Design and Implementation of a Stone Rotation Measurement System with IMU Sensor and Stone Behavior Presentation System

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Abstract: In the strategic sport of curling, referred to as “chess on ice,” precise measurement and real-time presentation of stone dynamics are critical for performance optimization. This study introduces a novel system that integrates Inertial Measurement Units (IMUs) and real-time data processing to track and analyze the rotational dynamics of curling stones accurately. Additionally, our system includes the Stone Behavior Presentation System, which interactively displays real-time data on a tablet device, providing instant feedback to players and coaches. This dual approach not only enhances the accuracy of data collection but also improves the immediacy and applicability of the information for strategic decision-making in training and competitive environments.

1 BACKGROUND

Curling is a sport in which players slide stones on ice, aiming to achieve a higher score than their opponents. Curling is a strategic sport, also known as chess on ice, and information sharing among players is essential. For example, it is no exaggeration to say that who wins or loses a match is determined by how accurately the behavior of a thrown stone, such as its moving speed and rotation speed, can be collected. Therefore, being able accurately and quickly to understand the ever-changing behavior of the stones is one of the most important skills for curling players.

Takegawa et al. have developed a technique for estimating the position and moving speed of stones on a curling sheet(Takegawa et al., 2023). Additionally, curling requires precise control of a stone’s movement on ice, where understanding its rotational dynamics is crucial for performance analysis and improvement(Maeno, 2014). Traditional methods for measuring the rotation of a curling stone rely heavily on manual observation and post-event video analysis, which can be time-consuming and prone to inaccuracies. Particularly in the case of curling, players may inadvertently obstruct the cameras, making it impossible to accurately confirm the rotation through slow-motion replay. Additionally, in post-event analysis, frequent replays are necessary, so good visualization is a valuable factor for efficient data interaction.

Accurate and real-time measurement of the curling stone’s rotation is imperative for coaches, players, and researchers to gain insights into the mechanics of the sport. Such data is essential for optimizing strategies, improving training methods, and advancing the scientific understanding of curling dynamics. Moreover, real-time feedback during training sessions can potentially enhance performance by allowing immediate adjustments based on precise rotational data, making this a worthwhile research consideration.

The primary objective of this study is to develop a novel system that utilizes smart IMU sensors and quaternion data to accurately measure and analyze the rotational dynamics of a curling stone. Thus, we develop “Tablet Stone,” a system that acquires real-time stone behavior data (moving speed, rotation speed, and rpm) and interactively displays the stone’s behavior on a tablet device attached to the stone.

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2 RELATED RESEARCH

2.1 Rotation Measurement

Previous studies (Barbour and Schmidt, 2001) have explored various methods for tracking and analyzing the movement of sports equipment, including the use of video analysis and mechanical sensors. However, these methods often fall short in terms of real-time data acquisition and processing capabilities. Recent advancements in Inertial Measurement Unit (IMU) sensors have opened new possibilities for sports analytics, providing high-resolution data on motion dynamics.

In particular, IMU sensors have been successfully applied to real-time motion tracking in fields such as biomechanics and robotics(Verdel et al., 2023). The application of these sensors in curling, however, remains relatively unexplored. This study aims to bridge this gap by developing a system that leverages smart IMU sensors to measure the rotational angle and speed of a curling stone in real time, providing immediate feedback and detailed post-analysis capabilities.

2.2 Feedback Methods in Curling

There is, even now, no established theory regarding what causes the stones to curve as they travel(Murata, 2022). Due to the complex and advanced element of strategy and the fact that technique is dependent on players, there are few scientific approaches to curling, in comparison with other sports. Nevertheless, Masui et al. have started research titled 'Curling Science', which is an initiative to create new strategy support that integrates information technology[1]. This project involves research on digital curling(Ito and Kitasei, 2015), tactical analysis, measurement of stone behavior, and sweeping(Gwon et al., 2020; Won et al., 2018). Digital curling refers to the proposal of a virtual curling space, created using a computer's physical simulator, that acts as a space to enable discussion of curling strategy. This concept has been developed by a large number of people(Yamamoto et al., 2015). In addition, systems, such as the Portable Tactical Support DB System, have been developed to record information, e.g., shots, stone layout, match scores, players taking part, and the condition of the ice, on a tablet device (Masui et al., 2015; Masui et al., 2016; Otani et al., 2016).

[1]https://kaken.nii.ac.jp/en/grant/KAKENHI-PROJECT-15H02797/

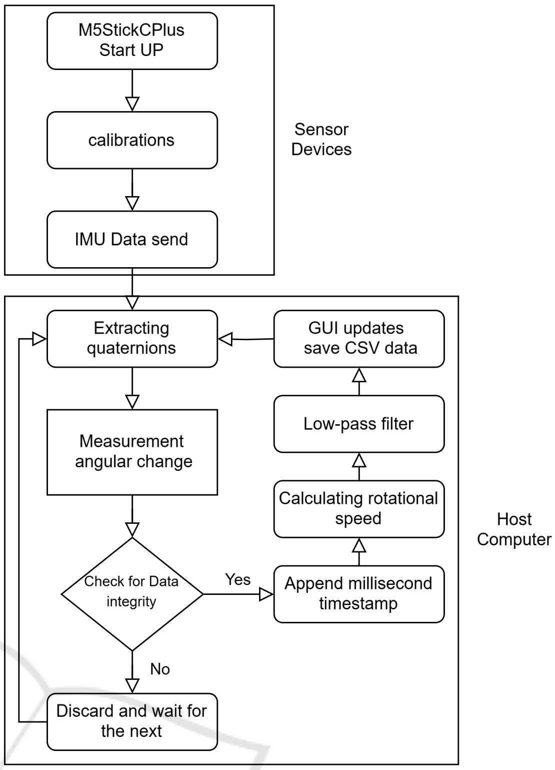

Figure 1: Work loop.

3 MEASUREMENT METHOD

3.1 System Proposal

3.1.1 System Overview

The proposed system utilizes the BNO055 IMU sensor to monitor and analyze the rotational dynamics of a curling stone in real-time. The sensor operates in NDOF (Nine Degrees of Freedom) mode and transmits data packets via UDP at approximately 9.2 Hz. These packets include quaternions, raw accelerometer, gyroscope, and magnetometer data. The host computer, implemented using Python on a Surface Pro 8, is responsible for receiving the quaternion data, converting it to Euler angles, and calculating the rotation angle and speed. A low-pass filter is applied to the rotation speed data to reduce noise. The processed data is displayed using a graphical user interface (GUI) implemented with matplotlib and saved in CSV format for post-experiment analysis. Figure 1 illustrates the overall workflow of the system, detailing the data flow and processing steps involved in real-time monitoring and analysis.

Figure 2: Sensor device.

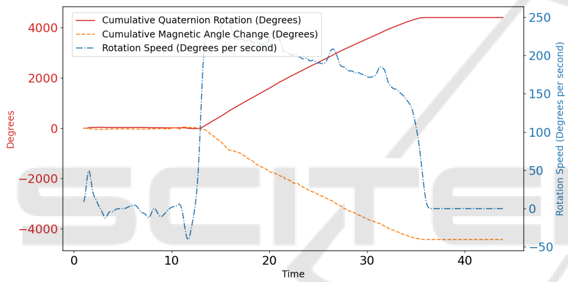

Figure 3: Results and analysis.

3.1.2 Hardware Components

BNO055 Sensor. The BNO055, developed by Bosch, is a high-precision IMU sensor integrating a triaxial 14-bit accelerometer, a high-precision triaxial 16-bit gyroscope, and a triaxial geomagnetic sensor. This advanced integration reduces size and complexity while minimizing potential errors. [2]

BME280 Sensor. The BME280 sensor collects barometric pressure data, which can be used for future research. This additional data can provide insights into environmental conditions that might affect the curling stone's performance.

ESP32 M5StickC PLUS. This microcontroller handles the data acquisition from both the BNO055 and BME280 sensors, with all components connected via the I2C interface. The combined weight is minimized to only 19.8g, reducing the impact on the curling stone.

[2]Information from Bosch's official documentation. https://www.bosch-sensortec.com/products/smart-sensor-systems/bno055/

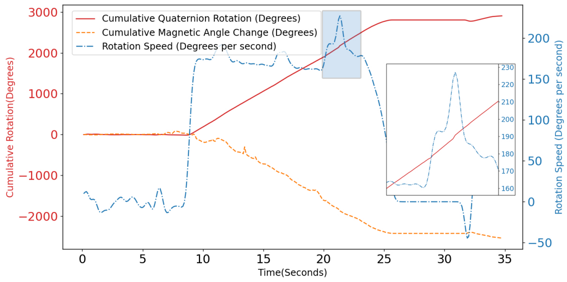

Figure 4: Collision analysis.

3.1.3 Data Transmission

Data packets, including quaternions and sensor readings, are sent from the ESP32 M5StickC PLUS to the host computer using the UDP protocol. This ensures minimal latency and efficient data transfer for real-time processing.

3.1.4 Data Processing on the Host Computer

The host computer runs a Python-based program to receive and process the data. Below is a detailed explanation of the implementation steps:

Data Reception: A UDP socket is configured to listen for incoming data packets. The data is decoded and parsed into individual sensor readings.

Quaternion to Euler Angle Conversion: Using the scipy.spatial.transform library, the received quaternions are converted to Euler angles. This conversion is crucial for calculating the rotation angle and speed of the curling stone. Quaternions are used because they avoid the gimbal lock problem (Bernardes and Viollet, 2022) that can occur with Euler angles, providing a more stable representation of orientation.

Rotation Angle. The cumulative rotation angle is computed from the Euler angles. The formula used is:

$$\text{Cumulative Rotation} = \sum_{i=1}^{n} (\theta_i - \theta_{i-1}) \qquad (1)$$

where θ represents the Euler angle around the z-axis.

The speed of rotation is calculated by differentiating the Euler angles over time. The formula used is:

$$\text{Rotation Speed} = \frac{\Delta\theta}{\Delta t} \qquad (2)$$

This measures how quickly the stone is rotating in degrees per second.

To reduce noise in the rotation speed data, a low-pass filter is applied. The filter formula is as follows:

$$\text{Filtered Speed} = \alpha \cdot \underset{\text{Rotation Speed}}{\text{Current Speed}} + (1-\alpha) \cdot \underset{\text{Rotation Speed}}{\text{Previous Speed}} \tag{3}$$

where α is the filter coefficient that determines the amount of smoothing.

Data Visualization. A real-time GUI is implemented using Matplotlib to display the cumulative rotation and rotation speed. The GUI updates at a frequency of approximately 9 Hz, providing immediate visual feedback.

In Figure 3, the red line represents the curling stone's rotational angle(degree), which can be seen to increase as the stone rotates. The blue line indicates the rotational speed(degree per second), and the yellow line represents the raw magnetometer data(rotational angle).

Data Storage. All processed data, including timestamps, cumulative rotation angles, and rotation speeds, are saved to a CSV file for later analysis. This ensures that detailed records of each experiment are maintained.

By following these steps, the system can provide accurate and real-time measurements of the curling stone's rotational dynamics, offering valuable insights for both training and research purposes.

3.1.5 Post-Experiment Analysis

The post-experiment analysis involves processing the recorded data from the experiments to gain insights into the rotational dynamics of the curling stone. This section details the steps taken to analyze the data, including data cleaning, quaternion to Euler angle conversion, rotation calculation, and visualization. Loading Data: The recorded data is loaded from a CSV file, which contains timestamps and sensor readings, including quaternions and magnetometer data.

Timestamp Conversion. Timestamps are converted to a proper time format and adjusted to relative time from the start of the experiment. This allows for accurate calculation of time intervals between data points.

Offset Calculation. For each timestamp, offsets are calculated based on the number of data points to dynamically determine intervals. This helps in accurately plotting the data over time.

Quaternion to Euler Angle Conversion: Using the scipy.spatial.transform library, quaternions are converted to Euler angles. This conversion is essential for calculating the rotation angles of the curling stone.

Cumulative Rotation Changes. The changes in rotation angles (yaw) are calculated and accumulated to obtain the cumulative rotation over time.

Magnetic Angle Calculation. The changes in the magnetic field angle are also calculated and accumulated to provide additional insights into the stone's rotation dynamics.

Rotation Speed: The rotation speed is calculated by dividing the rotation changes by the time intervals. A Gaussian filter is applied to smooth the rotation speed data.The alpha value of the low-pass filter is adjusted during the post-experiment analysis to optimize the smoothness of the speed curves, ensuring accurate representation of the curling stone's dynamics.

Visualization. The processed data is visualized using Matplotlib, displaying both cumulative rotation and rotation speed over time. Annotations are added to show total rotation in degrees and turns, as well as cumulative magnetic angle changes.

3.2 Experiments

3.2.1 Equipment Setup and Procedure

To evaluate the feasibility and performance of the prototype device, a series of experiments were conducted. The lower unit, comprising the sensors and M5StickC PLUS, was powered on, calibrated using a figure-of-eight motion to ensure accurate orientation tracking, and securely attached to the curling stone's top cover. Following this setup, the host computer's Python program was initiated to start data reception. Throughout the experiments, a camera continuously tracked and recorded the curling stone's movements to validate the data post-experiment. Various experimental conditions were tested, including combinations of low, medium, and high speeds, clockwise and counterclockwise rotations, and collisions. The objective was to evaluate the prototype under different scenarios.

3.2.2 Data Collection and Initial Findings

During the experiments, data transmission, reception, and parsing were successful. The angle calculation algorithms performed correctly, and the GUI refreshed as expected. Once the experiments were complete, the data, including the computed and raw data, was automatically saved.

3.2.3 Post-Experiment Analysis

The post-experiment analysis involved using the saved raw data to recreate the experiments. Additionally, the raw magnetometer data was used to verify the results and mitigate potential errors from Micro-Electro-Mechanical Systems (MEMS) algorithms.

3.2.4 Example and Observations

As illustrated in the accompanying Figure 2, a medium-speed clockwise rotation experiment showed that the curling stone's rotational angle(degree), represented by a red line, increases as the stone rotates. The blue line indicates the rotational speed(degree per second), and the yellow line represents the raw magnetometer data(rotational angle). The smoothness of the red line compared to the yellow line is evident, highlighting the effectiveness of the data smoothing process. The optimized UI from the post-experiment analysis quickly displays the number of rotations and specific degrees. The Matplotlib component allows for zooming in on specific areas for detailed visual analysis.

3.2.5 Additional Insights and Improvements

Interesting observations were made from the collision data set, which is valuable for future collision detection functionality. In Figure 4, the rotational speed showed an upward trend at the moment of collision before decreasing, providing crucial information for monitoring collisions. Additionally, the experiments demonstrated the ability to distinguish between clockwise and counterclockwise rotations. As shown in Figure 5, the positive and negative changes in rotational magnitude correspond to clockwise and counterclockwise rotations, respectively.

Furthermore, the experiments revealed several design improvement points for the prototype:

1. **Increase Sampling Rate.** Improving the sensor sampling rate can provide more granular data, leading to more precise analysis of the curling stone's rotational dynamics.
2. **Enhance Program Stability.** Ensuring the stability of the Python software is crucial for long-term experiments. This can be achieved by implementing better error handling and optimizing the code.
3. **Implement Asynchronous and Multithreaded Processing.** Utilizing asynchronous and multithreaded processing can reduce CPU load and improve the system's real-time capabilities. This enhancement will enable smoother and more efficient data handling, especially during high-frequency data acquisition.
4. **Improve Real-Time Visualization.** Enhancing the real-time visualization capabilities of the system can provide immediate feedback to users. This can be achieved by optimizing the GUI and ensuring that it can handle high-frequency data updates without lag.
5. **Ensure Reliable Wireless Network Support.** Reliable wireless network support is essential to maintain data transmission integrity, especially during high-frequency updates.
6. **Reduce Power Consumption.** The cold environment of the curling rink affects battery performance. Reducing unnecessary power consumption can extend battery life, ensuring longer operational periods during experiments.

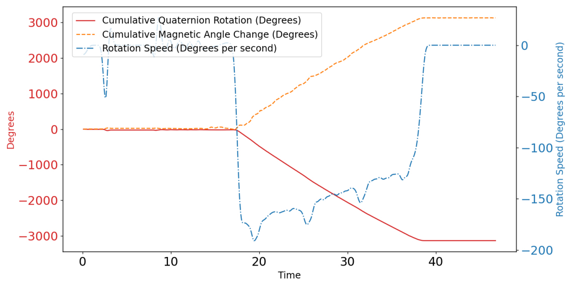

Figure 5: clockwise and counterclockwise rotations.

4 TABLET STONE

The Tablet Stone is intended for players who have competed in the All-Japan University Curling Championships, or a higher-level competition, and is intended to be used during practice, such as when practising delivery and sweeping. The requirements for the development of the Tablet Stone are listed below.

1. Since the players are concentrating on delivery and sweeping, it is appropriate to present information on the behavior of the stones in the vicinity where the players are looking.
2. Since the throwers and sweepers comprise different numbers of people, who also assume different postures and require different information, the

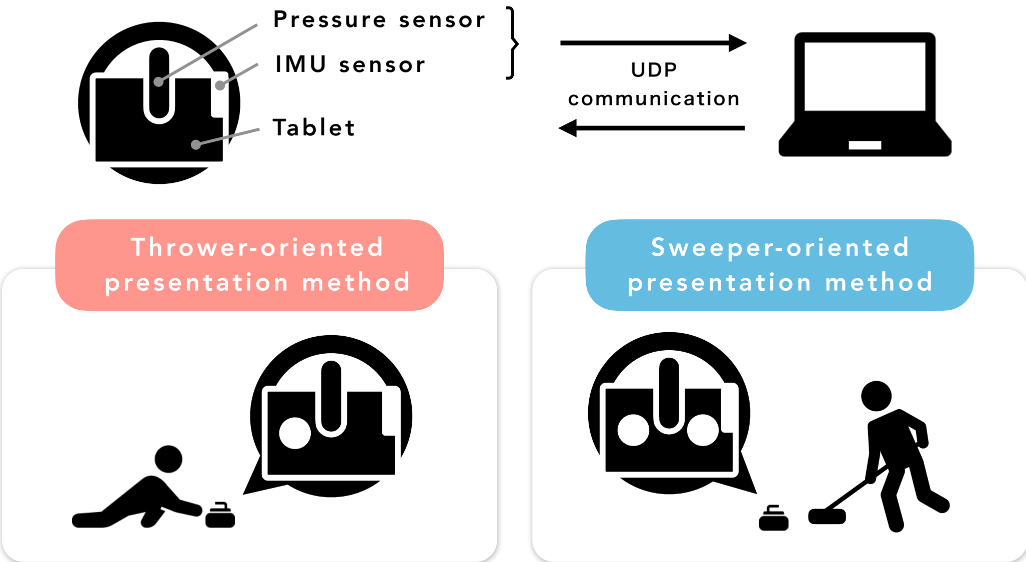

Figure 6: System configuration.

Figure 7: Examples of thrower-oriented presentation method.

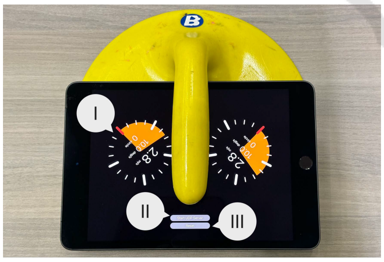

Figure 8: Examples of sweeper-oriented presentation method.

information presentation method must take these factors into account. In particular, the sweepers need to view information from a display on a rotating stone, and it is necessary to consider a presentation method that is not affected by the rotation of the stone.

The system configuration of the proposed Tablet Stone is shown in Figure 6. Tablet Stone displays the stone's behavior in real-time on the screen of an onboard tablet device. The sensor data from the IMU sensor mounted on the tablet and the data from the pressure sensor mounted under the handle are converted into moving speed, rotation speed, and rpm on a server located outside the curling sheet. These data are sent to the tablet and displayed. Data between devices is sent and received via UDP communication. The tablet was developed as an iOS application using SwiftUI on an iPad mini.

We propose two presentation methods, one for throwers and the other for sweepers. The pressure sensor mounted on the stone's handle is used to switch between the two presentation methods. Each presentation method is described in detail in subsections 4.1 and 4.2.

4.1 Thrower-Oriented Presentation Method

The thrower-oriented presentation method is used in situations where the thrower is holding the stone handle and delivering the stone. The appearance of the thrower-oriented presentation method is shown in Figure 7. The posture of the throwers is low, and the handle itself and the hand holding the handle obstruct the display. These factors were taken into consideration when deciding the placement of the presentation content and the size of the text. Figure 7-(I) is a meter that displays the stone's behavior in real-time. The values are, from the top, the moving speed and the rotation angle. The moving speed is also indicated by an orange circle meter. The maximum value of the circle meter is 10.0 m/s, which makes it easy to visually understand how fast the stone is sliding. The rotation angle is displayed to confirm that the slide is straight.

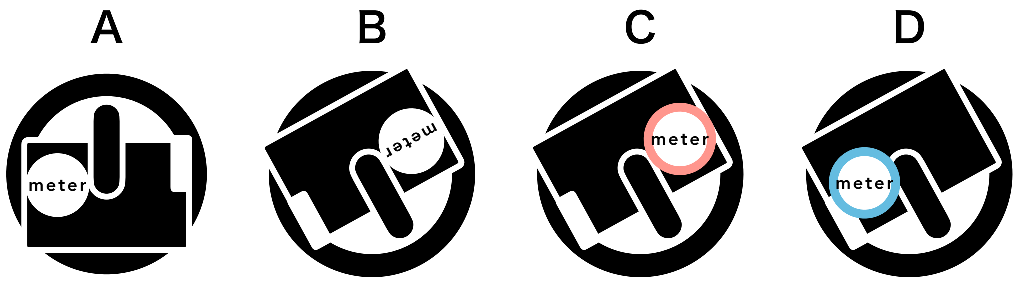

Figure 9: Examples of meter rotation direction fixation function and meter absolute position fixation function.

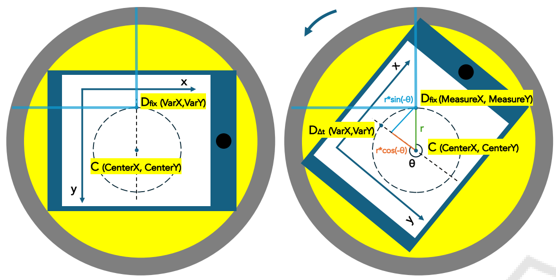

Figure 10: Example of meter absolute position fixation function.

Figure 7-(II) is a button to start UDP communication. Figure 7-(III) is a button to reset the orientation of the meter. After resetting, the meter faces the thrower's side.

4.2 Sweeper-Oriented Presentation Method

The sweeper-oriented presentation method is used in the situation where a stone has been thrown and the sweepers are sweeping the stone. The sweepers are in pairs and are positioned on either side of the stone as shown in Figure 8. The same information as in the thrower-oriented presentation method is displayed on the meter. Specifically, Figure 8-(I) is a meter that displays the stone's behavior in real-time. The values are, from the top, moving speed, rotation speed, and rpm. The moving speed is the same as that in the thrower-oriented presentation method. The rotation speed is displayed to allow the user to check how fast the stone is rotating. Rpm is displayed to allow the user to check how many rpm have been made. Figure 8-(II) is a button to start UDP communication. Figure 8-(III) is a button to reset the orientation of the meter. After resetting, the meter will face the sweepers on the left and right, respectively.

For the sweeper-oriented presentation method, we propose a Meter Rotation Direction Fixation Function and a Meter Absolute Position Fixation Function in order to maintain readability of the meter when the stone is rotating.

4.2.1 Meter Rotation Direction Fixation Function

The assumed initial position of the stone is as in Figure 9-A. When the stone rotates, the meter seen by the player also rotates (Figure 9-B), resulting in poor visibility of the meter. The meter rotation direction fixation function estimates the rotation angle of the stone from the rotation angle of the IMU sensor mounted on the tablet and rotates the meter in the opposite direction, as shown in Figure 9-C.

4.2.2 Meter Absolute Position Fixation Function

Even if the Meter Rotation Direction Fixation Function is applied, the meter will appear in front of the handle or behind the handle depending on the rotation of the stone, as shown in Figure 9-C. By applying the Meter Absolute Position Fixation Function, the position on the stone where the meter is displayed is fixed regardless of the rotation of the stone, as shown in Figure 9-D.

This function fixes the absolute position of the displayed meter by rotating the meter by θ degrees with respect to the center point. An illustration of the function is shown in Figure 10. The left figure shows the initial state without rotation, and the right figure shows the state with rotation. In the initial state without rotation, the coordinates of the reference position are $D_{fix}(VarX, VarY)$ and the center coordinates of the stone are $C(CenterX, CenterY)$. With rotation, $D_{\Delta t}(VarX, VarY)$ denotes the coordinates of the reference position, $C(CenterX, CenterY)$ denotes the coordinates of the center of the stone, and $D_{fix}(MeasureX, MeasureY)$ denotes the coordinates of the position drawn after rotation by θ degrees. Let r be the distance from C to D_{fix}. θ is the angle converted from the rotation angle of the built-in sensor to radians. The formulas for $MeasureX$ and $MeasureY$ are described below.

$$MeasureX = CenterX + r \times \sin(-\theta) \quad (4)$$

$$MeasureY = CenterY - r \times \cos(-\theta) \quad (5)$$

5 CONCLUSION

The developed system, featuring advanced IMU sensors and robust data processing techniques, represents a significant breakthrough in the real-time analysis of curling stone dynamics. This system not only measures rotational dynamics accurately, but also features the innovative Stone Behavior Presentation System, which displays real-time data interactively on a tablet device. This dual functionality enhances training effectiveness and strategic decision-making for both coaches and players.

Future enhancements will focus on increasing the sampling rate, improving system stability, and expanding real-time processing capabilities, ensuring the system remains cutting-edge. As for verification, we plan to verify if the tablets affect the trajectory of the stones and the players, and to test the two proposed methods to see if they affect the training effectiveness. Additionally, we plan to refine the Stone Behavior Presentation System to offer more customized and user-friendly interfaces that can adapt dynamically to different game scenarios and user preferences. Through these advancements, our system promises to revolutionize training methods and strategic planning in the sport of curling.

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