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Magnetic Tactile Display for Heartbeat Emulation

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Abstract

Recently, humanoid robots have developed rapidly and have the potential to become a medical innovation, enhancing human interaction. The ability to realistically mimic a heartbeat is a key feature under development. This research aims to design a ferrofluid-based magnetic tactile display to represent a heartbeat in a humanoid robot. This system utilizes an electromagnetic matrix, ferrofluid, and an Arduino Uno as a magnetic flield controller. Electrocardiogram (ECG) data is used to represent various heart rate patterns, such as normal, bradycardia, and tachycardia. The development results indicate that the magnetic tactile display is capable of providing tactile feedback that corresponds to the heart rate pattern. This device mimics heartbeats based on ECG data by controlling ferrofluid through magnetic field settings, allowing users to feel it tactilely. Testing using an accelerometer sensor shows that the system can replicate normal heartbeats and bradycardia with a small average time difference of 4.52% and 3.93%, respectively. However, in tachycardia, there were difficulties in handling rapid interval changes, resulting in a time error of 31.67%. The results of this study indicate that magnetic tactile displays have great potential in physiological emulation in humanoid robots.

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Abstrak

Dalam beberapa tahun terakhir robot humanoid berkembang pesat dan berpotensi menjadi inovasi di bidang medis dalam meningkatkan interaksi manusia. Salah satu fitur utama yang dikembangkan adalah kemampuan meniru detak jantung secara realistis. Penelitian ini bertujuan merancang magnetic tactile display berbasis ferrofluid untuk merepresentasikan detak jantung pada robot humanoid. Sistem ini memanfaatkan matriks elektromagnet, ferrofluid, dan Arduino Uno sebagai pengendali medan magnet. Data elektrokardiogram (EKG) digunakan untuk merepresentasikan berbagai pola detak jantung, seperti normal, bradikardia, dan takikardia. Hasil pengembangan menunjukkan bahwa magnetic tactile display mampu memberikan umpan balik taktil yang sesuai dengan pola detak jantung. Perangkat ini meniru detak jantung berdasarkan data EKG dengan mengontrol ferrofluid melalui pengaturan medan magnet, memungkinkan pengguna merasakannya secara taktil. Pengujian menggunakan sensor akselerometer menunjukkan bahwa sistem dapat mereplikasi detak normal dan bradikardia dengan rata-rata selisih waktu kecil, masing-masing 4,52% dan 3,93%. Namun, pada takikardia, terjadi kesulitan dalam menangani perubahan interval yang cepat, menghasilkan eror waktu sebesar 31,67%. Hasil penelitian ini menunjukkan bahwa magnetic tactile display memiliki potensi besar dalam emulasi fisiologis pada robot humanoid.

1. INTRODUCTION

Humanoid robots have advanced quickly and are increasingly being used in healthcare, with a major development being the integration of human physiological traits, like heartbeats, to improve robot-human interactions. Research by Janamla et al. shows how humanoid robots can improve healthcare outcomes by mimicking biological processes, such as heartbeats, which greatly increase patient comfort and confidence. [1]

In the medical domains of patient care, rehabilitation, and health education, heartbeat-mimicking robots open up new possibilities. These robots aid in the development of more flexible and responsive

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healthcare systems by mimicking cardiac rhythms. Moreover, this technology offers an interactive and realistic approach to teaching heart care techniques in medical training.

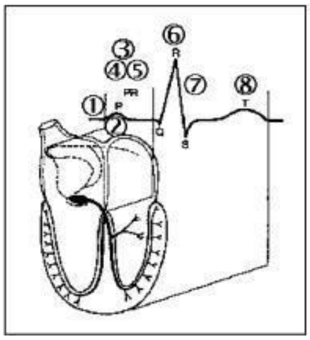
A promising method of emulating heart rhythms is using magnetic tactile displays, which provide tactile feedback using ferrofluid and electromagnets. By using electrocardiogram (ECG) data, this method allows humanoid robots to replicate human heartbeats, providing a more realistic and engaging interaction experience. [2]

2. LITERATURE REVIEW

2.1 Heart Anatomy and Function

Two atria and two ventricles make up the heart's four chambers, which collaborate to pump blood throughout the body. Electrical impulses start at the sinoatrial (SA) node, the heart's natural pacemaker, and spread through the atria, causing them to contract and push blood into the ventricles. The signal then travels to the ventricles through the atrioventricular (AV) node, causing them to contract and push blood out. [3]

An electrocardiogram's (ECG) PQRST waveform shows the electrical activity of the heart during its cycle. The P wave indicates atrial depolarization, while the PR interval shows the time it takes for the electrical signal to reach the ventricles. Ventricular depolarization is represented by the QRS complex, while ventricular repolarization is represented by the T wave. It is important for looking at these components in order to detect cardiac problems such as arrhythmia. [4] See Figure 1 for an illustration of the heart's ECG and muscle polarization.



	Physiologic Event	ECG Evidence
1.	SA node initiates impulse	Not visible
2.	Depolarization of atrial muscle	P wave
3.	Atrial contraction	Not visible
4.	Depolarization of AV node & Common Bundle	Not visible
5.	Repolarization of atrial muscle	Not visible
6.	Depolarization of ventricular muscle	QRS complex
7.	Contraction of ventricular muscle	Not visible
8.	Repolarization of ventricular muscle	T wave

Figure 1. Heart Polarization

2.2 Arrhythmia (Heart Rhythm Disorders)

Arrhythmias occur due to disruptions in the heart's rhythmic beats, resulting in either too fast (tachycardia, over 100 bpm) or too slow (bradycardia, under 60 bpm) heart rates. These irregular heartbeats are often due to problems with the sinoatrial (SA) node, which normally produces the electrical signal that triggers coordinated atrial contractions. Tachycardia and bradycardia can usually be seen on ECG readings, where irregular timing indicates departures from a normal heart rhythm [5]. See Figure 2 for examples of arrhythmia ECGs: a) Tachycardia and b) Bradycardia.

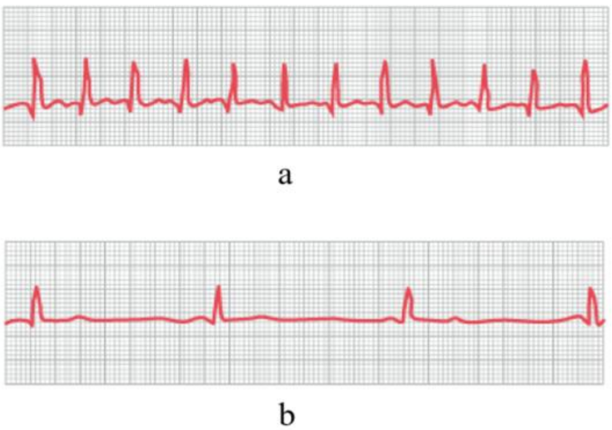


Figure 2. Arrhythmia ECG a. Tachycardia b. Bradycardia.

2.3 Arduino Uno R3

The Arduino Uno R3, equipped with the ATmega328P microcontroller, has 14 digital I/O pins (6 of which support PWM) and 6 analog inputs, making it perfect for basic prototyping. Its compact design and replaceable microcontroller chip allow for easy testing and versatility. This makes it an excellent option for controlling the electromagnets in the Magnetic Tactile Display. [6] See Figure 3 for images of the Arduino Uno R3.

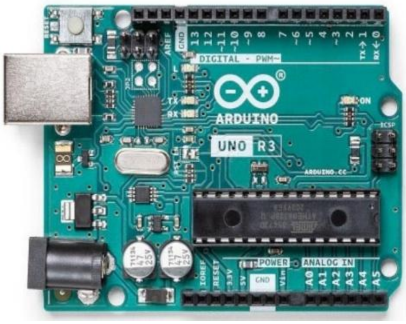


Figure 3. Arduino Uno R3

2.4 Arduino Nano 33 IoT

The Arduino Nano 33 IoT features an integrated Inertial Measurement Unit (IMU) sensor module (LSM6DS3), providing precise measurements of acceleration, orientation, and position. The integrated IMU sensor can be seen in Figure 4. This microcontroller facilitates real-time validation of tactile feedback, aligning ferrofluid-based responses with ECG signal patterns. [7][8]

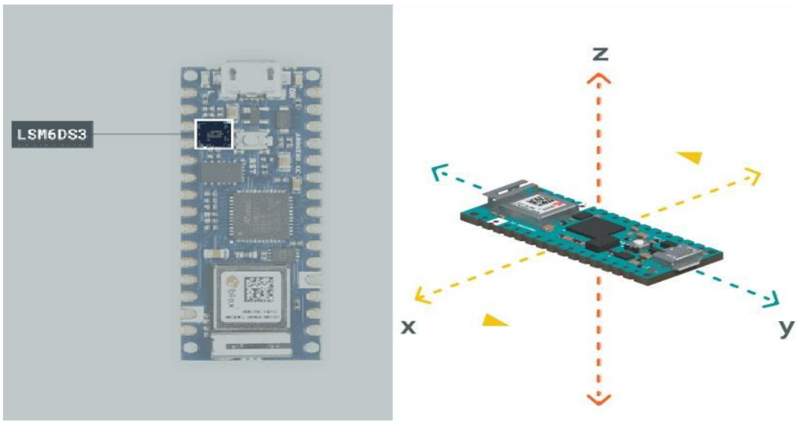


Figure 4. Arduino Nano Accelerometer.

2.5 Ferrofluid

Ferrofluid, a colloidal suspension of magnetic nanoparticles like iron oxide, exhibits unique rheological properties. When exposed to a magnetic field, it transitions from a liquid to a semi-solid state, forming controlled structures such as ridges or bumps. This behavior is utilized in haptic devices to provide tactile feedback, making it especially beneficial for visually impaired users [9]. See Figure 5 for an image of the ferrofluid pouch.

Figure 5. Ferrofluid pouch

2.6 Electromagnets

Electromagnets consist of a magnetic core wrapped with wire coils. When electric current flows through the coils, the core becomes magnetized, generating a magnetic field proportional to the number of turns (n) and the current (I), as described by Ampere's Law in Equation (1), where μ_0 is the vacuum permeability [10] [11].

$$B = \mu_0 \times n \times I \quad (1)$$

In the Magnetic Tactile Display, these electromagnets manipulate ferrofluid to produce tangible patterns, enabling users to physically perceive cardiac rhythm. An illustration of a vertically cut electromagnet, showing its internal structure, can be seen in Figure 6. [12]

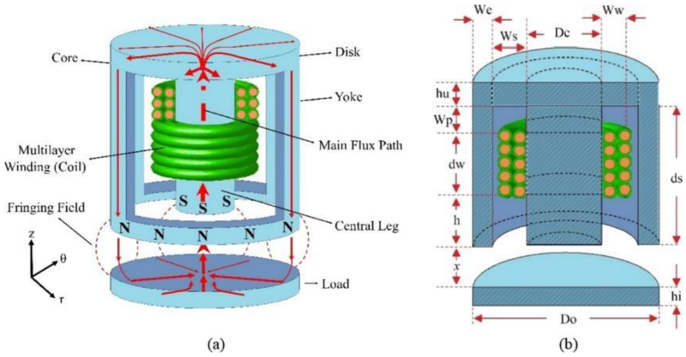


Figure 6. Vertically cut electromagnets.

2.7 Darlington Transistor Driver (ULN2803APG)

In the Magnetic Tactile Display, these electromagnets manipulate ferrofluid to produce tangible patterns, enabling users to physically perceive cardiac rhythm. An illustration of a vertically cut electromagnet, showing its internal structure, can be seen in Figure 6 [13]. The pin configuration is shown in Figure 7

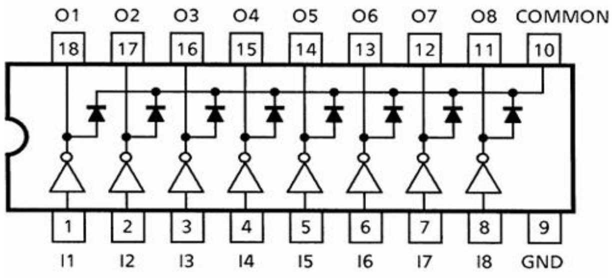


Figure 7. Darlington Transistor pinout.

3. METHODOLOGY

3.1 System Input and Processing

The system uses ECG data stored on a laptop, sourced from PhysioNet.org, a repository of freely accessible medical research data. The data is processed to detect R-peaks, which are transmitted via serial communication to an Arduino Uno. The Arduino activates Darlington transistors connected to electromagnets, enabling on-off control. Electromagnet outputs are validated using an accelerometer, with movement graphs and peak timestamps displayed on a secondary laptop. The system block diagram is shown in Figure 8.

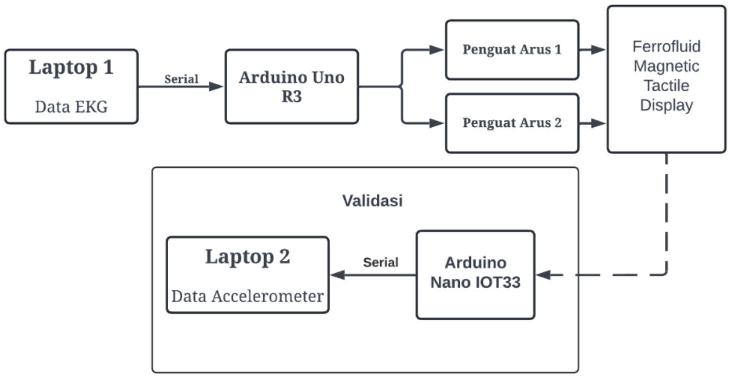
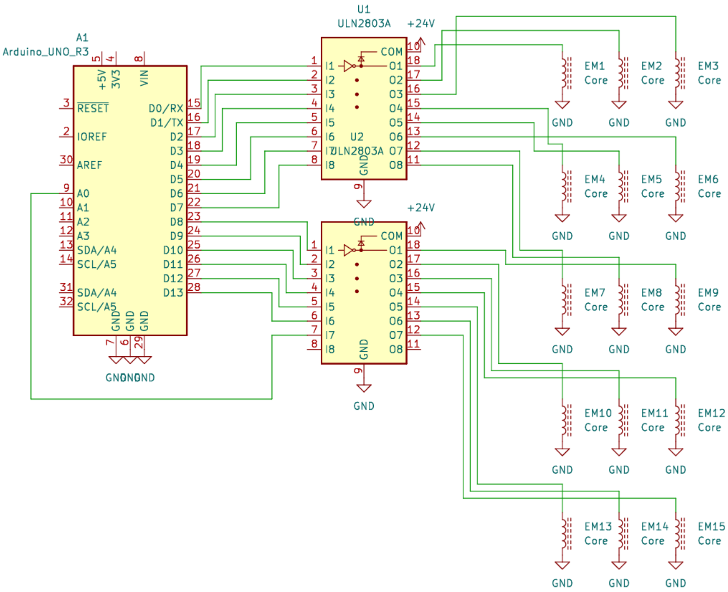


Figure 8. System Block Diagram

3.2 Tactile Display Device

The tactile display comprises a plastic casing, an electromagnet array, and a ferrofluid pouch. The electromagnets create tactile bumps on the ferrofluid surface, forming patterns users can feel. The system is designed as a 5x3 matrix for efficient coding. A silicone layer is added to reduce light reflection and enhance durability. The tactile display is shown in Figure 9, and its schematics are illustrated in Figure 10.

Figure 9. Magnetic Tactile Display Illustration.



Gambar 10. Magnetic Tactile Display schematics

3.3 Data Segmentation

The ECG data from PhysioNet.org contains hours of samples, segmented into one-minute intervals for efficient processing. This reduces memory load and improves analysis speed. A Python-based GUI provides tools for zooming and saving segments, streamlining analysis. The program's interface and features are shown in Figure 11.

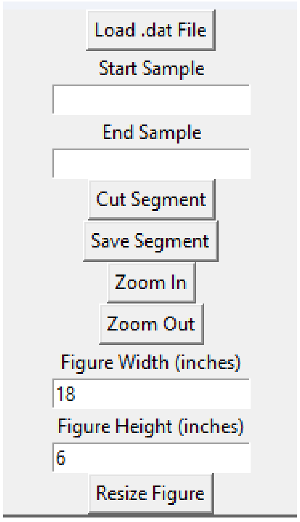


Figure 10. Data segmentation program GUI

3.4 R-Peak Detection

ECG data from PhysioNet.org, sampled at 180 Hz or 360 Hz, is processed to detect R-peaks using a 60% threshold of the signal's peak voltage. The R-peaks are identified by comparing the signal amplitude against this threshold. Once a peak is detected, a ‘peak’ string is sent via serial communication to external devices, and an audible beep is generated to simulate a real-time heart monitor. The flowchart detailing this process is shown in Figure 12.

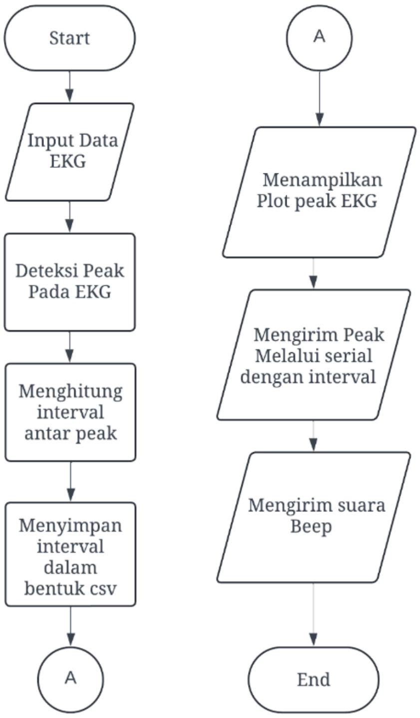


Figure 11. Peak detection program flowchart.

3.5 Arduino Uno Program

The Arduino initializes a 5x3 electromagnet matrix and continuously listens for serial commands. Upon receiving a ‘peak’ signal, all electromagnets in the matrix are activated for 100ms, providing a tactile simulation of the detected peak. The program runs in a continuous loop to process incoming signals and control the electromagnets in real time. The flowchart for the Arduino program is shown in Figure 13.

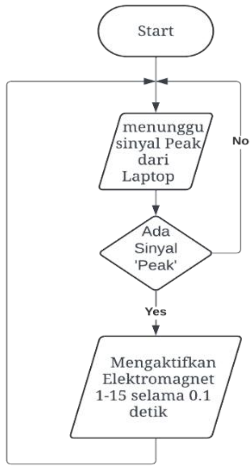


Figure 12. Arduino Uno Program

4. RESULT AND DISCUSSION

In system testing, ECG data is categorized into three types: Normal Heart Rate, Tachycardia, and Bradycardia. Each dataset represents real medical records converted into digital form with an 11-bit resolution range. Differences in sampling rates among the selected data require time calculations in the program to be adjusted according to the ECG data sampling rate. Below are the original ECG graphs alongside the output from the magnetic tactile display tested with an accelerometer.

4.1 Normal Heart Rate Test

Figure 14 compares the original EKG data (top) with the accelerometer graph (bottom). The graph shows that peak timestamps are generally aligned. The first peak matches the original EKG timestamp precisely, while the second and third peaks differ slightly by approximately 20ms. The fifth and sixth peaks show larger differences, around 100ms. Despite these differences, the accelerometer's peak shapes still follow the same pattern as the EKG graph. To further assess the average absolute differences between the datasets, the Mean Absolute Error (MAE) is calculated using Equation 2:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |\ y_{true}(i) - y_{pred}(i)|$$

- n is the number of data points (intervals or peaks).
- y_true(i) is the original EKG data value.
- y_pred(i) is the accelerometer data value.

The MAE for Normal Heartbeat data is 0.0428 seconds, indicating an average absolute time difference of approximately 42ms. This result suggests that, on average, the time differences between the original EKG and accelerometer data are within acceptable limits.

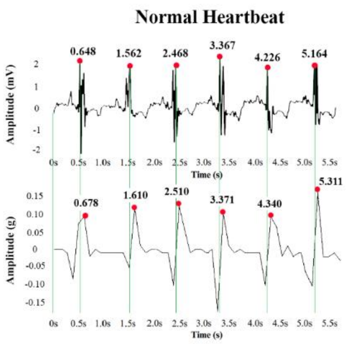


Figure 13. Normal Heartbeat Timestamp

Table 1. Normal interval

Interval	Asli (s)	Accelerometer (s)
1	0.914	0.932
2	0.906	0.900
3	0.899	0.861
4	0.859	0.969
5	0.929	0.971

4.2 Bradikardia Heart Rate Test

In Figure 4.2, the timestamp differences in bradycardia data suggest minor variations, likely due to system delays. To analyze similarity, interval tables are more suitable as they are unaffected by absolute time offsets or consistent internal delays. Table 2 shows interval differences: 0.034 seconds (34ms) in the first interval, indicating the accelerometer's slightly faster response, followed by 0.029 seconds (29ms) in the second interval, reflecting strong consistency. The third interval has a minimal difference of 0.001 seconds (1ms), indicating excellent alignment. However, the fourth interval shows a larger difference of 0.101 seconds (101ms), likely due to noise or recording delays. Overall, smaller differences in the first three intervals (under 35ms) demonstrate the accelerometer's accuracy, while the larger deviation in the fourth (over 100ms) suggests sensitivity to external factors. The MSE for bradycardia data is 0.00305, indicating minimal variance between datasets, while the MAE of 0.04125 seconds (41ms) confirms that the average absolute time difference remains within tolerance.

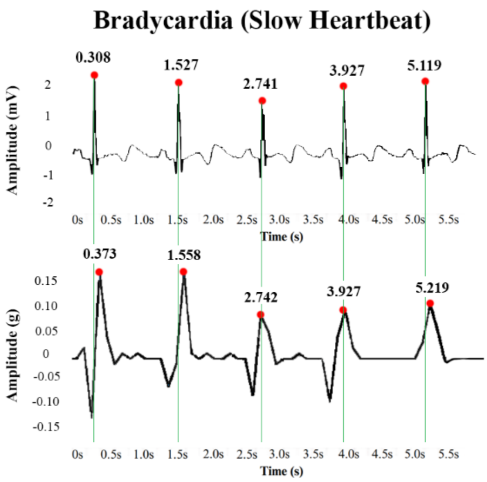


Figure 14. Bradycardia Heartbeat Timestamp

Table 2. Bradycardia interval

Interval	Asli (s)	Accelerometer (s)
1	1.219	1.185
2	1.213	1.184
3	1.186	1.185
4	1.191	1.292

4.3 Tachycardia Heartbeat Test

The MAE value of 0.082 seconds in tachycardia testing (Equation 4.2) indicates that the accelerometer provides accurate measurements with minimal average error across most intervals. However, the MSE of 0.01165 seconds^2 suggests the presence of significant outliers contributing to overall variation, particularly in intervals like interval 2. To improve accuracy and reduce fluctuations, data filtering or sensor recalibration is recommended. Despite these challenges, the accelerometer demonstrates reliable performance with room for further refinement. Figure 4.3 illustrates tachycardia comparisons, highlighting interval fluctuations and challenges in detecting rapid heart rate changes.

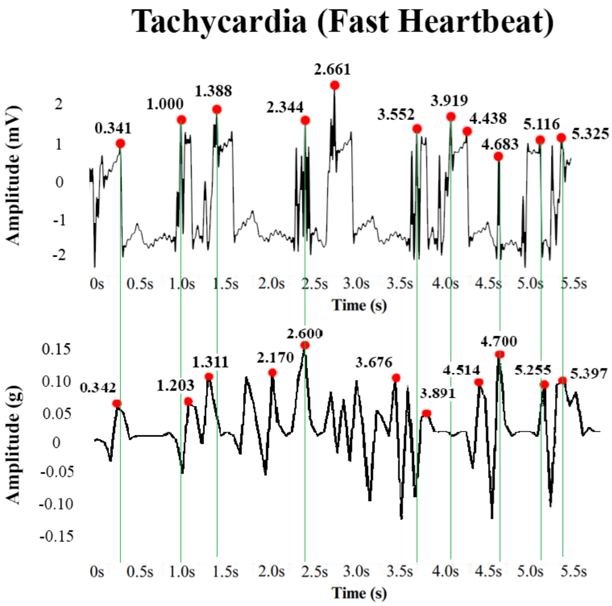


Figure 15. Tachycardia Heartbeat Timestamp

Table 3. Tachycardia interval

Interval	Asli (s)	Accelerometer (s)
1	0.659	0.861
2	0.388	0.108
3	0.956	0.859
4	0.317	0.430
5	0.891	1.076
6	0.367	0.215
7	0.519	0.623
8	0.235	0.186
9	0.434	0.555
10	0.209	0.142

5. CONCLUSION

The Magnetic Tactile Display effectively emulates heart rhythms with high accuracy across Normal Heartbeat, Bradycardia, and Tachycardia conditions. For Normal Heartbeat, the system achieved an MSE of 0.00313 and an MAE of 0.0428 seconds (42ms), with minor timestamp deviations (20ms for some peaks, 100ms for others) while maintaining consistent waveform patterns. For Bradycardia, the MSE was 0.00305 and the MAE was 0.04125 seconds (41ms), showing excellent alignment in the first three intervals (under 35ms difference) but a larger deviation (0.101 seconds) in one interval due to noise or system delay. For tachycardia, the MSE was 0.00452 and the MAE was 0.0556 seconds (56 ms), with more noticeable deviations due to the system's sensitivity to rapid changes.

Overall, the system performs reliably, with the smallest errors for Bradycardia and slightly larger deviations for Tachycardia. The results confirm the device's capability to emulate heart rhythms accurately, with room for improvement in handling rapid fluctuations and noise.

REFERENCE

[1] M. F. Fauzi, D. S. Devi, and I. Nazila, “Analisis Penilaian Kondisi Jembatan Ruas Jalan Peninggalan – Sei Lilin Dengan Metode Bridge Management System (BMS),” *J. Deform.*, vol. 9, no. 1, pp. 60–66, 2024, doi: 10.31851/deformasi.v9i1.14394.

[2] M. A. Ridla and M. F. Rahman, “Perancangan Prototype Monitoring Suhu Berbasis Internet Of Things (IoT),” *JUSIFOR J. Sist. Inf. dan Inform.*, vol. 3, no. 1, pp. 72–79, 2024, doi: 10.33379/jusifor.v3i1.4367.

[3] A. H. Widayatno, “Penggunaan Teknologi dalam Monitoring Ketahanan Struktur Jembatan,” Prodi Teknik Sipil, Sekolah Vokasi, Universitas Sebelas Maret, 2024. [Online]. Available: https://www.academia.edu/120937778

[4] A. ArjunPratikto, “Simulasi Kendali Dan Monitoring Daya Listrik Peralatan Rumah Tangga Berbasis ESP32,” *ALINIER J. Artif. Intell. Appl.*, vol. 3, no. 1, pp. 38–48, 2022, doi: 10.36040/alinier.v3i1.4855.

[5] F. R. Firdaus, “Sistem Pemantauan Infus Mandiri Untuk Pasien Lansia Yang Menjalani Perawatan Rawat Jalan Berbasis Internet of Things (IoT),” p. 9, 2024.

[6] R. Hendrawan, A. S. Rohman, D. Hidayat, and T. Nugroho, “Sistem Monitoring Berat Pada Alat Organic Waste Chopper (Gasper) Dengan Sensor Berat (Load Cell) Berbasis Arduino Mega 2560,” Institut Teknologi Sumatera, 2020.

[7] L. Sabillah and R. Hidayat, “Sistem Monitoring Pemakaian Energi Listrik Pada Kamar Kost Menggunakan Aplikasi Blynk Berbasis Internet of Things,” *J. Komput. dan Elektro Sains*, vol. 1, no. 2, pp. 25–29, 2023, doi: 10.58291/komets.v1i2.104.

[8] S. D. D. Satria and R. P. Astutik, “Perancangan Sistem Monitoring Ketahanan Jembatan Berbasis Iot (Internet Of Things),” vol. 13, no. 1, 2025.

[9] E. W. Batubara and P. Sitompul, “Implementasi Fast Fourier Transform dalam Penyelesaian Persamaan Difusi Panas Satu Dimensi Universitas Negeri Medan , Indonesia,” no. 6, 2024.

[10] M. R. Sholahuddin and B. H. Kusuma, “Sistem Lampu Lalu Lintas Pintar untuk Kendaraan Prioritas,” vol. 4, pp. 633–640, 2025.

[11] Zulkarnain and Arman, “Potensi Internet of Things (IoT) Untuk Masa Depan Perkotaan Cerdas (Smart Cities),” *J. Inf. Syst. Technol.*, vol. 06, no. 01, pp. 7–11, 2025, [Online]. Available: https://journal.uib.ac.id/index.php/joint/

[12] A. Fatah, U. Ungkawa, and M. M. Barmawi, “Implementasi Algoritma Fast Fourier Transform Pada Monitor Getaran Untuk Analisis Kesehatan Jembatan,” *Infotronik J. Teknol. Inf. dan Elektron.*, vol. 5, no. 2, p. 48, 2020, doi: 10.32897/infotronik.2020.5.2.414.

[13] S. A. E. Mahendra, S. Subairi, N. Nachrowie, D. C. Permatasari, S. Sulistiyanto, and S. Fuada, “Implementasi Mikrokontroler ESP8266 sebagai Sensor Berat dan Jumlah Orang pada Beban Jembatan,” *JASIEK (Jurnal Apl. Sains, Informasi, Elektron. dan Komputer)*, vol. 5, no. 1, pp. 17–24, 2023, doi: 10.26905/jasiek.v5i1.9950.