

Sensor Fusion and Control Algorithm Design for Precision Mechatronic Arms in Medical Robotics

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Abstract--- Mechatronic systems are becoming more essential in applications, necessitating great accuracy. Although a robot functions with fundamental sensor input in controlled settings, attaining micro-level precision necessitates more extensive data integration, particularly in dynamic situations. Integrating data from several sensors is essential for enhancing a robot's positioning precision, since the precision of a single sensor type is inadequate. The domain of micro-positioning introduces novel issues and tasks that have been progressively examined in the literature released between 2015 and 2025. Micro-positioning is a sophisticated process encompassing physical drift, ambient influences, and sensor signal inaccuracies. Hybrid fusion is an imaging fusion methodology that integrates components at several levels. Effective robot deployments in these circumstances necessitate integrating various sensors and ensuring accurate data fusion. This requires advanced fusion computations, multiple sensors, exact calibration techniques using sensor fusion, and sophisticated data processing methods. Sensor data fusion methods for precise robot micro-positioning are investigated in this work based on the literature. The focus is on the investigated detectors, the applied synthesis methods, developed computations, and how to find current shortcomings for possible system improvement. The results of the collected ideas and the exchanges are presented.

Keywords--- Sensor Fusion, Precision Mechatronics, Medical Robotics, Control Algorithm.

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I. Introduction

The healthcare industry uses more robots as medical tools and equipment advances (Holland et al., 2021). An indispensable technology enabling the complex activities in the medical domain, including surgical aid and rehabilitation training, is the flexible control and planning of paths of medical dual-arm cooperative robots (Abbas et al., 2023). Versatility control is the ability of the mechatronic control system to change with job requirements and the outside environment. In surgical operations, real-time management systems must be quickly installed. These systems guarantee the accuracy and safety of surgical treatments by excelling in spotting and adjusting for minute changes in the patient's psychological state.

These flexible control strategies improve the adaptability and performance of robots in completing challenging tasks (Jahanshahi & Zhu, 2024). This is especially clear when robots perform tasks in close human presence. In medical dual-arm robotics, flexible management is usually related to routing. A primary challenge in microrobotics is optimizing data fusion methods from different sensors. Effective operation across many fields, including robotics, machine learning, and Microelectromechanical Systems (MEMS) (Chircov & Grumezescu, 2022), depends on exact placement in multiaxial devices. These buildings have to operate across several dimensions, and precisely and regularly. Positional errors cause crises, lower efficiency, and faulty products. Managing multi-axis systems mostly depends on accurate and consistent positioning data for every axis. Mechanical opposition, vibration, thermal stretching, and external influences are among the several elements that complicate this problem. Optical detectors, encoding devices, and Inertial Measuring Units (IMUs) (Samatas & Pachidis, 2022) among stand-alone sensors have limits and do not regularly offer the required precision by themselves. The authors underscore the need to enhance sensor technology and sensor combination techniques to attain elevated degrees of independence and security.

Robots outfitted with integrated sensor systems can accurately place the end-of-arm tool or grabber with little deviation (Bleicher et al., 2023). A research integrated data from many sensors, reducing the robot's placement error by multiple micrometers and markedly enhancing the precision of its motions. The created

method facilitated early fault identification, potentially enhancing production effectiveness and lowering costs; it was not entirely mechanized. In the computerized welder of significant structures, it is crucial to account for material distortions; yet, the equipment requires considerable calibration efforts, which restrict deployment versatility. Using a sensor amalgamation to rectify inspection paths in real time might guarantee the manufacturing of superior welded joints. The study has shown improved welding precision due to multi-sensor fusion (Lee et al., 2023).

This research examines the current approaches of positional error compensating applicable to micrometer-scale manipulating operations and microrobotics using various sensor fusion techniques.

II. Background of Hierarchies of Sensor Fusion

Data-level fusion occurs immediately after the acquisition of data from sensors. This step involves amalgamating unprocessed data from diverse sensor inputs before applying filtration or statistical methods. Sensor-level fusing primarily analyzes raw data to enhance accuracy, reduce noise, and elevate overall data quality (Li et al., 2021). Standard techniques applied at this level are the weighted mean, the Kalman filter, and the complement filter. Data-level fusion is suitable when first filtration and noise reduction are crucial, since it integrates raw data from several detectors, fostering a more thorough awareness of the monitored procedure. During feature-level arrangement, the information is filtered and preprocessed; essential features are obtained from the original data using several techniques.

These properties are aggregated into a generalised feature vector, offering a more complete operational picture. This level seeks to preserve important data while reducing complexity and duplicate data. Feature-level fusion mainly uses Principal Component Analysis (PCA), Factor Evaluation, and Dimensionality Reducing Techniques, including Multidimensional Scaling (MDS). Especially helpful in situations with limited processing resources, combining features helps categorization management become more efficient and enhanced.

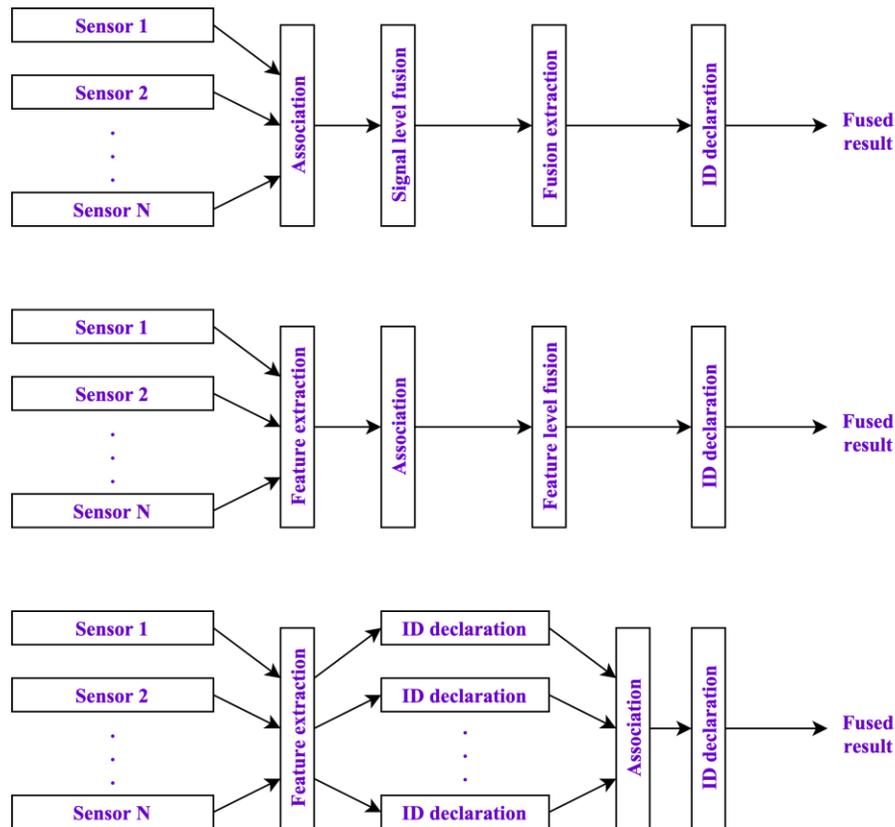


Figure 1: Data Fusion Levels: (a) Signal Level, (b) Feature Level, and (c) Decision Level

Decision-level fusion refers to integrating judgments given by separate classifiers to provide a conclusive outcome. The decision layer incorporates forecasts or categories from multiple models, amalgamating techniques such as voting by majority, Bayesian systems, Dempster-Shafer concept, and grouping approaches,

including boosting and bagging. The primary benefit of decision-level fusing is its enhancement of the accuracy and resilience of the final category, as it mitigates mistakes produced by separate classifications. This degree is used when error resilience and high decision precision are critical, particularly when limited training information or uncertainty is elevated. Fig. 1 illustrates the degrees of perceptual signal integration and their architectural arrangement.

Conversely, implementing machine learning techniques necessitates several trials, resulting in a time-consuming process when using actual machines for feedback acquisition. Practicing training on acquired datasets introduces uncertainties and cannot be deemed accurate; hence, dependability requires careful consideration.

Sensor Integration in Mobile Robots

Autonomous Mobile Robots (AMRs) have gained significant popularity in recent years and are used across several sectors, including industry, household applications, agriculture, and healthcare. They can navigate and avoid obstacles, which benefits jobs like heavy item transportation, surveillance, and search and rescue operations. The primary challenges in creating AMRs are navigation, course planning, and avoiding collisions.

Accurate robot localization necessitates dependable navigation, comprehension of the trajectory to the destination, and the capacity to avert accidents. To enhance localization precision, both relative and exact methodologies using diverse sensors and systems are essential.

A precondition for AMR capability is the capacity to identify and circumvent impediments along the route to the intended destination. The used methods include bug computations, Vector Field Histograms (VFHs), and composite navigation computations, which aid in choosing a path and collision avoidance. AMRs use several sensors and information fusion methodologies to enhance precision. Sensors are categorized into IMUs, monocular vision sensors, and marker-based devices. Data integration facilitates the amalgamation of knowledge from several sensors, improving the reliability and precision of ecological evaluations. It delineates data fusion techniques for processing sensor signals, including the Kalman filter and particle filtering. The integration of data enhances the accuracy and dependability of AMR devices. Fig. 2 depicts the operation of the traditional sensor fusion framework in mobile robots.

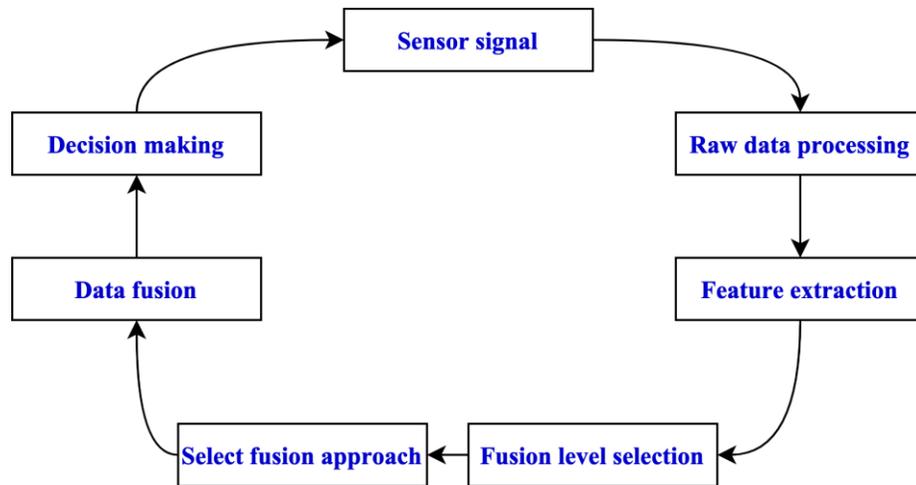


Figure 2: Data fusion workflow

III. Authentic machine validation

This study discusses adaptable control and trajectory planning with the healthcare dual-arm cooperative robot manufactured by Siasun Technologies. It illustrates the experimental outcomes of pharmaceutical distribution by the dual-arm mechatronic medical assistant.

1) Removing the bottle top: (utilizing a preopened pill, putting the broken aluminum top into a box), a machine's left arm seizes the bottle as the opposite arm holds the bottle openers. The left arm positions the bottle accordingly and visually verifies the notch alignment. If the arrangement is erroneous, the left arm

adjusts the glass to a designated orientation. The opposite arm seizes the bottle opening and promptly applies pressure to detach the metal cap from the pill.

The right arm repositions the bottle opening, while the opposite arm elevates the container and deposits the compressed metal top into the collecting box. A visual mechanism is shown to verify the effective opening of the container cap. A mistake notice is displayed if it remains connected to the container or the opening device. The container is returned to its designated location after discarding the metal cap.

(2) Medication Distribution Demonstrations: The opposite arm seizes the needle, whereas the left arm grasps the plunger. Both arms collaborate to illustrate the sucking of the medication from the vials and the injection of the medicine into the bottle.

IV. Discussion

The research suggested using an IMU to calibrate the joint angle data obtained from Kinect, which is applicable only when the discrepancy between the Kinect and IMU is significant and restricted to uniaxial motion. The suggested Kalman filter integrates two sensors, resulting in a cleaner fusion outcome while accommodating motion across the three axes of the shoulder joints. The fusion outcomes were used in a mechatronic arm, significantly reducing its jitter and enhancing the fluidity of its motion. This approach necessitates stringent standards for motion uniformity. During monitoring, the motions of the automated arm must be changed accordingly based on visual observation. The mechatronic arm's flexibility in movement is often confined to a single quadrant.

The research suggests avenues for further enhancements, considering the constraints above. Initially, the study explores enhanced sensor fusion techniques to increase the precision of certain activities. Secondly, by evaluating the causes of inaccuracy throughout the many quadrants covered by the manipulator, the research modifies the sensor placement or utilizes more sophisticated fusion techniques to enhance the system's reliability. For rapid movements or dynamic scenarios, the research improves the velocity of data collection and the responsiveness of the management system to enable swift adaptation to the operator's requirements. These enhancements will augment the efficiency and usability of the humanistic management system.

To enhance the structure, the researchers want to create bespoke glove sensing in the not-too-distant future to decrease costs and increase scalability. This self-engineered glove sensor will be tailored to the specific demands, hence enhancing the performance standards of the humanistic management system.

Human movement tracking devices are engineered to regulate several categories of robots. Many scientists have created soft autonomous arms and graspers for executing flexible gripping duties, and the movement tracking method described in this paper is used to control these soft mechatronic devices. A connection model is created to translate the positions of a person's shoulders, fingers, and forearms into the desired settings of a multi-segment soft mechanical arm, achieving a humanistic attitude. The movable structure of adaptable gripping devices is manipulated by finger bends to facilitate the opening and closing of the gripper, hence enhancing the convenience of the grasping operation. The remote functioning of human beings has a broad range of flexibility and is more natural and user-friendly.

V. Conclusion

This study highlighted many works focused on using sensor data fusion to enhance the precision and dependability of mechatronic systems' location and navigation. Multi-sensory fusion efficiently mitigates the limitations of individual detectors, strengthening the system's quality. Specific papers focused on integrating initial information from various sensors. Numerous research studies have focused on integrating derived characteristics from sensor data, such as amalgamating visual characteristics with data to enhance mapping and localisation in algorithms. This method employs intricate data from several sensor types to enhance environmental recognition accuracy. Fusion is used at the decision-making stage, when the outputs of separate algorithms or models are amalgamated to get a conclusion, such as in systems that integrate input from several robots for collaborative navigation and assembly.

Numerous investigations used a hybrid fusion approach, integrating low-, mid-, or high-level fusion techniques for optimal outcomes. This method benefits from the concurrent use of each fusion layer. In hybrid approaches, information collected by several sensors is first amalgamated at the information or feature level,

followed by integration at the decision level. This enhances the precision and dependability of systems in intricate and evolving situations.

Future studies in this domain create adaptable fusion techniques capable of dynamically determining the appropriate fusion level and procedure based on prevailing circumstances and tasks. Techniques based on Artificial Intelligence are potential approaches for enhancing the integration of data and immediate decision-making, while facilitating the development of increasingly intelligent and self-driving machines.

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