Integrating OpenPose into Autonomous Mobile Robotic Platforms for Enhanced Motion Analysis in Elderly and Mobility-Impaired Care

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Abstract— **As the population ages, there is a growing need for innovative solutions to monitor and assist the elderly and people with mobility impairments in their daily lives. This paper explores the integration of OpenPose, a state-of-the-art computer vision technology for motion analysis, into autonomous mobile robotic platforms. Such platforms aim to automatically position themselves in optimal locations for motion analysis, thereby providing a novel approach to monitor and support individuals requiring care. By leveraging the precision of OpenPose in capturing joint angles from video footage, the study addresses the challenge of providing continuous, non-invasive motion analysis in dynamic environments. The robotic platform's autonomy enhances real-time monitoring and intervention feasibility, potentially transforming care provision for the targeted demographics. This research outlines the system's design, implementation, and preliminary evaluation, demonstrating its capabilities in a controlled environment. The findings suggest significant potential for improving the quality of life and care efficiency while highlighting areas for further development. Integrating OpenPose into such platforms represents a promising step forward in intelligent healthcare, offering a scalable solution for motion analysis in elderly and mobility-impaired care.**

I. INTRODUCTION

In healthcare, the aging population and individuals with mobility impairments present significant challenges and opportunities for innovation in care and support. Accurate and continuous monitoring of physical movements and joint angles plays a crucial role in assessing these individuals' well-being and rehabilitation progress [1]. Traditionally, motion analysis in healthcare has been restricted to clinical settings, relying on complex marker-based tracking systems for precision, which may not be feasible or comfortable for continuous use in everyday environments [2].

The advent of computer vision technologies, notably OpenPose, has heralded a new era in motion analysis by providing the means to accurately estimate human joint positions and angles from standard video footage. This technology initially embraced for its potential within physiotherapy for injury risk assessment and rehabilitation monitoring, now stands at the cusp of transformative application in broader healthcare contexts [3], [4].

This paper explores the innovative integration of OpenPose into autonomous mobile robotic platforms designed to navigate and position themselves optimally within a home or care facility environment. It presents the concept of integrating OpenPose with ROS2 on mobile robots, highlighting a novel approach towards enhancing motion analysis in non-clinical environments. Such platforms aim to bring the advanced capabilities of motion analysis directly to the individuals who need it most, offering a novel solution for continuous, non-invasive monitoring of the elderly and people with mobility impairments. This integration promises to enhance the accuracy and relevance of motion analysis outside of clinical settings and provide a new level of autonomy in personal healthcare monitoring.

By leveraging OpenPose's capabilities within an autonomous robotic framework, this study aims to address the challenges of applying high-precision motion analysis in dynamic and unstructured environments typical of daily living. The objectives are twofold: firstly, to assess the feasibility and reliability of OpenPose when embedded in a mobile platform for real-time motion analysis, and secondly, to explore the potential benefits and implications of such technology in improving the quality of life and care for the elderly and mobility-impaired individuals. It is crucial to note that the focus of this paper is on validating the concept of such integration, rather than on the practical implementation within robotic platforms.

The remainder of this paper is structured to provide an in-depth exploration and evaluation of our proposed system. The second section, 'OpenPose and the Evolution of Motion Analysis', offers a comprehensive background on the OpenPose technology, tracing the evolution and advancements in motion analysis studies. It highlights the tool's applications and its significance in the current state of the art. Following this, the third section, 'Integrating OpenPose with ROS2 on Mobile Robots', delves into the specifics of combining OpenPose technology with ROS2 on mobile robotic platforms, setting the stage for our conceptual validation. The methodology section then outlines the theoretical framework and the operational parameters considered for our study, paving the way towards the practical application of this integration. In the 'Results' section, we present the outcomes of our preliminary assessments, showcasing the potential of the system in real-world scenarios. This is followed by a discussion where we evaluate the implications of our findings for healthcare providers, caregivers, and patients, addressing the strengths, limitations, and avenues for future research. Finally, the 'Conclusion and Future Work' section summarizes the key insights gleaned from our study and outlines the prospects for advancing this promising intersection of robotics, computer vision, and healthcare.

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II. OpenPose and the Evolution of Motion Analysis

OpenPose represents a significant leap forward in computer vision and motion analysis, thanks to its unique capability to accurately estimate human joint positions and angles from video footage. Developed by the Carnegie Mellon PerceptLab, OpenPose is the first real-time system to detect the critical points of the human body, hand, face, and foot. It is a versatile tool for many applications beyond traditional physiotherapy and healthcare [5].

At the core of OpenPose lies a sophisticated machine-learning model that processes video data to simultaneously identify and track multiple human body parts. This is achieved through a complex convolutional neural network (CNN) that has been trained on a vast dataset of images containing annotated human poses. The result is a highly robust system capable of performing detailed motion analysis in real time, even in environments with multiple individuals and varying lighting conditions [6].

While the initial development of OpenPose was geared towards enhancing motion analysis in physiotherapy, its potential applications span several fields, each benefiting from its precision and versatility. Here are a few notable examples:

a) Sports Science and Athletic Training: In sports science, OpenPose facilitates detailed analysis of athletes' movements to improve performance and prevent injuries. Coaches and trainers use data captured by OpenPose to refine techniques, optimize training regimens, and tailor rehabilitation programs for injured athletes.

b) Animation and Game Development: The entertainment industry has embraced OpenPose to create more realistic animations and enhance motion capture techniques. By accurately tracking body movements, OpenPose allows animators and game developers to generate natural-looking character animations, contributing to more immersive gaming and film experiences.

c) Surveillance and Security: OpenPose's ability to detect and analyze human postures in real time has applications in surveillance and security. Systems equipped with OpenPose can identify suspicious behaviors or detect individuals in distress, enhancing safety in public spaces.

d) Human-Computer Interaction (HCI): OpenPose has paved the way for more intuitive human-computer interaction systems. By recognizing gestures and body language, interfaces become more accessible and responsive, expanding the possibilities for how humans engage with digital devices and environments.

e) Rehabilitation Robotics: Beyond the autonomous mobile platforms discussed in this paper, OpenPose is instrumental in developing rehabilitation robots. These robots analyze patients' movements to provide personalized therapy sessions, combining the precision of OpenPose with the adaptability of robotic systems to aid recovery processes.

The integration of OpenPose into autonomous mobile robotic platforms for elderly and mobility-impaired care is just one example of how this technology pushes the boundaries of what is possible in motion analysis. As OpenPose continues to evolve, it is expected to catalyze further innovations across various disciplines, underscoring its role as a transformative tool in understanding and enhancing human movement.

III. Integrating OpenPose with ROS2 on Mobile Robots

Integrating OpenPose into an autonomous mobile robotic platform using ROS2 marks a sophisticated endeavor to enhance motion analysis, particularly for healthcare applications [7]. This process requires a judicious selection of hardware and software, alongside meticulous integration, to ensure seamless operation [8].

The hardware foundation includes a mobile robotic base capable of autonomous navigation, such as the HERA (RoboFEI@Home), or a custom platform with an Omnidirectional drive and LIDAR for navigation [9], [10]. A high-performance computing unit, like the NVIDIA Jetson Xavier NX, is essential for processing the complex computations required by OpenPose in real time. A high-quality camera, preferably with 1080p resolution or higher, is also necessary to capture detailed motion data. The Intel RealSense cameras are recommended for their depth-sensing capabilities, which can benefit detailed motion analysis.

On the software front, the latest version of ROS2 serves as the middleware, facilitating communication between the robotic platform's components. OpenPose, a state-of-the-art computer vision library for human pose estimation, must be compiled for the computing unit's specific operating system and architecture. This setup also necessitates ROS2-compatible driver packages for both the robotic platform and the camera, enabling direct hardware interfacing.

The integration process begins with setting up the ROS2 environment on the computing unit, followed by installing OpenPose. A ROS2 node is then developed in C++ or Python to initialize OpenPose and configure the camera input. This node is responsible for processing camera frames, converting them into a format suitable for OpenPose, and handling the pose estimation. An example code snippet in C++ might illustrate the initialization of an OpenPose wrapper in asynchronous mode for real-time processing. When a new frame arrives from the camera, it is converted and fed into OpenPose for joint position and angle estimation. Below is an example of the environment configuration in ROS2:

```
source /opt/ros/<ros2-distro>/setup.bash
mkdir -p ~/ros2_openpose/src
cd ~/ros2_openpose/
colcon build
source ~/ros2_openpose/install/local_setup.
    bash
```

Listing 1. Setting Up ROS2 Environment

Furthermore, the integration extends to controlling the robotic platform based on the analysis provided by OpenPose. This could involve navigating towards a person for closer monitoring or maintaining an optimal distance and angle for precise motion analysis. Implementing ROS2 services, actions, or topics for robotic control allows for dynamic adjustments based on real-time data.

Integrating OpenPose with ROS2 on a mobile robotic platform is complex but rewarding. It combines advanced computer vision with robotic autonomy, opening new possibilities for real-time human motion analysis in various environments. This sophisticated setup pushes the boundaries of traditional healthcare monitoring systems, offering innovative solutions for patient care and support.

```cpp
#include <openpose/headers.hpp>

// Initialize OpenPose wrapper
op::Wrapper opWrapper{op::ThreadManagerMode::
    Asynchronous};
opWrapper.start();

// Inside your frame processing callback
void processFrame(const sensor_msgs::msg::
    Image::SharedPtr& msg) {
    cv::Mat frame = cv_bridge::toCvShare(msg,
        "bgr8")->image;
    // Convert frame to OpenPose-format
    const op::Matrix inputImage =
        OP_CV2OPCONSTMAT(frame);
    // Process frame
    auto datumProcessed = opWrapper.
        emplaceAndPop(inputImage);
    if (datumProcessed != nullptr) {
        // Process and display results
    } else {
    std::cerr << "Frame-processing-failed" <<
        std::endl;
    }
}
```

Listing 2. Example C++ snippet for initializing OpenPose within a ROS2 node

IV. Methodology

In this study, we explore the concept of integrating the OpenPose algorithm within an autonomous mobile robotic platform to conduct motion analysis to assist in monitoring and supporting elderly and mobility-impaired individuals. The methodology encompasses the adaptation of OpenPose for real-time analysis on the robotic platform, modifications to accommodate the mobility and autonomy of the platform, and the procedures for data collection and analysis.

A. Data Collection

For this investigation, the autonomous mobile robotic platform is equipped with a high-definition camera capable of recording at sixty frames per second, similar to the Logitech C922 Pro Stream web cameras used in previous studies. The robotic platform, integrated with an NVIDIA Jetson Xavier NX for high-performance computing, autonomously navigates within a controlled environment where participants perform predefined movements or daily activities.

A group of volunteers, consisting of elderly and individuals with varying degrees of mobility impairment, is recruited to participate in the data collection process. The robotic platform autonomously positions itself to capture the activities from optimal angles, ensuring comprehensive coverage of the movements. The system is designed to autonomously adjust its position to maintain an optimal viewing angle and distance, utilizing onboard sensors and algorithms for obstacle avoidance and path planning.

B. Integration of OpenPose with the Robotic Platform

OpenPose is integrated directly into the computing unit of the robotic platform, allowing for real-time processing of video data captured by the platform's camera. The system's architecture is designed to prioritize efficient data processing, ensuring minimal latency between data capture, pose estimation, and subsequent analysis.

The integration involves the development of a custom ROS2 package that facilitates the communication between OpenPose and the robotic platform's control system. This package includes nodes responsible for video stream handling, pose estimation, and translating pose data into actionable insights for monitoring or intervention purposes.

C. Real-Time Analysis and Monitoring

The real-time analysis focuses on identifying fundamental postures and movements indicative of potential risks or the need for assistance. The OpenPose algorithm processes video frames to detect human joint positions, which are then analyzed to calculate the angles between joints based on the vertices generated by OpenPose. An auxiliary algorithm similar to the one used in previous studies calculates the angles and variations in joint positions.

To further enhance our analysis, we employ an auxiliary algorithm developed in Python, which computes the lengths of the sides of the triangle formed by the hip, knee, and ankle joints using the coordinates (x, y) of these points and the distance formula:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{1}$$

Once the side lengths are determined, the angles formed by the hip, knee, and ankle joints are calculated using the cosine rule:

$$\theta = \arccos\left(\frac{a^2 + b^2 - c^2}{2ab}\right) \tag{2}$$

This refined approach enables a more detailed analysis of movement patterns, such as falls, prolonged periods of immobility, or irregular walking patterns.

D. Data Analysis

Data collected during the study is subjected to a rigorous analysis process to evaluate the accuracy and reliability of the OpenPose algorithm when integrated into a mobile robotic platform. This includes assessing the precision of joint angle measurements and the algorithm's ability to operate effectively in a dynamic, real-world environment.

Additionally, to validate the precision and consistency of the OpenPose algorithm in detecting joint positions, we apply an analytical method from a prior detailed study on OpenPose's performance. This involves calculating the variation in pixels for each joint (ΔX and ΔY) through the entire dataset capture, using the formulas:

$$\Delta X = X_i - X_0 \tag{3}$$

$$\Delta Y = Y_i - Y_0 \tag{4}$$

where X_i and Y_i represent the coordinates of the joint at time 'i,' and X_0 and Y_0 represent the coordinates of the joint at the initial recording time.

Furthermore, we employ a standard mathematical procedure to center the data points for each joint and angle studied by subtracting the arithmetic mean from each data point. This operation shifts the mean value to the origin, thereby facilitating a precise evaluation of variations from the central position:

$$\text{Centered Data}(X_c)_i = X_i - \mu \tag{5}$$

where μ is the arithmetic mean of the data points, calculated as:

$$\mu = \frac{\sum_{i=0}^{n} X_i}{n} \tag{6}$$

This process ensures that the distribution of data points around the central position is accurately represented, allowing for an in-depth analysis of the variation in joint positions and angles. The centered data is then utilized to construct histograms that depict the frequency of frames featuring specific pixel coordinates or angles, thus providing valuable insights into the consistency and precision of the OpenPose algorithm in a dynamic, real-world setting.

The analysis also examines the robotic platform's performance in terms of its ability to navigate and position itself for optimal data collection autonomously. The system's effectiveness in real-time monitoring and its potential impact on the quality of care for elderly and mobility-impaired individuals are critical focal points of the study.

This methodology outlines a novel approach to applying advanced motion analysis in supportive and care settings, leveraging the capabilities of the OpenPose algorithm within an autonomous mobile robotic platform. By adapting and extending the use of OpenPose for real-time, dynamic environments, this study offers significant insights into developing intelligent systems for enhancing the care and support of elderly and mobility-impaired individuals.

V. Results

The preliminary results from this study reveal a dual perspective on the accuracy and precision of the OpenPose algorithm. While the data points to a variability in joint angle estimation, it is important to contextualize these findings within the scope of intended applications.

The analysis of the OpenPose algorithm's accuracy in static scenarios yielded histograms for both the left and right knee joint angles. Despite the expectation of minimal variability for a stationary subject, the histograms revealed variations of up to 5 degrees more and less from the expected angle, with a notable number of occurrences.

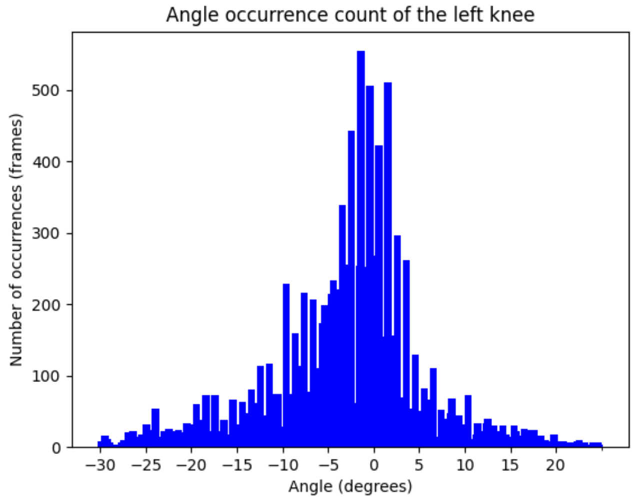

Fig. 1. Histogram of the angle occurrence count of the left knee

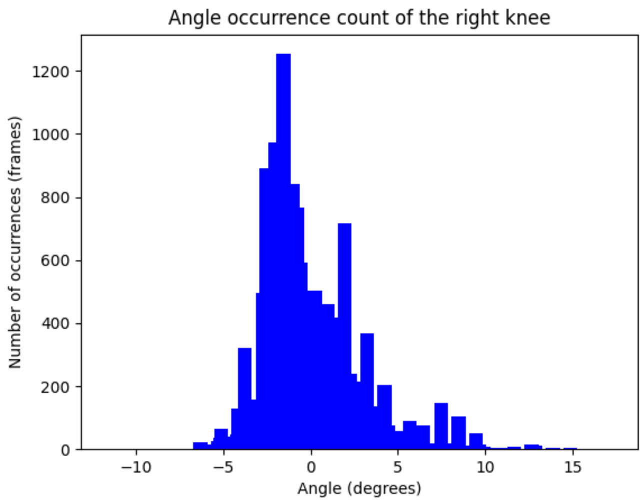

Fig. 2. Histogram of the angle occurrence count of the right knee

For the left knee, the distribution encompassed a range of angles with a concentration around -2, 0, and 3 degrees. The right knee showed a similar pattern with a peak at -2 degrees and a second peak at 2 degrees. These variations suggest that while OpenPose can detect broad movement patterns, there are discrepancies in angle estimations that may affect its precision in more demanding applications.

VI. Discussion

Integrating OpenPose into an autonomous mobile robotic platform presents unique opportunities and challenges for motion analysis, especially in monitoring elderly and mobility-impaired individuals. This discussion section evaluates the implications of OpenPose's performance in this innovative application, addressing reliability, potential clinical impacts, and future research directions.

A. Contextual Precision of OpenPose

In the domain of robotic assisted living, especially in elderly care, the precision provided by OpenPose is deemed sufficient. The algorithm's capability to detect significant movements and postures related to common elderly activities—such as sitting down, standing up, or walking—is within the necessary tolerance for reliable operation. This is in contrast to the high-precision demands of clinical applications for physiotherapy assessments or injury risk analysis in athletes, where minute variations are critical.

The observed variability in angle estimation by OpenPose, while noteworthy, does not diminish the algorithm's utility for the targeted applications in this study. In fact, the results demonstrate that OpenPose can reliably identify larger movement patterns and postures that are crucial in assessing the risk of falls or unusual movements in a domestic environment.

B. Implications for Robotic Applications

These findings underscore OpenPose's potential for integration into autonomous robotic platforms intended for elderly care. The degree of precision observed is appropriate for the monitoring tasks envisioned, which involve detecting significant deviations in movement patterns that could indicate a risk of falling or the need for assistance.

While acknowledging that OpenPose may not meet the stringent accuracy requirements for certain medical or high-performance sports applications, its performance is adequate for the broader context of mobility analysis in robotics. The adaptability and robustness of OpenPose make it a valuable tool for developing intelligent robotic systems capable of enhancing care for the elderly and improving their quality of life by providing timely interventions and support.

C. Adaptation and Reliability of OpenPose on Mobile Platforms

Pimentel's research aimed to evaluate and compare various social navigation methods to enhance interaction with the Home Environment Robot Assistant (HERA) developed by FEI University Center [11]. It focused on assessing multiple parameter combinations, including environment types, obstacles, local and global planning algorithms, cost maps, and interaction with people in static, dynamic, and interacting states. Considering aspects such as safety, time and space estimation accuracy, smooth trajectory, and personal space respect, the research conducted 1,000 trials across 37 method, environment, and sensor combinations, totaling 37,000 attempts. The findings highlighted the effectiveness of the Timed Elastic Band (TEB) as a local planner and a proxemic costmap combination, achieving a 97.6% success rate in complex environments [12], [13]. This reference is relevant as it integrates with the current project, with future implementation with OpenPose and ROS2, underlining the necessity for navigation and people tracking integration to enhance the robotic platform's positioning and maximize OpenPose's potential.

Adapting OpenPose for use on a mobile robotic platform introduces considerations of dynamic environmental factors and the robot's ability to position itself for optimal analysis. Initial findings suggest that while OpenPose can reliably estimate joint positions in a controlled setting, its performance in a dynamic, real-world environment warrants further examination. The robot's autonomous positioning capabilities, combined with OpenPose's analysis, showed promise in achieving optimal angles and distances for accurate motion analysis. However, variations in joint position estimation highlighted in stationary settings were also evident during mobile monitoring, underscoring the need for enhanced stability in the algorithm's output when adapted to this new application.

D. Clinical Implications in Elderly and Mobility-Impaired Care

In caring for the elderly and individuals with mobility impairments, precise motion analysis can significantly impact the effectiveness of interventions and monitoring. The ability of the mobile platform to autonomously navigate and adjust to the subjects' movements adds a layer of complexity to the analysis. Despite this, the potential for OpenPose to provide real-time feedback on joint angles and movements offers a valuable tool for caregivers and healthcare professionals. The observed variations in joint estimations raise essential considerations for the clinical application of this technology. Ensuring the accuracy of motion analysis is paramount, as incorrect assessments could lead to inappropriate care strategies or missed opportunities for intervention.

E. Limitations and Future Directions

The pioneering nature of integrating OpenPose with autonomous mobile robotic platforms brings inherent limitations. The current study's focus on the feasibility and initial performance assessment indicates the need for extensive field trials to fully understand the technology's capabilities and limitations in real-world settings. Future research should aim to refine the integration of OpenPose with robotic platforms, exploring algorithmic enhancements and adaptive positioning strategies to mitigate the observed variations in joint position estimations. Additionally, expanding the scope of analysis to include a broader range of movements and conditions common among the target population will be crucial for validating this approach's clinical relevance and utility.

Integrating OpenPose into autonomous mobile robotic platforms for elderly and mobility-impaired care represents a significant step forward in healthcare technology. While the initial assessment highlights promising applications and areas for improvement, ongoing research and development are essential to realize the full potential of this innovative approach to motion analysis.

VII. Conclusion and Future Work

In this study, we explored the innovative integration of OpenPose into autonomous mobile robotic platforms for motion analysis, focusing on applications in elderly care and support for individuals with mobility impairments. Our investigation revealed that while OpenPose exhibits the potential to provide detailed joint position and movement analysis, the adaptation of this technology to a mobile platform introduces challenges in ensuring consistent accuracy, particularly in dynamic environments.

The deployment of OpenPose on a mobile platform has shown promising results in enhancing the ability to monitor and assess the physical movements of elderly individuals and those with mobility impairments in real time. This capability could significantly improve the quality of care and the effectiveness of interventions by allowing for immediate adjustments to treatment plans based on accurate motion analysis. However, variations in joint position estimations highlight the necessity for further refinement of the OpenPose algorithm when used with autonomous robotic systems.

Looking ahead, several avenues for research and development present themselves. Future efforts should concentrate on enhancing the stability and accuracy of OpenPose in dynamic settings, which could involve algorithmic improvements tailored to the unique challenges of mobile monitoring. This includes developing adaptive algorithms that can compensate for the movement of the robotic platform and the environmental variability of non-clinical settings.

Further, expanding the research to include a broader range of activities and conditions typical of the target population will be essential. A more extensive and diverse dataset will enable a comprehensive evaluation of the system's performance across different scenarios, including variations based on age, mobility level, and environmental factors.

Another critical area of future work will involve comparing OpenPose's performance on the robotic platform with traditional motion analysis systems. Such comparative studies could help validate the accuracy and reliability of OpenPose in real-world applications, establishing its feasibility as a tool for healthcare monitoring and support.

In Conclusion, integrating OpenPose into autonomous mobile robotic platforms represents a significant advancement in healthcare technology. By addressing the identified challenges and building on the current study's foundation, there is a clear path toward developing a highly effective tool for motion analysis. This tool not only has the potential to revolutionize care for the elderly and individuals with mobility impairments but also opens new possibilities for the application of autonomous robotic systems in healthcare.

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