Inertial Sensors in Consumer Applications

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***Abstract*—This paper provides an insight into the important role of Inertial Measurement Unit (IMU) sensors in consumer applications, particularly in disease detection and motion analysis. We first present the basics of IMU technology and its applications in consumer electronics. We then focus on analysing the potential of IMUs for medical applications, particularly in the detection and monitoring of neurological disorders such as Parkinson's disease. Through a comprehensive review of existing studies, we show how IMU sensors can provide accurate motion tracking data, which is essential for understanding and assessing the clinical performance of movement disorders. In addition, the article explores the use of IMUs in sports science and daily health monitoring, highlighting their value in motion analysis and behavioural monitoring. Taken together, this article not only highlights the versatility and effectiveness of IMU technology in consumer applications, but also provides insights and directions for further use of this technology in healthcare.**

***Index Terms*—Acceleratio, Gyroscopes, Magnetometeters, Inertial Measurement Unit(IMU).**

I. Introduction

IN today's technology-driven marketplace, Inertial Measurement Unit (IMU) sensors have become an important and increasingly valuable part of commercial applications.Advances in IMU technology are not only bringing innovation to consumer electronics, but are also playing a central role in a wider range of applications. The aim of this paper is to explore the diverse applications of IMU sensors in the commercial sector and their potential value, with a particular focus on their use in disease detection, motion analysis and navigation. With the continuous development of the technology, IMU sensors have become a key component in a variety of products such as smartphones, wearable devices [1] and car navigation systems [2].

This paper will first introduce the fundamentals and technological evolution of IMU sensors to provide the reader with a comprehensive understanding of the background to this technology. We will then explore in detail the specific uses of IMU sensors in various commercial applications, including their use in the medical field to diagnose specific diseases (e.g. Parkinson's disease) [3] and their ability to perform accurate motion analysis in sports science. In addition, this paper discusses the use of IMU sensors in providing accurate navigation and positioning services, which are particularly important for modern vehicles and personal devices. By comprehensively analysing these key applications of IMU sensors, this paper aims to demonstrate the potential of this technology for a wide range of applications in current and future commercial markets. Finally, the article will summarise the commercial value of IMU sensors and provide an outlook on their future trends and potential markets.

II. Type of IMU sensor

An Inertial Measurement Unit (IMU) sensor is an electronic device used to measure and report certain physical quantities of an object, including accelerometers, gyroscopes and magnetometers. [4].

- **Acceleration**: These sensors, known as accelerometers, are capable of detecting and measuring the rate of acceleration along three spatial axes, typically referred to as the X, Y and Z axes. Their ability to sense gravitational forces enables them to help determine the orientation of a device.
- **Gyroscopes**: Gyroscopes measure the angular velocity of an object about three axes.
- **Magnetometers**: Some IMUs also contain magnetometers to measure the direction and strength of the earth's magnetic field.

Detecting changes in acceleration and rotation, including pitch, roll and yaw, is the principle of an Inertial Measurement Unit (IMU) [5].

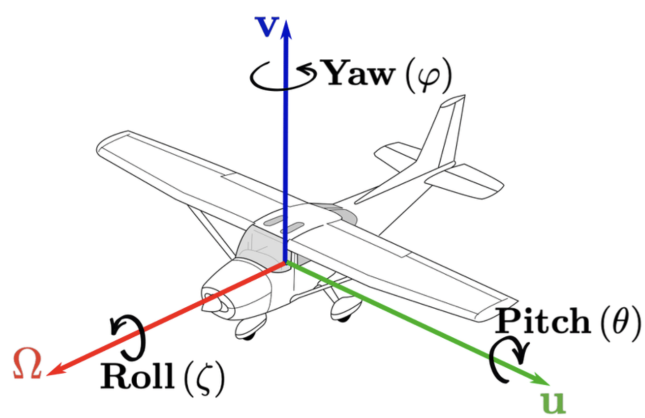


Fig. 1: Rotation Angle (Pitch, Yaw, Roll) [6]

III. IMU Technique

IMU sensor development has evolved from bulky mechanical systems to sophisticated technologies such as MEMS and optical sensors. It includes various gyroscopes and accelerometers, with a focus on MEMS for its compactness and efficiency. The integration of these sensors into advanced

IMUs enables applications ranging from consumer electronics to aerospace. Future trends focus on improving accuracy, reducing size and lowering cost. [7] Inertial sensors are widely used in a variety of contexts due to their ability to detect motion, vibration and shock. Advances in micro-electro-mechanical systems (MEMS) technology have opened up many new consumer and industrial applications for accelerometers and gyroscopes. Most modern accelerometers are manufactured using MEMS technology, which was originally developed in the 1970s for military and aerospace markets [8]. By 2016, production of MEMS inertial sensors had reached approximately 7.5 billion units, with a significant concentration in consumer electronics and automotive applications [8]. Future trends are focused on further reducing size and cost while increasing performance, thereby expanding the range of applications in areas such as consumer electronics, automotive and aerospace. Ongoing research into error modelling and performance optimisation continues to drive the evolution of IMU technology.

IV. Common IMU sensor commercialisation

Inertial Measurement Unit (IMU) sensors are used in a wide range of commercial applications and have become an integral part of modern technology. In smartphones and tablets, they are primarily used to detect the orientation and motion of the device, enabling automatic screen rotation, game control and other motion-based features. In aerospace, high-precision IMU sensors are used for aircraft navigation and control and are critical to the precise operation of aircraft, satellites and even spacecraft. In robotics, particularly unmanned aerial vehicles (UAVs) and automated guided vehicles (AGVs), IMU sensors are used for precise balance control and navigation. Wearable technologies use IMUs to track user activity and movement in applications such as motion tracking and health monitoring. In virtual reality (VR) and augmented reality (AR), IMU sensors are used to track the user's head and hand movements to provide an immersive interactive experience. In addition, IMU sensors are used in sports science to analyse athletes' movements and improve training results. As technology continues to advance, the use of IMU sensors in emerging fields continues to grow, and their versatility and ubiquity make them a key component of today's technological development. Here we look at some of the more commercially significant of these.

A. Disease recognition

Inertial measurement unit (IMU) sensors, particularly accelerometers, have shown significant potential in the diagnosis and management of Parkinson's disease (PD). These sensors have been used in several studies to quantify movement disorders in PD patients, including gait analysis, arm swing, step length measurement and trunk rotation. Combined with advanced data processing techniques such as support vector machines (SVM) and wavelet analysis [3], IMU sensors are able to provide detailed information about gait abnormalities and other movement disorders. These technologies not only improve the accuracy of Parkinson's diagnosis, but also provide new non-invasive methods for monitoring and managing the disease. In exploring the use of inertial measurement unit (IMU) sensors in the diagnosis and management of Parkinson's disease, we refer to the work of Vasco Ponciano, Ivan Miguel Pires, Fernando Reinaldo Ribeiro, Gonçalo Marques and others. Their systematic review, "Identification of Diseases Based on the Use of Inertial Sensors [3]: a Systematic Review", analyses in detail the effectiveness of IMU sensors in quantifying movement deficits in Parkinson's patients, including gait analysis, arm swing, step length measurements and trunk rotation, among many other features. In addition, the literature explores the use of advanced techniques in PD classification and gait disorder detection using Android-based apps, wavelet analysis combined with support vector machines (SVMs). These studies highlight the potential of IMU sensors for non-invasive monitoring and management of PD.

Early signs of Parkinson's disease include tremors, muscle rigidity and slow movements (bradykinesia). When a patient wears a wearable device such as a smartwatch or medical sensor, the IMU sensor can collect accelerations or angular accelerations from the patient's activities of daily living [9], which can be used to detect the condition through machine learning (KNN, SVM).

Inertial Measurement Unit (IMU) sensors play a key role in

Fig. 2: Common Parkinson's symptoms [10]

disease detection, particularly in the monitoring and diagnosis of conditions that affect motor function. These sensors pro-

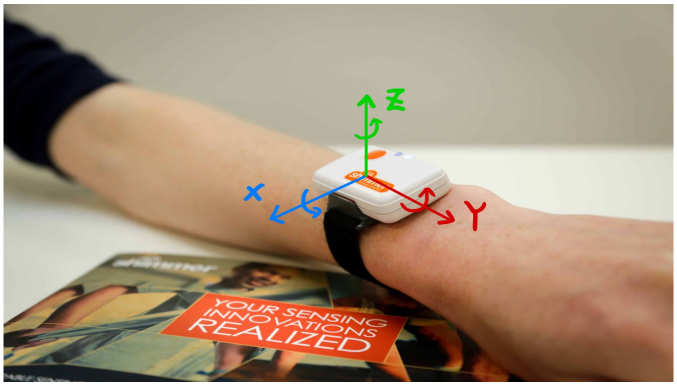


Fig. 3: Shimmer Sensor, Shimmer Research is a world-leading wearable technologies services and sensor manufacturing company supplying customized sensor development services. [11]

vide a non-invasive, continuous way to monitor a person's movement and posture, enabling unobtrusive collection of critical data during daily activities. By accurately measuring movement parameters such as gait, velocity and acceleration, IMU sensors can help clinicians and researchers detect early signs of motor dysfunction, monitor disease progression and evaluate the effectiveness of treatments. As a result, they are becoming increasingly important in modern medical diagnostics and patient monitoring.

B. *Analytics in sport*

Inertial Measurement Unit (IMU) sensors are an important part of motion analysis, able to accurately track an individual's trajectory and speed, providing detailed data for motion analysis. With integrated accelerometers and gyroscopes, the IMU is able to monitor and analyse a person's posture and orientation. At the same time, IMU sensors provide real-time motion feedback to help athletes optimise technique and improve performance, as well as capturing small changes in motion, which is valuable for advanced motor skill analysis and fine-tuning training programmes.

For example, the IMU can be used to perform a variety of exercise tests on footballers at different intensities. The paper "Inertial Sensor-Based Motion Tracking in Football with Movement Intensity Quantification" [12] uses IMU sensors to analyse the lower body movements of football players. IMUs are placed on the pelvis, thigh and calf to measure 3D acceleration, angular velocity and magnetic field strength. These sensors provide detailed data on flexion and extension angles and angular velocities of the knee and hip joints at different exercise intensities. The IMUs were found to have good validity compared to optoelectronic systems, highlighting their potential to accurately track and quantify the intensity of football movements, thus aiding training and performance analysis. For the future, it is possible to combine inertial measurement unit (IMU) sensors and deep learning, which are linked in football motion analysis by their combined ability to capture and interpret complex motion data.IMU sensors provide detailed, real-time motion data that captures the subtle movements of a player as he or she moves through the game of football. This data contains a wealth of information about the player's speed, direction and type of movement (e.g. running, passing or shooting). Deep learning algorithms, particularly those using neural networks, can analyse this complex data and identify patterns and insights that may not be apparent to the human eye.The synergy between IMU sensor data and advanced deep learning techniques allows for more sophisticated and accurate analysis of a footballer's performance, enabling coaches and sports scientists to make informed decisions and develop tailored training programmes [13].

Adidas used the 500Hz IMU sensor for the first time at the 2022 World Cup in Qatar. Throughout the match, the sensor collects highly accurate ball movement data in seconds and transmits it to the video referee, providing VAR teams with real-time, accurate ball data to support fast, accurate offside calls [14]. However, sensor footballs are not currently available for retail sale and can only be used in top-level football matches.

Fig. 4: adidas: 2022 World Cup to feature 500Hz match ball [14]

IMU sensors play an important role in a variety of sports, including basketball and skiing. In basketball, wrist-worn sensors can effectively detect and analyse various basketball movements such as shooting, dribbling and passing [15]. In skiing, data from IMU sensors not only helps determine the optimal sensor position on the skier's body, but also helps analyse and improve skiing technique, especially in terms of turning ability and stability. The use of these sensors greatly enhances the ability to understand and analyse an athlete's performance, providing invaluable data for training and improving skills [16].

C. *Inertial navigation system*

An Inertial Navigation System (INS) is a navigation technique used to determine the position and orientation of an object that does not rely on external signals such as GPS or any other external reference point. The core component of an inertial navigation system is the inertial measurement unit (IMU). This process is called 'integration' because it involves integrating acceleration to obtain velocity and then integrating

velocity to obtain position. Because INS does not rely on external signals, it is particularly useful in environments where GPS is not available (e.g. tunnels, deep sea or indoor environments). However, INS has its limitations. The main problem is that the small errors due to the integration process increase over time. This means that the INS must be periodically calibrated with an external signal (e.g. GPS) to correct these accumulated errors. Nevertheless, due to its independence and effectiveness when GPS is not available, the INS is still a very important component of modern navigation systems [17] [18] [19].
INS has a wide range of applications in aerospace, defence and self-driving cars. In self-driving cars, for example, in urban environments where good GPS data may not be available, IMUs can be used to help the car safely negotiate intersections or make turns. In this case, the IMU uses an algorithm called ”dead reckoning” to calculate the vehicle’s position directly from the IMU data. This involves integrating the 3-axis rate output into a direction, using the direction to rotate the measured body frame acceleration into the earth frame, then removing gravity and finally double integrating the earth frame acceleration into the position [18].
Integrating IMU sensors into smartphones to improve navigation accuracy, especially in GPS-impaired environments such as indoors or urban canyons. The combination of inertial sensors with image recognition-based positioning and technologies such as pedestrian inertial navigation (PDR) and INS measurements demonstrates the potential of smartphone inertial sensors for navigation applications [2]. These sensors can accurately measure rotational and linear motion, which is essential for calculating position and orientation in the absence of an external reference [7]. The accuracy of the IMU sensor determines the accuracy and reliability of the navigation system. Gyroscope bias, accelerometer bias and sensor noise are key parameters. These parameters determine the accuracy of IMU measurements and directly affect the system’s ability to accurately calculate position and orientation over time. Careful selection of the IMU based on these performance metrics is important, especially for applications requiring short-term navigation accuracy [20].

D. VR and console applications

Virtual reality (VR) games and gamepads use inertial measurement unit (IMU) accelerometers and gyroscopes to detect motion and measure acceleration and rotation speed. In VR games, IMU sensors are used to track the player’s head and hand movements for precise interaction and control. For example, IMUs in head-mounted displays (HMDs) respond quickly to the player’s head movements, reducing image drift and adding a sense of realism to the experience. The low latency of such sensors (less than 3 milliseconds) is critical for today’s high-definition AR/VR applications to maintain stability and ensure accuracy in highly variable environments [21].
Inertial Measurement Units (IMUs) can be used to track the movement of upper limbs in virtual reality (VR) in real time [23].IMU sensors collectively measure linear acceleration, angular rotation and magnetic fields. This data is used to

Fig. 5: VR Controller[22]

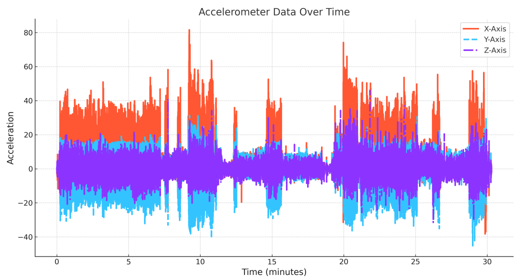
determine the orientation and motion of a connected device, such as a VR controller or headset. In VR gaming, the IMU data is translated into corresponding movements in the game environment that approximate the player’s actual physical movements. For example, the VR gaming experience is greatly enhanced by accurate, low-latency tracking of arm movements, which is critical for an immersive gaming experience. In VR environments such as third-person shooters, the technology enables precise control of a game avatar’s arms to realistically mimic the player’s actual movements [23].

V. Extended Motion Analysis

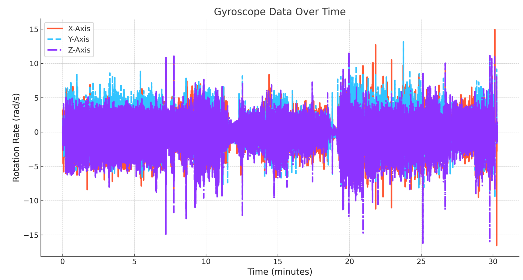
When it came to motion analysis, we did a test. We did a 30-minute run and a 12-minute walk wearing an Apple Watch Ultra with a high-gravity accelerometer and a high-dynamic-range gyroscope [24] on our right wrist. Linear acceleration and rotation rate were recorded using the Sensor Logger app on the iPhone.
The first graph 7(a), entitled ’Acceleration data over time’,

Fig. 6: Apple Watch Ultra [24]

shows the acceleration over time for the three axes (X, Y and Z). The unit of time is the minute and is shown on the horizontal axis from 0 to 30 minutes. Acceleration units are



(a) Acceleration data over time



(b) Gyroscope data over time

Fig. 7: Acceleration and Gyroscope Data Visualization

not labelled and are shown on the vertical axis. In the graph, data on the X-axis is shown in red, data on the Y-axis is shown in blue and data on the Z-axis is shown in purple. There appears to be rapid change on all three axes, with the Z axis showing the greatest change, followed closely by the X and Y axes. The second graph, 7(b), entitled 'Gyroscope data over time', shows the rate of rotation of the three axes over time. Similarly to the first graph, the horizontal axis is the time from 0 to 30 minutes and the vertical axis is the rate of rotation in radians per second (rad/s). Again, the data on the X-axis is shown in red, the data on the Y-axis is shown in blue and the data on the Z-axis is shown in purple. This graph shows a relatively smooth variation in the data, but there are some spikes indicating large variations in the rotation rate at certain times.

After receiving the data, we extracted 12 minutes of running and walking data and used the k-nearest neighbours algorithm (KNN) [25] [26] for classification and prediction.

As shown in Figure 8, a scatter plot entitled 'KNN Classification Result Visualisation (X and Y Acceleration)', this scatter plot shows the classification results using the K-Nearest Neighbours (KNN) model on the test set, where only the acceleration on the X and Y axes is considered. In the figure, the position of each point is determined by the acceleration values on the X and Y axes, and the colour of the points indicates the predictive labels of the KNN model (red for walking, blue for running). Looking at the colour distribution of the points, you can see how the model classifies the data points as running or walking based on the acceleration values on the X and Y axes. Looking at the scatter plot, there are certain areas of overlap, indicating that the model has some difficulty distinguishing between the two categories in these areas.

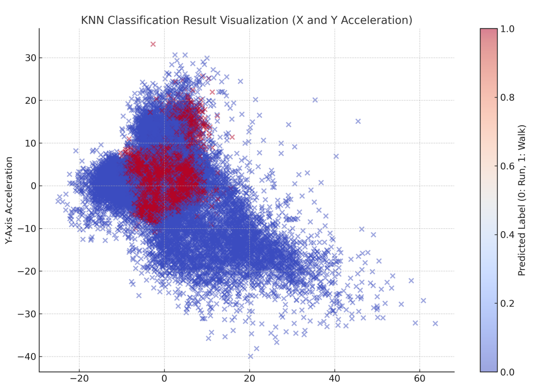


Fig. 8: KNN Classification Result Visualisation (X and Y Acceleration)

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Classification Report:
              precision    recall  f1-score   support

           0       0.83      0.78      0.80     22120
           1       0.79      0.84      0.81     22255

    accuracy                           0.81     44375
   macro avg       0.81      0.81      0.81     44375
weighted avg       0.81      0.81      0.81     44375


Confusion Matrix:
[[17187  4933]
 [ 3562 18693]]
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Fig. 9: Classification Report

Figure 9 is a text output showing the performance metrics of a binary classification model. It includes measures of precision, recall, F1 score and support. For label 0, the precision is 0.83 (how accurately the model predicts runs), the recall is 0.78 (the proportion of runs correctly identified by the model), the F1 score is 0.80 (a balanced metric of precision and recall) and the number of supports is 22,120. For label 1, the precision is 0.79, the recall is 0.84, the F1 score is 0.81 and the number of supports is 22,255. The overall accuracy is 0.81 and the macro average and the weighted average have precision, recall and F1 scores of 0.81. The confusion matrix shows the true labels versus the predicted labels: running was correctly classified as walking 17,187 times for label 0, and running was incorrectly classified as walking 4,933 times for label 1. Walking was misclassified as walking 4,933 times; walking was correctly classified with label 1,18693 times and walking was misclassified as walking 1,693 times: 18693 times and walking was misclassified as running 3562 times. Combining these metrics, the model performed relatively well with an overall accuracy of 0.81.

VI. Discussion

The future development of Inertial Measurement Unit (IMU) sensors in the commercial sector faces a number of limitations, but at the same time there are potential developments.

A. Limitation

- **Accuracy and Stability Issues**:Especially with low-cost IMUs, factors such as temperature changes, vibration and prolonged use can cause accuracy to degrade.
- **Cost Concerns**: High accuracy IMUs tend to be expensive. This limits their use in cost-sensitive applications.
- **Integration Challenges**: Integrating IMUs with other systems (such as GPS, cameras, etc.) to better position and navigate can present technical difficulties.

B. Future trends

- **Adaptive and Self-Learning Systems**:Using artificial intelligence and machine learning, IMUs can adapt to changing environments and improve performance over time.
- **Material and Design Innovations**: The accuracy and stability of IMUs could be improved and costs reduced through new materials and design approaches.

In other words, the advancement of IMU sensors depends on the fusion of cutting-edge technology and cross-disciplinary collaboration aimed at overcoming existing limitations and extending their usefulness to different commercial scenarios.

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