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## ADVANCEMENTS IN SENSOR TECHNOLOGY FOR AUTONOMOUS WALKER

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**Abstract.** This study presents a detailed analysis of gait trajectory and orientation using Time of Flight sensors and Inertial Measurement Units during controlled movement tests in a robotic walker. The tests were performed on three distinct path configurations: straight-line, rectangular, and lemniscate paths. The Time-of-Flight sensors measured changes in distance, while the Inertial Measurement Units captured yaw and orientation data. Notably, during sharp turns, the Time-of-Flight sensors detected significant distance fluctuations corresponding to the directional changes captured by the Inertial Measurement Units yaw data. The results highlight the effectiveness of combining Time of Flight and Inertial Measurement Units data to track stable movement, detect sudden turns, and monitor orientation adjustments in complex trajectories. This combined approach can offer critical insights for gait analysis, rehabilitation, and robotics navigation.

**Keywords:** *walker, rollator, sensors, Inertial Measurement Units; Time-of-Flight sensors.*

**Rezumat.** Acest studiu prezintă o analiză detaliată a traiectoriei și orientării mersului, utilizând senzori Timpul de Zbor și Unități de Măsurare Inerțială, în timpul testelor de mișcare controlată efectuate cu un cadru robotic de mers. Testele au fost realizate pe trei configurații distincte de traseu: linie dreaptă, traseu dreptunghiular și traiectorie în formă de lemniscată. Senzorii Timpul de Zbor au măsurat modificările distanței, în timp ce Unități de Măsurare Inerțială a înregistrat datele privind yaw-ul și orientarea. În mod remarcabil, în timpul virajelor bruște, senzorii Timpul de Zbor au detectat fluctuații semnificative ale distanței, corespunzătoare schimbărilor de direcție înregistrate de datele yaw ale Unități de Măsurare Inerțială. Rezultatele evidențiază eficiența combinării datelor Timpul de Zbor și Unități de Măsurare Inerțială pentru a urmări mișcarea stabilă, a detecta virajele bruște și a monitoriza ajustările de orientare în traiectorii complexe. Această abordare combinată poate oferi perspective esențiale pentru analiza mersului, reabilitare și navigația robotică.

**Cuvinte cheie:** *cadru de mers, rollator, senzori, unități de măsurare inerțială, senzori, Timpul de Zbor.*

## 1. Introduction

By 2050, the world's populace will encounter a significant demographic transformation, characterized by a pronounced increment in the older demographic. The proportion of the demographic aged 65 years and above is projected to rise from 10% in the year 2022 to 16% by the year 2050 [1]. Even more remarkable is the anticipated triple of the cohort aged 80 and over during the same timeframe [2,3]. This swift proliferation of the senior population has generated increased interest in developing technologies designed to enhance senior citizens' quality of life, independence, and security.

Regions such as Japan, the United States, and Europe are among those exhibiting the highest percentages of elderly populations. In these areas, the global market for medical walking aids is forecasted to expand by 5% between 2022 and 2029 [4,5]

Furthermore, the World Health Organization (WHO) estimates that approximately 2.5 billion people worldwide [6] will require one or more assistive devices, underscoring the growing need for such technologies. Maintaining personal autonomy in old age is not only essential for physical health but also critical for psychological well-being. Walking aids, therefore, are increasingly used not just in therapeutic settings, but also in the day-to-day lives of senior citizens.

Among the essential technologies that support aging populations, walkers play a vital role. These devices have long been relied upon for providing mobility and independence to individuals with limited movement capabilities. Nonetheless, despite their prevalent application, conventional walkers frequently exhibit deficiencies concerning their functionality and flexibility in accommodating the evolving requirements of their users. As a result, there is a growing demand for innovations that enhance their functionality through intelligent monitoring systems and improved design. These improvements are not only crucial for facilitating movement but also for ensuring safety and monitoring the health of the elderly users who depend on them [7].

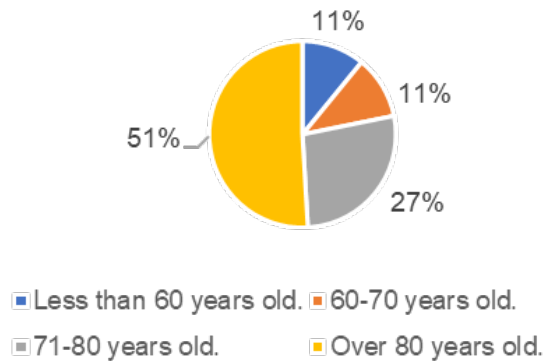
Considering these challenges, this paper presents the concept and evolution of a "smart walker," which is intended to support older adults in their everyday tasks. In contrast to conventional walkers, this innovative model integrates cutting-edge sensors capable of monitoring and evaluating the user's movements, thereby providing significant insights into their ambulation patterns. This information can subsequently be employed to identify potential problems such as balance issues or a heightened risk of falls. By incorporating user input throughout the design phase, the walker seeks to tackle real-life challenges while remaining cost-effective, ensuring that these cutting-edge technologies are available to a wider demographic of elderly individuals.

## 2. Materials and Methods

### 2.1. Surveys

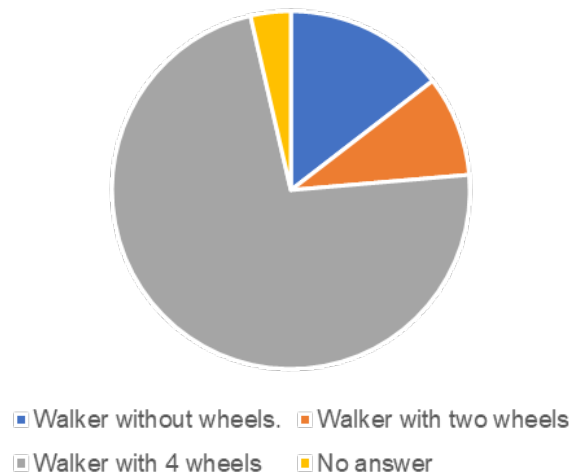
The initial phase in the creation of this smart walker involves conducting thorough surveys with current walker users. In the survey 55 elderly people participated. The objective of these investigations was to collect data regarding the obstacles encountered by users and to ascertain prospective domains for enhancement in the design and operational efficacy of current walking aids. Among the most mentioned issues were challenges with maneuverability, insufficient feedback on walking performance, and safety concerns, especially regarding fall prevention. By administering these surveys, participants emphasized the need for a mobility aid that not only promotes walking but also provides real-time feedback on their gait dynamics and stability while moving.

The data gathered from the surveys, as shown in the Figure 1, provide valuable insights into the demographic distribution and the types of walkers currently used by individuals. It is imperative to acknowledge that a substantial proportion, exceeding fifty percent (51%), of the individuals surveyed were aged over 80 years, indicating that the necessity for advanced mobility assistance devices is particularly paramount for this age group. Furthermore, 27% of participants belong to the 71-80 age bracket, which further underscores the necessity of developing devices that specifically address the requirements of elderly individuals. Interestingly, only 11% of users were under the age of 60, underscoring that most walker users are from the senior population, where mobility challenges are more prevalent.



**Figure 1.** Age distribution of walkers users.

The Figure 2 reveals that a significant majority (73%) of users rely on walkers equipped with four wheels, suggesting that these devices are preferred for their stability and ease of use. However, 14% of users still utilize walkers without wheels, which may indicate a demand for greater support, but potentially at the expense of manoeuvrability. Utilization of walkers equipped with two wheels was reported by 9% of the participants, whereas a minor fraction (4%) of the respondents abstained from disclosing information pertaining to their specific type of walker. These results underscore the importance of incorporating real-time feedback mechanisms into walker designs, particularly for most users who are in the 80+ age bracket and primarily using four-wheeled walkers. For these users, safety and balance monitoring are critical due to the higher risk of falls. By focusing on these demographic and user preference insights, the development of the smart walker can address the most pressing concerns, ensuring that the device not only provides mobility support but also enhances safety and gait stability for older adults who are the primary users of such devices.



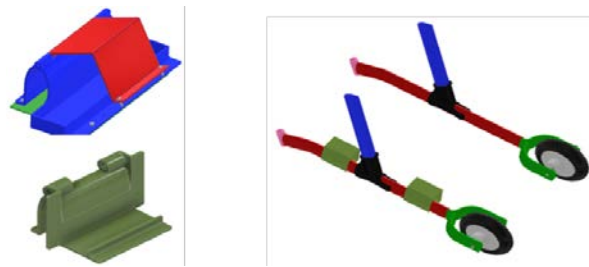
**Figure 2.** Types of walkers used by current users.

## 2.2. Prototype Design

The development of a smart walker began by sourcing cost-efficient components, including sensors and batteries, guided by user feedback to ensure practicality and affordability. The team modified a commercial walker by designing and installing prototypical supports for essential components such as batteries, screens, and regulators. These modifications allowed for the seamless integration of a custom-designed electronic board equipped with multiple sensors.

The constituent elements of the prototype were conceptualized employing Autodesk Inventor® and subsequently manufactured via additive manufacturing techniques, specifically utilizing polylactic acid (PLA) and resin materials, as illustrated in Figure 3. The selection of these materials was predicated on their robust durability and minimal weight characteristics, which are paramount for optimizing user comfort and facilitating ease of utilization.

As seen in Figure 3, the battery, controller, and other components were strategically placed to optimize the walker's functionality.



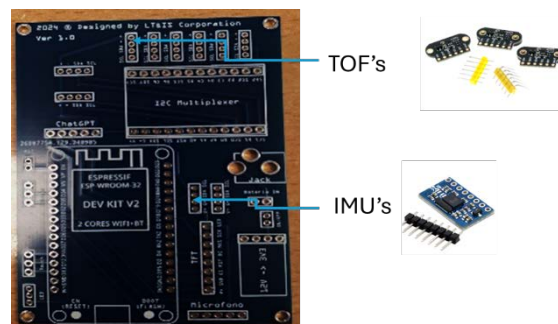
**Figure 3.** Age Distribution of Walkers Users.

Thanks to 3D printing, using materials such as polylactic acid (PLA) and resins, it is much easier and cheaper to create prototypes. In this way, it is possible to perfect at a lower cost the different prototypes of the parts that are necessary for our final prototype.

## 2.3. Design the electronic board

The inclusion of sensors in mobility aids such as walkers is crucial for monitoring and improving gait performance, especially for elderly users. These sensors assess gait in real time and provide precise data on speed, balance, and stability. This information helps detect gait issues that could indicate health problems or an increased risk of falls [8].

The electronic board, designed for scalability (Figure 4), uses a low-power ESP32 microcontroller with multiple communication interfaces and a 32-bit processor for real-time data processing. This setup allows for future updates and improvements.



**Figure 4.** ESP32 Development Board with Integrated I2C Multiplexer, IMU BNO055 [9] and Sensor Connections VL53L1X [10].

The sensors integrated into the walker record speed, direction, and balance during use. The primary goal is for users to feel supported by technology, not overwhelmed by it. This data can be analyzed in real time to alert the user or caregiver of any unusual movement patterns that might suggest a higher risk of falling.

Various sensors have been incorporated on this board, including proximity sensors, heart rate sensors, and pressure modules. However, in this article we will focus specifically on the Time of Flight (ToF) and Inertial Measurement Unit (IMU) sensors [11,12]. These sensors are critical for motion analysis and accurate distance measurement, allowing for better stability assessment and early detection of imbalances during device use. When deciding where to locate the IMU, we analyzed which part of the walker would be best and decided to integrate everything within the board to protect the sensor [13].

#### **2.4. Time of Flight sensors for user legs detection**

Time-of-Flight (TOF) sensors are incorporated into robotic walker systems to provide precise, real-time distance measurements between the user's legs and the walker. These sensors operate by measuring the time it takes for emitted light to reflect off the user's legs, enabling accurate detection of leg position and movement, even during dynamic locomotion. The data collected by the TOF sensors is non-intrusive, high-resolution, and processed in real time, supporting critical functionalities such as gait cycle identification, continuous monitoring of leg motion and posture, and dynamic adjustment of the walker's speed to synchronize with the user's walking velocity.

The primary objective of integrating TOF sensors is to enhance gait analysis by offering detailed spatiotemporal metrics. These include measurements of step length and width, walking speed, and cadence, as well as postural assessments to evaluate alignment and stability.

$$\text{Step Length} = |x_{n+1} - x_n|, \quad (1)$$

where:  $x_n$  is the position of one foot and  $x_{n+1}$  is the position of the opposite foot in the forward direction.

$$\text{Step Width} = |d_{\text{left}} - d_{\text{right}}|, \quad (2)$$

where:  $d_{\text{left}}$  and  $d_{\text{right}}$  are the distances from the sensor to the left and right legs respectively.

This information allows for the characterization of the user's walking patterns and facilitates improvements in mobility and ergonomics. By tracking these parameters, the sensors estimate walking speed and step frequency, enabling the robotic walker to adapt dynamically to the user's pace, ensuring synchronized operation.

TOF sensors also play a vital role in ensuring user safety and system adaptability. The system can autonomously halt or adjust its behaviour in response to irregularities in the user's gait, providing enhanced support and mobility. The integration of TOF sensors in robotic walkers creates a reliable platform for advanced gait analysis and real-time adaptability, significantly improving user mobility, stability, and rehabilitation outcomes.

#### **2.5. Wrapping effect of the IMU correction**

Due to the cyclical nature of angular measurements from Inertial Measurement Unit (IMU) sensors, particularly when orientation is represented using Euler angles or yaw-pitch-roll conventions, a phenomenon known as the wrapping effect can occur. Angular data is

typically constrained within a fixed range (e.g.,  $-180^\circ$  to  $180^\circ$  or  $0^\circ$  to  $360^\circ$ ), and transitions across these boundaries may result in discontinuities in the data, manifesting as abrupt changes or "jumps" in the recorded values.

The wrapping effect interfere real-time navigation, gait analysis, and trajectory prediction in robotic walkers. Effectively managing this issue ensures seamless data interpretation, enabling reliable performance even in complex environments. To address this issue and prevent the wrapping effect, is necessary to correct the IMU values using the following equation.

$$\theta_{unwrap}(n) = \theta(n) + 2\pi \cdot k \quad (3)$$

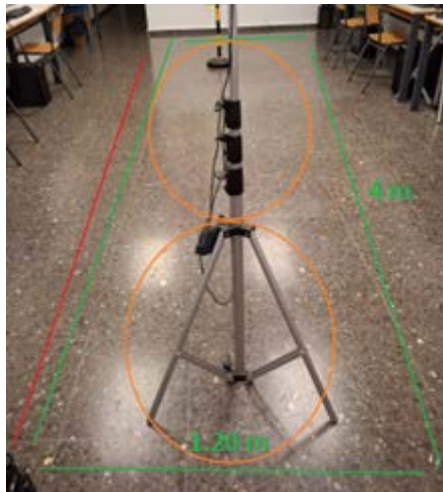
where:  $\theta(n)$  is the original angle at index  $n$ ;  $k$  is an integer correction factor, adjusted based on whether the difference between consecutive angles  $\theta(n) - \theta(n - 1)$  exceeds a threshold, typically set to  $\pi$  radians.

### 3. Results and Discussion

Three road configurations were used to test performance and maneuverability as in [14].

The length of the routes in the case of the rectangle is 4 meters deep and 1.2 meters wide as can be seen in Figure 5.

- Straight Line Tests (Red): These tests focused on basic metrics like speed, acceleration, and stability on a straight path without turns.
- Rectangular Road Tests (Green): This phase introduced right-angle turns, simulating urban conditions and evaluating the ability to handle sharp directional changes.
- Lemniscate Curve Tests (Orange): The final tests involved a more complex path shaped like a lemniscate curve to assess agility and control through continuous directional changes and sharp turns.



**Figure 5.** Paths configurations used in the laboratory test with the developed walker.

*(It is originally developed by the authors).*

In Figure 6, the TOF sensors are strategically positioned to detect the movement of the legs rather than focusing on the feet. This setup is designed to capture the dynamic range and motion of the legs, which provides more relevant data for gait analysis for our objective. Monitoring leg detection [15], rather than foot movement, is important because the legs provide a clearer picture of gait patterns, balance, and overall mobility in the walker.

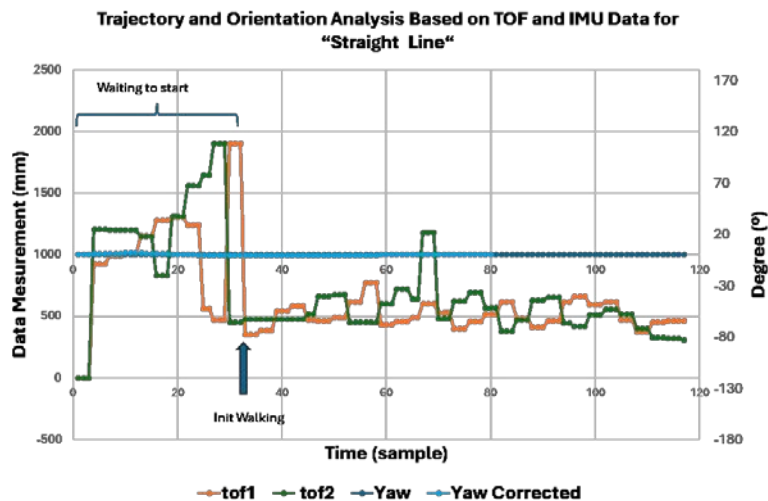


**Figure 6.** Developed Walker with electronic board integrated in its structure.

The feet, on the other hand, are more influenced by minor changes in terrain or posture, which could distort the data related to the biomechanics of walking. Therefore, TOF sensors are better positioned to track the legs for a more accurate representation of the user's motion and gait characteristics.

In Figure 7, we can observe the representation of the trajectory and orientation analysis based on data obtained from 2 TOF's and 1 IMU sensors during a straight-line movement. The yaw angle in degrees indicates the orientation. TOF1 and TOF2 show the distance measurements captured by the TOF sensors during the movement. In the first samples (0-30), there is a significant increase in the measurements, indicating an initial movement but these movements were initial and stopped movements during the test, just movements of the legs. After those values, the fluctuations reflect adjustments in the measured distance as the person progresses, suggesting small movements or variations in the terrain.

The Yaw angle value, remains almost constant, indicating that the movement was mainly in a straight line without major turns. This is key for verifying directional stability during a straight path.

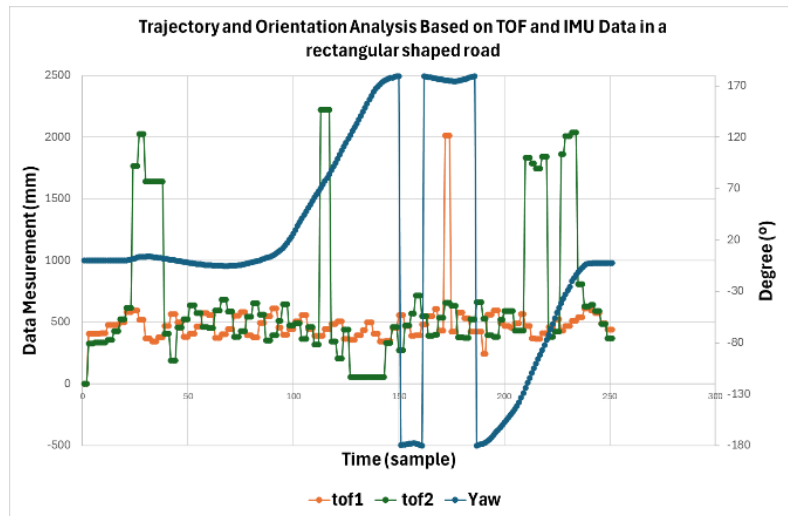


**Figure 7.** Visualization of a straight-line trajectory captured using Time of Flight (TOF) sensors combined with Inertial Measurement Units (IMUs).

In Figure 8, the analysis of trajectory and orientation during a rectangular-shaped movement is shown where TOF and IMU data were used to detect changes in distance and orientation. The horizontal sections of the trajectory are visible in the stable parts of the TOF1 and TOF2 lines. These parts represent when the subject is moving along the straight sections of the rectangle. The values for TOF1 and TOF2 remain relatively stable during these periods,

indicating that the distance to the environment does not change significantly, similar to what was observed in Figure 7 when analyzing the straight-line movement.

Figure 8 shows pronounced fluctuations and peaks in the TOF1 and TOF2 lines during the sharp turns of the rectangular trajectory. These are especially evident when the measurements increase or decrease rapidly, reflecting the abrupt directional changes, nearly  $180^\circ$ , as the subject turns the corners of the rectangle.

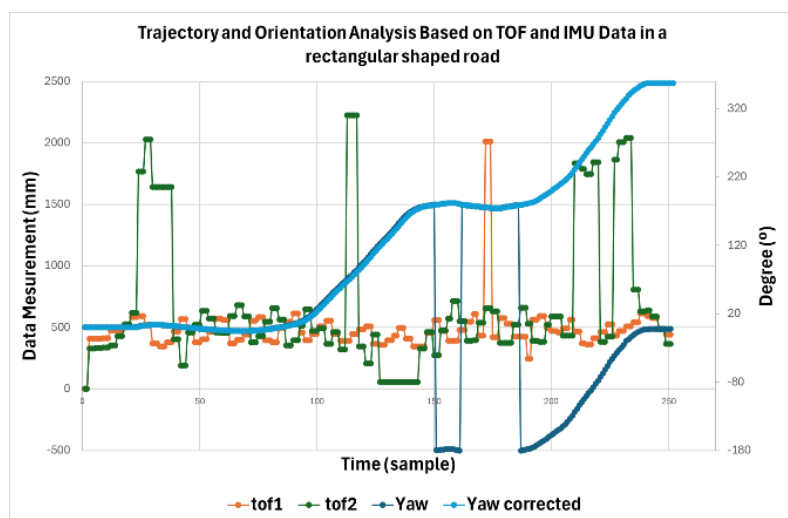


**Figure 8.** Visualization of a rectangular-shaped road trajectory captured using TOF/IMU sensors.

The rectangle is not wide, and there is little displacement needed to perform these turns, as can be seen in the following figure.

The yaw angle captures changes in orientation. As expected in the narrow rectangle, the yaw values show a rapid transition during the turns, where the orientation changes sharply. The IMU *wrapping effect* is also evident during these segments, as the yaw angle wraps around due to the IMU's limitations in representing continuous rotational data, leading to sudden changes in yaw values near  $\pm 180^\circ$ .

This Figure 9 demonstrates how TOF and IMU sensors can detect both stable linear movements and sharp directional changes in a rectangular trajectory with a Yaw corrected from the unwrapping effect.

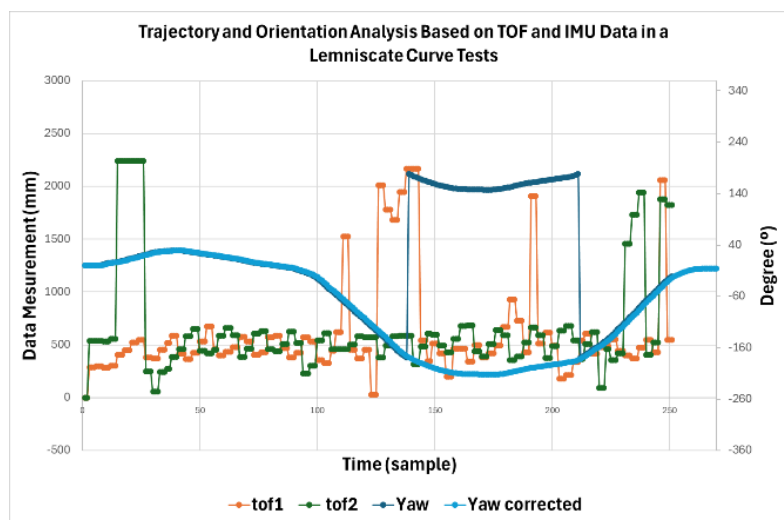


**Figure 9.** Visualization of a rectangular-shaped road trajectory captured using TOF/IMU sensors with corrected YAW of the wrapping effect.

In Figure 10, we observe how the TOF and IMU data together reflect the subject's movement through a lemniscate path. The TOF data show peaks that correspond to sharp turns in the trajectory. These peaks occur precisely at points where the subject is performing a directional change, aligning with the pronounced curves in the Yaw angle.

Yaw angle measures the orientation or rotation of the subject as they follow the lemniscate curve. The Yaw corrected line remains smooth, indicating how the IMU compensates for continuous directional changes and the wrapping effect during the Lemniscate Curve Tests. Around the middle of Figure 10, particularly after sample 150, there is a clear transition in Yaw, representing the subject making a significant turn along the curve. This transition highlights both large and small orientation adjustments, demonstrating the complexity of the lemniscate trajectory.

Overall, this Figure 10 illustrates how TOF data can detect sudden changes in direction, while the IMU provides detailed orientation information, compensating for the continuous directional shifts experienced in such complex paths. The combination of TOF and IMU allows for accurate tracking of both stable movements and abrupt turns throughout Lemniscate Curve Tests.



**Figure 10.** Visualization of the third test using a path shaped as a lemniscate curve.

According to the empirical data and analytical findings derived from the Time of Flight (TOF) and Inertial Measurement Unit (IMU) sensors depicted in the preceding figures. The combination of TOF and IMU sensors significantly increases the overall reliability and accuracy of the developed system. TOF sensors accurately detect variations in step distance, while the speed of these alterations indicates the individual's walking speed. This dual-sensor methodology provides comprehensive data on gait movement onset and gait speed.

TOF sensors exhibit marked efficacy in recognising abrupt directional deviations, as substantiated by pronounced spikes in the data. Concurrently, the IMU facilitates the smoothing of the yaw angle and mitigates challenges such as angle unwrapping. The TOF sensors specifically document alterations in foot movement, delivering real-time insights into the dynamics of walking.

Our inquiry reveals the capability to detect sudden gait modifications and abrupt directional shifts utilizing strategically positioned sensors and Inertial Measurement Units (IMUs). This proficiency is pivotal for comprehending and analysing distinctive locomotion patterns, particularly in individuals exhibiting atypical gait characteristics. By meticulously

capturing these swift transitions, our methodology provides profound biomechanical insights essential in contexts that necessitate stability and adaptive directional responses, such as rehabilitation or mobility assistance devices.

The lemniscate trajectory effectively encapsulates the curves users may encounter in urban environments. It serves as a valuable instrument for our testing, simulating authentic conditions. Our analysis indicates that the IMU data enables us to investigate the turning maneuvers along the lemniscate curve, while the TOF sensors yield detailed information regarding foot positioning and step count during locomotion.

The rationale underpinning our methodology resides in the high precision and immediate feedback our sensor system provides. By integrating IMUs with other sensors, we amass nuanced data that contributes to advancing sophisticated assistive technologies, including robotic walking aids or prosthetics. This data-centric strategy guarantees that forthcoming innovations can dynamically adapt to users' requirements, enhancing stability and safety across diverse environments.

Our testing identified areas for improvement in the performance of TOF sensors. For example, we observed that people with very thin legs or who walked with their legs too close together were sometimes not detected, which slightly affected the accuracy of the data. To improve our system, we propose integrating two TOF sensors per leg into future walker designs, providing greater redundancy and improving detection accuracy. Additionally, we noticed that low light conditions affected the performance of the TOF. To address this, we plan to add LED lights to the walker to improve visibility and ensure the sensors work optimally in both the front and rear sections.

These observations highlight opportunities for refinement and emphasise the importance of the proposed improvements, which will ensure more consistent and reliable data collection in various scenarios.

## 5. Conclusions

The combination of TOF and IMU sensors provides a robust system for analyzing movement trajectory and orientation changes, especially in complex paths like the lemniscate curve for robotic walkers.

TOF sensors are highly effective in detecting sharp directional changes, as evidenced by the pronounced peaks during turns, while the IMU's yaw data accurately reflects orientation shifts.

In narrow trajectories, such as the rectangular path, the system captures abrupt 180° turns, providing valuable insights into directional stability and control. The IMU wrapping effect, particularly in yaw measurements, requires consideration, as it can influence data interpretation when continuous rotations occur.

These findings demonstrate the potential application of this sensor fusion technique in fields like rehabilitation, robotics, and human motion tracking, where accurate trajectory and orientation analysis are essential.

**Conflicts of Interest:** The authors declare no conflict of interest.

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