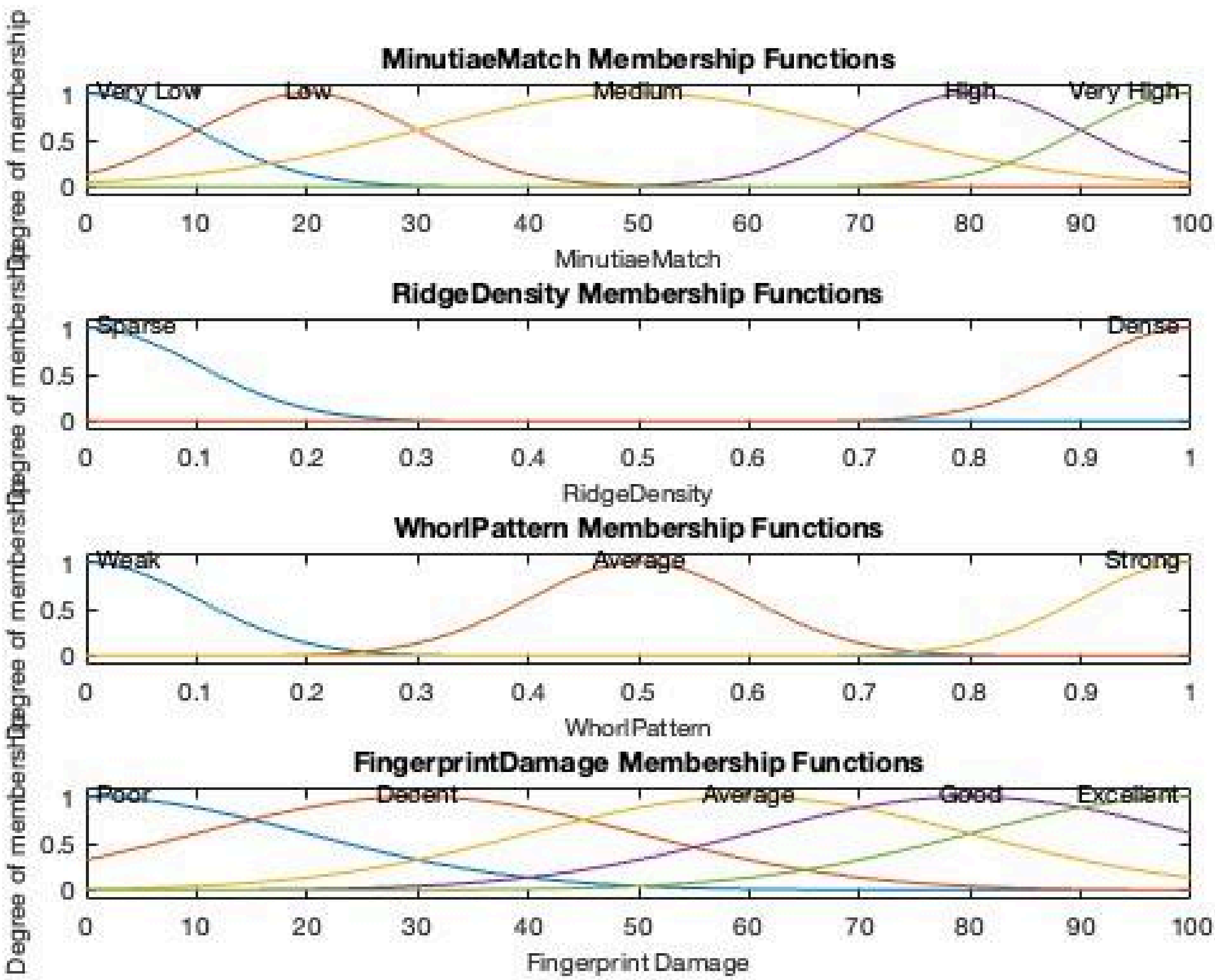
Max Rules: (MF)MinutaieMatch ⨉ (MF)RidgeDensity ⨉ (MF)WhorlPattern ⨉ (MF)Fingerprint Damage

Number of Base Rules: 5 ⨉ 2 ⨉ 3 ⨉ 5= 150

Fuzzy Set Distribution TrapMF:



Fuzzy Set Distribution GaussMF:



Data and Test Subjects Estimates

Group 1: Age 71+

Person A (74, Female): Retired nurse, has arthritis, avid gardener.

- MinutiaeMatch: 30
- RidgeDensity: 0.4
- WhorlPattern: 0.5

Person B (76, Male): Ex-military, occasional smoker, enjoys woodworking.

- MinutiaeMatch: 25
- RidgeDensity: 0.5
- WhorlPattern: 0.4

Person C (78, Female): Former teacher, diabetes, enjoys knitting.

- MinutiaeMatch: 35
- RidgeDensity: 0.45
- WhorlPattern: 0.55

Person D (80, Male): Retired chef, history of eczema, enjoys painting.

- MinutiaeMatch: 20
- RidgeDensity: 0.3
- WhorlPattern: 0.4

Person E (82, Female): Retired librarian, Birth defect, enjoys reading and writing.

- MinutiaeMatch: 40
- RidgeDensity: 0.3
- WhorlPattern: 0.6

Group 2: Age 41 - 70

Person F (45, Female): Office worker, long-term smoker.

- MinutiaeMatch: 60
- RidgeDensity: 0.35
- WhorlPattern: 0.5

Person G (50, Male): Construction worker, no known health issues.

- MinutiaeMatch: 55
- RidgeDensity: 0.7
- WhorlPattern: 0.7

Person H (55, Female): High school teacher, suffers from psoriasis.

- MinutiaeMatch: 50
- RidgeDensity: 0.4
- WhorlPattern: 0.45

Person I (65, Male): Retired banker, has hypertension.

- MinutiaeMatch: 45
- RidgeDensity: 0.5
- WhorlPattern: 0.55

Person J (70, Female): Yoga instructor, vegan, very health-conscious.

- MinutiaeMatch: 65
- RidgeDensity: 0.65
- WhorlPattern: 0.7

Group 3: Age 20 - 40

Person K (25, Male): University student, avid gamer, healthy.

- MinutiaeMatch: 80
- RidgeDensity: 0.75
- WhorlPattern: 0.8

Person L (30, Female): Nurse, allergic dermatitis, enjoys outdoor sports.

- MinutiaeMatch: 70
- RidgeDensity: 0.6
- WhorlPattern: 0.65

Person M (35, Male): Chef, occasional smoker, enjoys cycling.

- MinutiaeMatch: 75
- RidgeDensity: 0.7
- WhorlPattern: 0.76

Person N (38, Female): Freelance writer, history of dry skin, yoga enthusiast.

- MinutiaeMatch: 78
- RidgeDensity: 0.68
- WhorlPattern: 0.7

Person O (40, Male): IT professional, healthy, enjoys rock climbing.

- MinutiaeMatch: 85
- RidgeDensity: 0.8
- WhorlPattern: 0.85

Test 1:

Test Data:

Test No.	Subject Group	Minutiae Match	Ridge Density	Whorl Pattern
1	Elderly	30	0.4	0.5
2	Elderly	25	0.5	0.4
3	Elderly	35	0.45	0.55
4	Elderly	20	0.3	0.4
5	Elderly	40	0.3	0.6
6	Middle Aged	60	0.35	0.5
7	Middle Aged	55	0.7	0.7
8	Middle Aged	50	0.4	0.45
9	Middle Aged	45	0.5	0.55
10	Middle Aged	65	0.65	0.7
11	Young	80	0.75	0.8
12	Young	70	0.6	0.65
13	Young	75	0.7	0.76
14	Young	78	0.68	0.7
15	Young	85	0.8	0.85

Expected Outcomes:

Test No.	Fingerprint Damage
1	Poor
2	Poor
3	Poor
4	Poor
5	Poor
6	Decent
7	Average
8	Poor
9	Decent
10	Average
11	Excellent
12	Good
13	Excellent
14	Good
15	Excellent

	Centroid	Bisector
Test No.	Fingerprint Damage	Fingerprint Damage
1	50	50
2	75	75
3	79.89	79
4	57.65	57
5	81.47	81
6	75	75
7	97	97
8	75	75
9	91.07	91
10	96.88	97
11	96.38	96
12	91.97	92
13	96.78	97
14	96.56	97
15	95.87	96

Defuzzification Values (Centroid vs Bisector):

LOM vs SOM vs MOM:

	LOM	SOM	MOM
Test No.	Fingerprint Damage	Fingerprint Damage	Fingerprint Damage
1	65	35	50
2	86	64	75
3	86	64	75
4	67	33	50
5	100	65	82.5
6	82	68	75
7	100	100	100
8	85	65	75
9	100	84	92
10	100	99	99.5
11	100	95	97.5
12	100	97	98.5
13	100	98	99
14	100	96	98
15	100	93	96.5

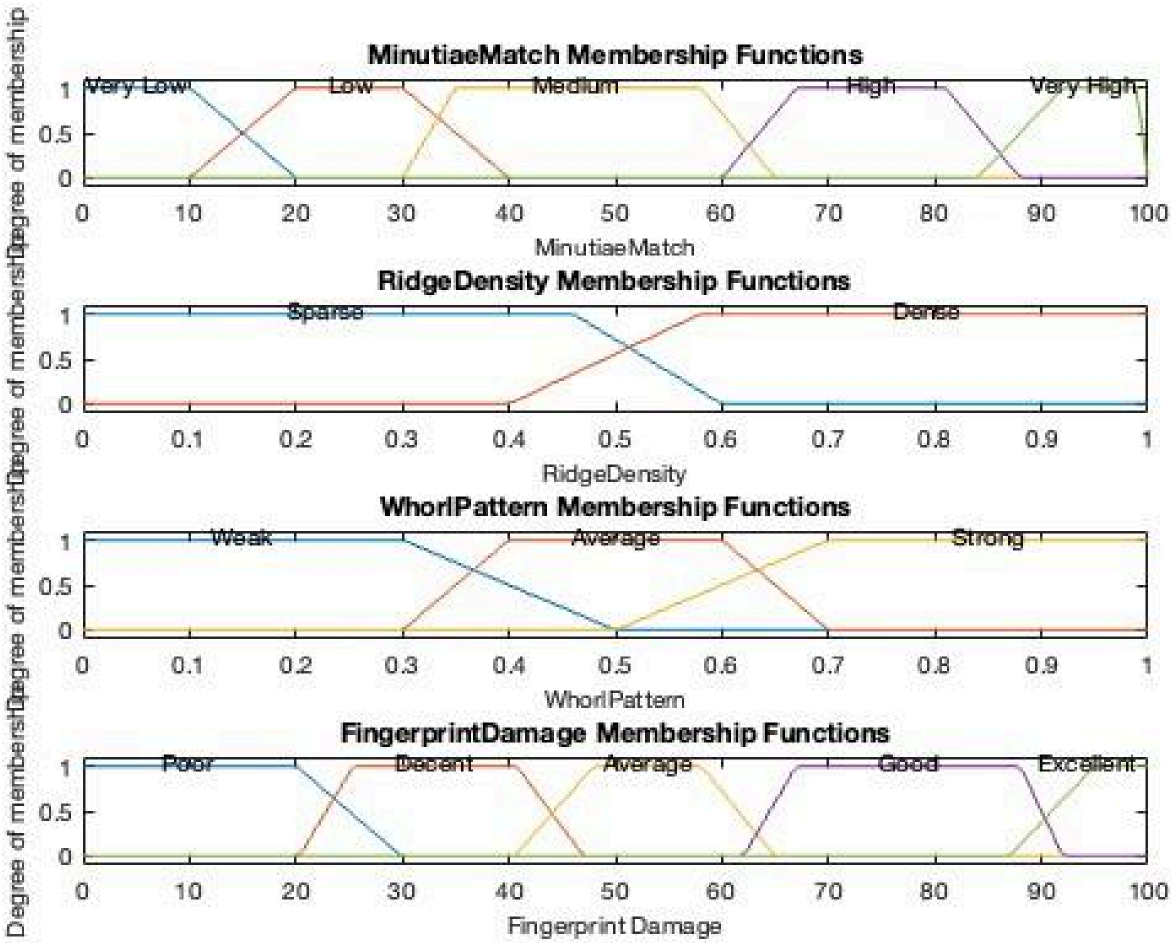
Expected Outcomes Vs Actual Outcomes

	Centroid	Bisector
Test No.	Fingerprint Damage	Fingerprint Damage
1	FALSE	FALSE
2	FALSE	FALSE
3	FALSE	FALSE
4	FALSE	FALSE
5	FALSE	FALSE
6	TRUE	TRUE
7	TRUE	TRUE
8	FALSE	FALSE
9	FALSE	FALSE
10	FALSE	FALSE
11	FALSE	FALSE
12	TRUE	TRUE
13	FALSE	TRUE
14	TRUE	FALSE
15	FALSE	FALSE

Expected Outcomes Vs Actual Outcomes

	LOM	SOM	MOM
Test No.	Fingerprint Damage	Fingerprint Damage	Fingerprint Damage
1	FALSE	TRUE	FALSE
2	FALSE	FALSE	FALSE
3	FALSE	FALSE	FALSE
4	FALSE	TRUE	FALSE
5	FALSE	FALSE	FALSE
6	FALSE	FALSE	TRUE
7	FALSE	FALSE	FALSE
8	FALSE	FALSE	FALSE
9	FALSE	FALSE	FALSE
10	FALSE	FALSE	FALSE
11	TRUE	FALSE	TRUE
12	FALSE	FALSE	FALSE
13	TRUE	TRUE	TRUE
14	FALSE	TRUE	FALSE
15	TRUE	FALSE	FALSE

New Fuzzy Distributions



Changing of intervals

```
% Define input variables for Minutiae Match
fisQuality = addvar(fisQuality,'input','MinutiaeMatch',[0 100]);
% Define membership functions for Minutiae Match
fisQuality = addmf(fisQuality,'input',1,'Very Low','trapmf',[0 0 10 20]);
fisQuality = addmf(fisQuality,'input',1,'Low','trapmf',[10 20 30 40]);
fisQuality = addmf(fisQuality,'input',1,'Medium','trapmf',[30 35 58 65]);
fisQuality = addmf(fisQuality,'input',1,'High','trapmf',[60 67 81 88]);
fisQuality = addmf(fisQuality,'input',1,'Very High','trapmf',[84 92 99 100]);

% Define input variables for Ridge Density
fisQuality = addvar(fisQuality,'input','RidgeDensity',[0 1]);
% Define membership functions for Ridge Density
fisQuality = addmf(fisQuality,'input',2,'Sparse','trapmf',[0 0 0.46 0.6]);
fisQuality = addmf(fisQuality,'input',2,'Dense','trapmf',[0.4 0.58 1 1]);

% Define input variables for Whorl Pattern
fisQuality = addvar(fisQuality,'input','WhorlPattern',[0 1]);
% Define membership functions for Whorl Pattern
fisQuality = addmf(fisQuality,'input',3,'Weak','trapmf',[0 0 0.3 0.5]);
fisQuality = addmf(fisQuality,'input',3,'Average','trapmf',[0.3 0.4 0.6 0.7]);
fisQuality = addmf(fisQuality,'input',3,'Strong','trapmf',[0.5 0.7 1 1]);

% Define output variable for Fingerprint Quality
fisQuality = addvar(fisQuality,'output','Fingerprint Damage',[0 100]);
% Define membership functions for Fingerprint Damage
fisQuality = addmf(fisQuality,'output',1,'Poor','trapmf',[0 0 20 29.9]);
fisQuality = addmf(fisQuality,'output',1,'Decent','trapmf',[20.3 25.4 40.7 47]);
fisQuality = addmf(fisQuality,'output',1,'Average','trapmf',[40.5 48 58 65]);
fisQuality = addmf(fisQuality,'output',1,'Good','trapmf',[62 67 88 92]);
fisQuality = addmf(fisQuality,'output',1,'Excellent','trapmf',[87 95 100 100]);
```

Additional Rules

```
rule3 = [1 1 3 2 1 1]; %
rule4 = [1 2 1 2 1 1]; %
rule5 = [1 2 2 2 1 1]; %
rule6 = [1 2 3 3 1 1]; %
rule7 = [2 1 1 2 1 1]; %
rule8 = [2 1 2 2 1 1]; %
rule9 = [2 1 3 3 1 1]; %
rule10 = [2 2 1 3 1 1]; %
rule11 = [2 2 2 3 1 1]; %
rule12 = [2 2 3 4 1 1]; %
rule13 = [3 1 1 3 1 1]; %
rule14 = [3 1 2 3 1 1]; %
rule15 = [3 1 3 4 1 1]; %
rule16 = [3 2 1 4 1 1]; %
rule17 = [3 2 2 4 1 1]; %
rule18 = [3 2 3 5 1 1]; %
rule19 = [4 1 1 4 1 1]; %
rule20 = [4 1 2 4 1 1]; %
rule21 = [4 2 1 5 1 1]; %
rule22 = [4 2 2 5 1 1]; %
rule23 = [4 2 3 5 1 1]; %
rule24 = [5 1 1 5 1 1]; %
rule25 = [5 1 2 5 1 1]; %
rule26 = [5 1 3 5 1 1]; %
rule27 = [5 2 1 5 1 1]; %
rule28 = [5 2 2 5 1 1]; %
rule29 = [5 2 3 5 1 1]; %
rule30 = [1 2 3 2 1 1]; %
rule31 = [1 1 2 2 1 1];
rule32 = [1 1 3 3 1 1];
rule33 = [1 2 1 2 1 1];
rule34 = [1 2 2 2 1 1];
rule35 = [1 2 3 3 1 1];
rule36 = [2 1 1 2 1 1];
rule37 = [2 1 2 3 1 1];
rule38 = [2 1 3 3 1 1];
rule39 = [2 2 1 3 1 1];
rule40 = [2 2 2 3 1 1];
rule41 = [2 2 3 4 1 1];
rule42 = [3 1 1 3 1 1];
rule43 = [3 1 2 3 1 1];
rule44 = [3 1 3 4 1 1];
rule45 = [3 2 1 4 1 1];
rule46 = [3 2 2 4 1 1];
rule47 = [3 2 3 5 1 1];
rule48 = [4 1 1 4 1 1];
rule49 = [4 1 2 4 1 1];
rule50 = [4 1 3 5 1 1];
```

Test 2:

Expected Outcomes:

Test No.	Fingerprint Damage
1	Decent
2	Poor
3	Average
4	Decent
5	Decent
6	Average
7	Good
8	Good
9	Good
10	Good
11	Excellent
12	Good
13	Excellent
14	Excellent
15	Good

Defuzzification Values (Centroid vs Bisector):

	Centroid	Bisector
Test No.	Fingerprint Damage	Fingerprint Damage
1	42.1	41
2	42.28	42
3	58.8	58
4	42.1	41
5	63.66	60
6	52.82	53
7	95.5	96
8	52.8	53
9	67.8	67
10	95	95
11	95.5	96
12	95.11	95
13	95.47	96
14	95.47	96
15	94.58	95

LOM vs SOM vs MOM:

	LOM	SOM	MOM
Test No.	Fingerprint Damage	Fingerprint Damage	Fingerprint Damage
1	58	26	41.46
2	59	24	41.,27
3	59	46	52.5
4	58	26	41.46
5	58	48	53
6	60	46	53
7	100	95	97.5
8	58	48	53
9	59	46	52.5
10	100	93	96.5
11	100	95	97.5
12	100	94	97
13	100	95	97.5
14	100	95	97.5
15	100	91	95.5

	Centroid	Bisector
Test No.	Fingerprint Damage	Fingerprint Damage
1	TRUE	TRUE
2	FALSE	FALSE
3	TRUE	TRUE
4	TRUE	TRUE
5	FALSE	FALSE
6	TRUE	TRUE
7	FALSE	FALSE
8	FALSE	FALSE
9	TRUE	TRUE
10	FALSE	FALSE
11	TRUE	TRUE
12	FALSE	FALSE
13	TRUE	TRUE
14	TRUE	TRUE
15	FALSE	FALSE

Expected Outcomes Vs Actual Outcomes

Expected Outcomes Vs Actual Outcomes

	LOM	SOM	MOM
Test No.	Fingerprint Damage	Fingerprint Damage	Fingerprint Damage
1	FALSE	TRUE	TRUE
2	FALSE	TRUE	FALSE
3	TRUE	TRUE	TRUE
4	FALSE	TRUE	TRUE
5	FALSE	FALSE	FALSE
6	TRUE	TRUE	TRUE
7	FALSE	FALSE	FALSE
8	FALSE	FALSE	FALSE
9	FALSE	FALSE	FALSE
10	FALSE	FALSE	FALSE
11	TRUE	TRUE	TRUE
12	FALSE	FALSE	FALSE
13	TRUE	TRUE	TRUE
14	TRUE	TRUE	TRUE
15	FALSE	TRUE	FALSE

Additional / Changes to Rules

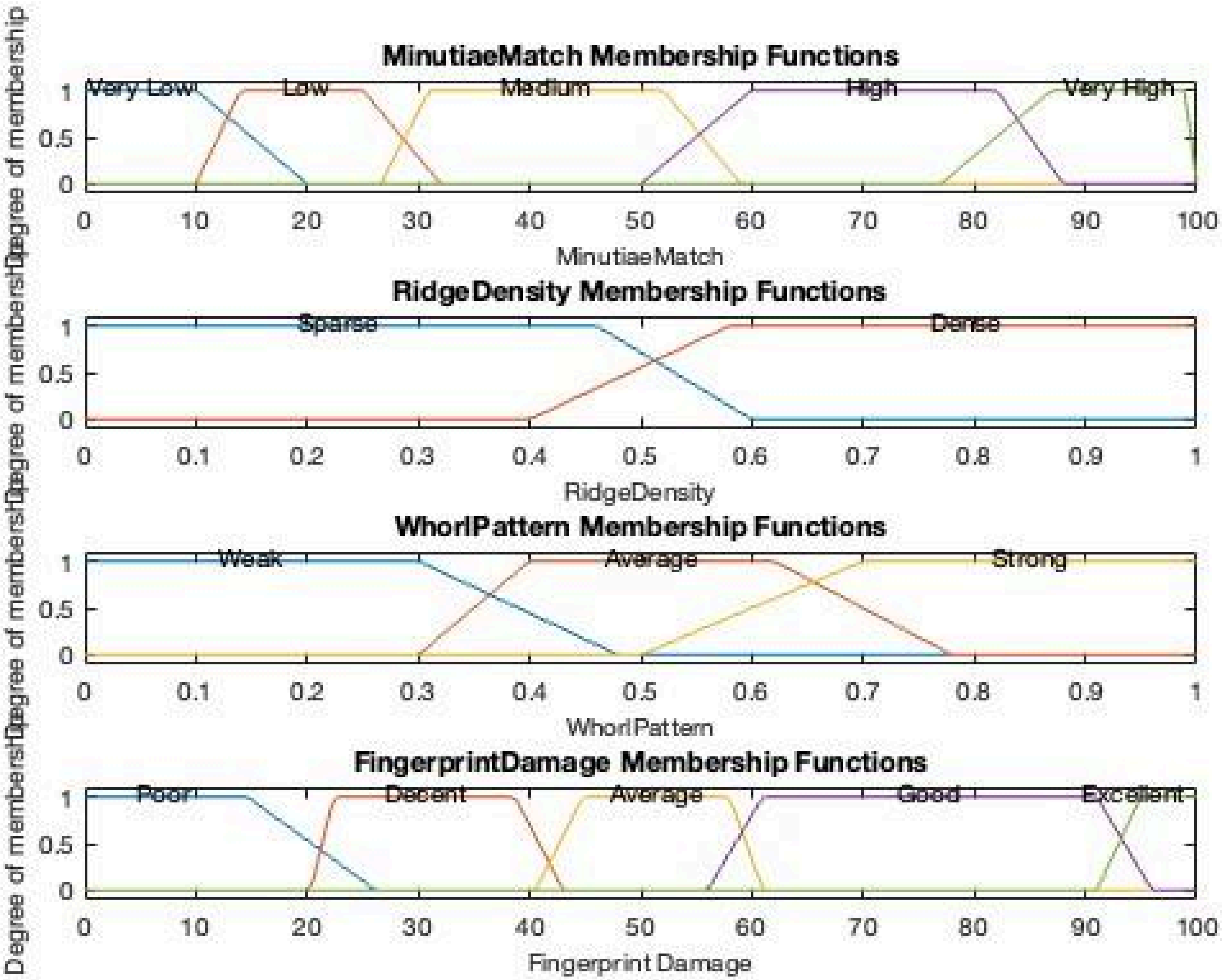
```
rule15 = [3 1 3 4 0.8 1];
rule16 = [3 2 1 4 0.8 1];
rule17 = [3 2 2 4 0.8 1];
rule18 = [3 2 3 5 0.7 1];
rule19 = [4 1 1 4 0.7 1];
rule20 = [4 1 2 4 0.7 1];
rule21 = [4 2 1 5 0.7 1];
rule22 = [4 2 2 5 0.75 1]
rule23 = [4 2 3 5 0.7 1];
rule24 = [5 1 1 5 0.7 1];
rule25 = [5 1 2 5 0.7 1];
rule26 = [5 1 3 5 0.7 1];
rule27 = [5 2 1 5 0.8 1];
rule28 = [5 2 2 5 0.8 1];
rule29 = [5 2 3 5 0.8 1];
rule30 = [1 2 3 2 0.8 1];
```

```
rule51 = [4 2 1 5 1 1];
rule52 = [4 2 2 5 1 1];
rule53 = [4 2 3 5 1 1];
rule54 = [5 1 1 5 1 1];
rule55 = [5 1 2 5 1 1];
rule56 = [5 1 3 5 1 1];
rule57 = [5 2 1 5 1 1];
rule58 = [5 2 2 5 1 1];
rule59 = [5 2 3 5 1 1];
rule60 = [1 1 1 1 1 1];
rule61 = [1 2 2 2 1 1];
rule62 = [2 1 3 2 1 1];
rule63 = [2 2 1 3 1 1];
rule64 = [3 1 2 3 1 1];
rule65 = [3 2 3 4 1 1];
rule66 = [4 1 1 4 1 1];
rule67 = [4 2 2 5 1 1];
rule68 = [5 1 3 5 1 1];
rule69 = [1 2 3 2 1 1];
rule70 = [5 2 1 5 1 1];
rule71 = [1 2 1 1 1 1];
rule72 = [2 1 1 1 1 1];
rule73 = [2 1 2 1 1 1];
rule74 = [2 2 1 1 1 1];
rule75 = [3 1 1 1 1 1];
rule76 = [1 2 2 1 1 1];
rule77 = [3 1 2 1 1 1];
```

Changing of intervals

```
% Define input variables for Minutiae Match
fisQuality = addvar(fisQuality,'input','MinutiaeMatch',[0 100]);
% Define membership functions for Minutiae Match
fisQuality = addmf(fisQuality,'input',1,'Very Low','trapmf',[0 0 10 20]);
fisQuality = addmf(fisQuality,'input',1,'Low','trapmf',[10 14 25 32]);
fisQuality = addmf(fisQuality,'input',1,'Medium','trapmf',[26.6 31 52 59]);
fisQuality = addmf(fisQuality,'input',1,'High','trapmf',[50 60 82 88]);
fisQuality = addmf(fisQuality,'input',1,'Very High','trapmf',[77 87 99 100]);

% Define input variables for Ridge Density
fisQuality = addvar(fisQuality,'input','RidgeDensity',[0 1]);
% Define membership functions for Ridge Density
fisQuality = addmf(fisQuality,'input',2,'Sparse','trapmf',[0 0 0.46 0.6]);
fisQuality = addmf(fisQuality,'input',2,'Dense','trapmf',[0.4 0.58 1 1]);

% Define input variables for Whorl Pattern
fisQuality = addvar(fisQuality,'input','WhorlPattern',[0 1]);
% Define membership functions for Whorl Pattern
fisQuality = addmf(fisQuality,'input',3,'Weak','trapmf',[0 0 0.3 0.48]);
fisQuality = addmf(fisQuality,'input',3,'Average','trapmf',[0.3 0.4 0.62 0.78]);
fisQuality = addmf(fisQuality,'input',3,'Strong','trapmf',[0.5 0.7 1 1]);

% Define output variable for Fingerprint Quality
fisQuality = addvar(fisQuality,'output','Fingerprint Damage',[0 100]);
% Define membership functions for Fingerprint Damage
fisQuality = addmf(fisQuality,'output',1,'Poor','trapmf',[0 0 14.59 26.2]);
fisQuality = addmf(fisQuality,'output',1,'Decent','trapmf',[20.3 22.4 38.7 43]);
fisQuality = addmf(fisQuality,'output',1,'Average','trapmf',[40.5 44.8 58 61]);
fisQuality = addmf(fisQuality,'output',1,'Good','trapmf',[56 61 91 96]);
fisQuality = addmf(fisQuality,'output',1,'Excellent','trapmf',[91 95 100 100]);
```

New Fuzzy Distributions



Test 3:

Test No.	Fingerprint Damage
1	Decent
2	Poor
3	Decent
4	Decent
5	Average
6	Good
7	Average
8	Decent
9	Average
10	Excellent
11	Excellent
12	Excellent
13	Excellent
14	Excellent
15	Excellent

	LOM	SOM	MOM
Test No.	Fingerprint Damage	Fingerprint Damage	Fingerprint Damage
1	58	0	27.82
5	58	0	28.48
7	100	59	79.5
9	58	0	27.81
12	100	95	97
13	100	95	97

LOM vs SOM vs MOM final short test to determine output

Defuzzification Values (Centroid & Bisector & MOM):

	Centroid	Bisector	MOM
Test No.	Fingerprint Damage	Fingerprint Damage	Fingerprint Damage
1	29.12	27	27.82
2	29.6	30	28.76
3	40.1	46	28.5
4	29.44	30	29.2
5	43.8	49	28.5
6	76	76	76
7	78.99	79	79.5
8	28.45	19	28.48
9	49.36	54	27.81
10	96.67	97	97.5
11	96	97	97.5
12	96.5	97	97.5
13	96	97	97
14	96	97	97
15	96	97	97

	Centroid	Bisector	MOM
Test No.	Fingerprint Damage	Fingerprint Damage	Fingerprint Damage
1	TRUE	TRUE	TRUE
2	FALSE	FALSE	FALSE
3	TRUE	FALSE	TRUE
4	TRUE	TRUE	TRUE
5	TRUE	TRUE	FALSE
6	TRUE	TRUE	TRUE
7	FALSE	FALSE	FALSE
8	TRUE	FALSE	TRUE
9	TRUE	TRUE	FALSE
10	TRUE	TRUE	TRUE
11	TRUE	TRUE	TRUE
12	TRUE	TRUE	TRUE
13	TRUE	TRUE	TRUE
14	TRUE	TRUE	TRUE
15	TRUE	TRUE	TRUE

Expected Outcomes Vs Actual Outcomes

Final System Design in MATLAB

```
% To remove the warning messages for using old syntax
warning('off','fuzzy:general:warnDeprecation_Newfis')
warning('off','fuzzy:general:warnDeprecation_Addvar')
warning('off','fuzzy:general:warnDeprecation_Addmf')
warning('off','fuzzy:general:warnDeprecation_Evalfis')

fisQuality = newfis('FingerprintQuality','DefuzzificationMethod', 'mom');


% Define input variables for Minutiae Match
fisQuality = addvar(fisQuality,'input','MinutiaeMatch',[0 100]);
% Define membership functions for Minutiae Match
fisQuality = addmf(fisQuality,'input',1,'Very Low','trapmf',[0 0 10 20]);
fisQuality = addmf(fisQuality,'input',1,'Low','trapmf',[10 14 25 32]);
fisQuality = addmf(fisQuality,'input',1,'Medium','trapmf',[26.6 31 52 59]);
fisQuality = addmf(fisQuality,'input',1,'High','trapmf',[50 60 82 88]);
fisQuality = addmf(fisQuality,'input',1,'Very High','trapmf',[77 87 99 100]);

% Define input variables for Ridge Density
fisQuality = addvar(fisQuality,'input','RidgeDensity',[0 1]);
% Define membership functions for Ridge Density
fisQuality = addmf(fisQuality,'input',2,'Sparse','trapmf',[0 0 0.46 0.6]);
fisQuality = addmf(fisQuality,'input',2,'Dense','trapmf',[0.4 0.58 1 1]);

% Define input variables for Whorl Pattern
fisQuality = addvar(fisQuality,'input','WhorlPattern',[0 1]);
% Define membership functions for Whorl Pattern
fisQuality = addmf(fisQuality,'input',3,'Weak','trapmf',[0 0 0.3 0.48]);
fisQuality = addmf(fisQuality,'input',3,'Average','trapmf',[0.3 0.4 0.62 0.78]);
fisQuality = addmf(fisQuality,'input',3,'Strong','trapmf',[0.5 0.7 1 1]);

% Define output variable for Fingerprint Quality
fisQuality = addvar(fisQuality,'output','Fingerprint Damage',[0 100]);
% Define membership functions for Fingerprint Damage
fisQuality = addmf(fisQuality,'output',1,'Poor','trapmf',[0 0 14.59 26.2]);
fisQuality = addmf(fisQuality,'output',1,'Decent','trapmf',[20.3 22.4 38.7 43]);
fisQuality = addmf(fisQuality,'output',1,'Average','trapmf',[40.5 44.8 58 61]);
fisQuality = addmf(fisQuality,'output',1,'Good','trapmf',[56 61 91 96]);
fisQuality = addmf(fisQuality,'output',1,'Excellent','trapmf',[91 95 100 100]);
```

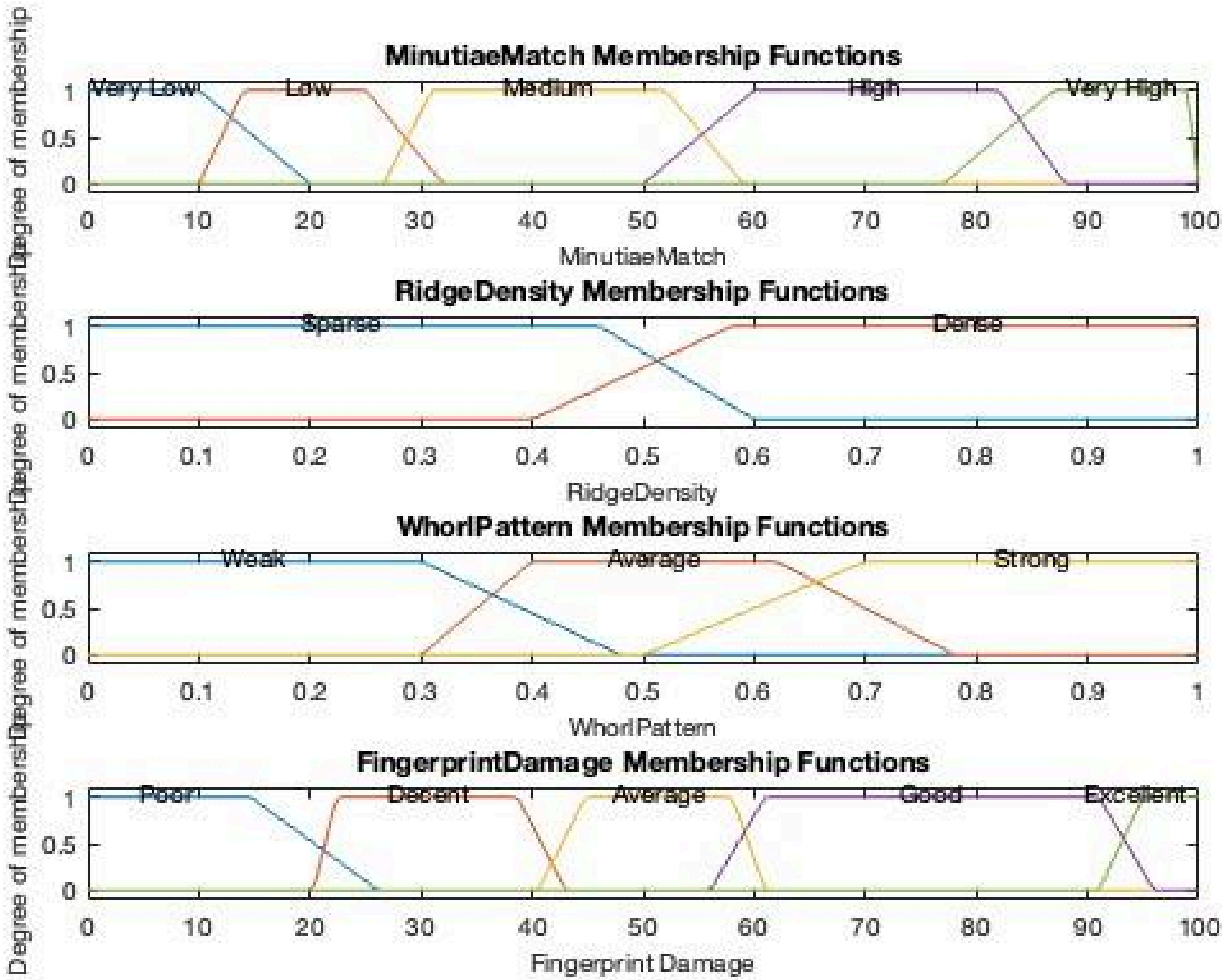
```
rule1 = [1 1 1 1 1 1]; %
rule2 = [1 1 2 1 1 1]; %
rule3 = [1 1 3 2 1 1]; %
rule4 = [1 2 1 2 1 1]; %
rule5 = [1 2 2 2 1 1]; %
rule6 = [1 2 3 3 1 1]; %
rule7 = [2 1 1 2 1 1]; %
rule8 = [2 1 2 2 1 1]; %
rule9 = [2 1 3 3 1 1]; %
rule10 = [2 2 1 3 1 1]; %
rule11 = [2 2 2 3 1 1]; %
rule12 = [2 2 3 4 1 1]; %
rule13 = [3 1 1 3 1 1]; %
rule14 = [3 1 2 3 1 1]; %
rule15 = [3 1 3 4 0.8 1];
rule16 = [3 2 1 4 0.8 1];
rule17 = [3 2 2 4 0.8 1];
rule18 = [3 2 3 5 0.7 1];
rule19 = [4 1 1 4 0.7 1];
rule20 = [4 1 2 4 0.7 1];
rule21 = [4 2 1 5 0.7 1];
rule22 = [4 2 2 5 0.75 1]
rule23 = [4 2 3 5 0.7 1];
rule24 = [5 1 1 5 0.7 1];
rule25 = [5 1 2 5 0.7 1];
rule26 = [5 1 3 5 0.7 1];
rule27 = [5 2 1 5 0.8 1];
rule28 = [5 2 2 5 0.8 1];
rule29 = [5 2 3 5 0.8 1];
rule30 = [1 2 3 2 0.8 1];
```

```
rule31 = [1 1 2 2 1 1];
rule32 = [1 1 3 3 1 1];
rule33 = [1 2 1 2 1 1];
rule34 = [1 2 2 2 1 1];
rule35 = [1 2 3 3 1 1];
rule36 = [2 1 1 2 1 1];
rule37 = [2 1 2 3 1 1];
rule38 = [2 1 3 3 1 1];
rule39 = [2 2 1 3 1 1];
rule40 = [2 2 2 3 1 1];
rule41 = [2 2 3 4 1 1];
rule42 = [3 1 1 3 1 1];
rule43 = [3 1 2 3 1 1];
rule44 = [3 1 3 4 1 1];
rule45 = [3 2 1 4 1 1];
rule46 = [3 2 2 4 1 1];
rule47 = [3 2 3 5 1 1];
rule48 = [4 1 1 4 1 1];
rule49 = [4 1 2 4 1 1];
rule50 = [4 1 3 5 1 1];
rule51 = [4 2 1 5 1 1];
rule52 = [4 2 2 5 1 1];
rule53 = [4 2 3 5 1 1];
rule54 = [5 1 1 5 1 1];
rule55 = [5 1 2 5 1 1];
rule56 = [5 1 3 5 1 1];
rule57 = [5 2 1 5 1 1];
rule58 = [5 2 2 5 1 1];
rule59 = [5 2 3 5 1 1];
rule60 = [1 1 1 1 1 1];
```

```
rule61 = [1 2 2 2 1 1];
rule62 = [2 1 3 2 1 1];
rule63 = [2 2 1 3 1 1];
rule64 = [3 1 2 3 1 1];
rule65 = [3 2 3 4 1 1];
rule66 = [4 1 1 4 1 1];
rule67 = [4 2 2 5 1 1];
rule68 = [5 1 3 5 1 1];
rule69 = [1 2 3 2 1 1];
rule70 = [5 2 1 5 1 1];
rule71 = [1 2 1 1 1 1];
rule72 = [2 1 1 1 1 1];
rule73 = [2 1 2 1 1 1];
rule74 = [2 2 1 1 1 1];
rule75 = [3 1 1 1 1 1];
rule76 = [1 2 2 1 1 1];
rule77 = [3 1 2 1 1 1];
```

```
ruleList = [rule1; rule2; rule3; rule4; rule5; rule6; rule7; rule8; rule9; rule10;
            rule11; rule12; rule13; rule14; rule15; rule16; rule17; rule18; rule19; rule20;
            rule21; rule22; rule23; rule24; rule25; rule26; rule27; rule28; rule29; rule30
            rule31; rule32; rule33; rule34; rule35; rule36; rule37; rule38; rule39; rule40;
            rule41; rule42; rule43; rule44; rule45; rule46; rule47; rule48; rule49; rule50;
            rule51; rule52; rule53; rule54; rule55; rule56; rule57; rule58; rule59; rule60;
            rule61; rule62; rule63; rule64; rule65; rule66; rule67; rule68; rule69; rule70;
            rule71; rule72; rule73; rule74; rule75; rule76; rule77;];

fisQuality = addrule(fisQuality, ruleList);

% Input values
MinutiaeMatchInput = 78;
RidgeDensityInput = 0.68;
WhorlPatternInput = 0.5;
format long;

evalQuality = evalfis([MinutiaeMatchInput, RidgeDensityInput, WhorlPatternInput], fisQuality);
disp(['Fingerprint Quality Evaluation: ', num2str(evalQuality)]);

% Using Centroid Method
fisQuality.DefuzzificationMethod = 'centroid';
evalCentroid = evalfis([MinutiaeMatchInput, RidgeDensityInput, WhorlPatternInput], fisQuality);

% Using Bisector Method
fisQuality.DefuzzificationMethod = 'bisector';
evalBisector = evalfis([MinutiaeMatchInput, RidgeDensityInput, WhorlPatternInput], fisQuality);

% Display or process the results
disp(['Centroid Method Output: ', num2str(evalCentroid)]);
disp(['Bisector Method Output: ', num2str(evalBisector)]);

%Plotting the Data
```

```
%figure; % Create a new figure
subplot(4,1,1), plotmf(fisQuality, 'input', 1); % MinutiaeMatch
title('MinutiaeMatch Membership Functions');

subplot(4,1,2), plotmf(fisQuality, 'input', 2); % RidgeDensity
title('RidgeDensity Membership Functions');

subplot(4,1,3), plotmf(fisQuality, 'input', 3); % WhorlPattern
title('WhorlPattern Membership Functions');

subplot(4,1,4), plotmf(fisQuality, 'output', 1); % FingerprintDamage
title('FingerprintDamage Membership Functions');
```


MinutiaeMatch Membership Functions
Very Low
Low
Medium
High
Very High
MinutiaeMatch
RidgeDensity Membership Functions
Sparse
Dense
RidgeDensity
WhorlPattern Membership Functions
Weak
Average
Strong
WhorlPattern
FingerprintDamage Membership Functions
Poor
Decent
Average
Good
Excellent
Fingerprint Damage
Degree of membership