

Integrated Multi Sensor Fusion for Robotic Manipulator Systems

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Abstract. Robotic manipulators have found extensive use in automation, healthcare, and collaborative robotics, with precision and safety paramount. The use of a single-sensor solution can be insufficient in unstructured conditions, and though the concept of multi-sensor integration enhances the performance, systematic engineering analysis is still scanty. In this paper, the research studies concerning the multi-sensor application on robotic manipulators are reviewed with respect to combining joint encoders, force/torque sensors, and vision sensors. Actual experimental performance demonstrates the use of millimeter-inch positioning in visits, sub-newton force estimation precision, and millisecond collision detection in visits. The results reveal that multi-sensor technology is always more accurate and safe compared to single-sensor ones. However, the real-life problems of calibration, synchronization, and system complexity are still pertinent problems to be taken into consideration.

Keywords: Robotic manipulators; Sensor fusion; Force sensing; Vision sensing; Human-robot interaction

1 Introduction

Modern robotics is dominated by robot manipulator systems; they are used in industries in the field of automation, in healthcare, in service robotics, and in human-robot collaboration. As the demand continues to grow to use mechanical arms within unstructured workplaces and in safe manners around people, the programmed position and motion control is no longer completely trustworthy. Robots have acquired perception, flexibility, and safety through sensing being a part of robotic arms. As an example, it is impossible to rely on a single sensor to sense the whole state of the robotic manipulator system in motion and contact with the environment. The multi-sensor systems have emerged as a significant aspect in enhancing the precision and reliability of tasks of robotic manipulation.

In the prior studies, the ability of multi-sensor fusion to increase the performance of robotic arms in terms of control and interaction has been proven effective. To illustrate, a teleoperation system of the anthropomorphic robotic arm was developed by Yang et al. through a visual, force, and motion capture sensor fusion method, and the suggested system supported stable and natural human-robot interaction, as was confirmed in the experiments [1]. Their multi-sensor fusion system was demonstrated to make the control performance and the stability better than the conventional teleoperation ones and provided the ability to track the arm and dexterous hands in real time with better responsibility and fewer motion anomalies [1]. Besides, Han and Kim proposed a proprioceptive multi-sensor scheme of contact localization and measuring the interaction force of robotic manipulators with the use of the torque sensor and a base force/torque sensor, and the method has been proven to be more accurate in estimating the forces in simulation including single contact object localization and also in multi-contact object localization with 7-degree-of-freedom robots [2]. Moreover, a series of investigations conducted at the experimental level on collaborative robots also confirmed that joint encoder and force or torque sensor integration can markedly improve safety and compliance in the process of human-robot interaction, as well as effective contact detection and minimal estimation errors, as compared to single sensors. More so, experimental studies have also confirmed the suitability of joint sensors and/or force or torque sensors in collaborative robots integration to improve safety and interaction between humans and robots [3].

Nonetheless, in spite of these accomplishments, the current literature investigations are generally focused on specific tasks and control algorithms, and little has been done in terms of an engineering overview of multi-sensor applications in robotic arms. The research studies focusing on the use of multi-sensors in robotic manipulators will be reviewed in this paper, but the focus will be placed on the ability of different sensor combinations to provide precision, interaction, and safety. This paper is aimed at giving a general overview of the use of multi-sensor systems in robotic manipulators and showcasing the major design requirements and problems.

2 Sensor types and multi-sensor configurations

Robotic manipulators work through a complicated interplay among the mechanical movements, external forces, and constraints of the environment. Robotic arms adopt various types of sensors that are complementary to each other in order to successfully estimate how the system is and to react to the task requirements. These include, most commonly, joint encoders, force/torque (F/T) sensors, and vision sensors, in industry and in research-oriented robotic manipulators. The sensors of each type are used to detect a different physical quantity and hence have different strengths and limitations so multi-sensor planning is necessary rather than a design option.

The basic proprioceptive sensors used in a robotic arm are joint encoders installed in the actuated joints. They give a direct scale of the joint position, usually in angular displacement form, that allows reconstruction of the kinematic configuration of the manipulator with accuracy. To an n -degree-of-freedom manipulator, the encoder readings may take the form of a joint state vector:

$$\mathbf{q} = [q_1, q_2, \dots, q_n]^T \quad (1)$$

where q_i denotes the measured position of the i -th joint. Encoder-based measurements have high resolution, low latency, and good repeatability and have become a mandatory requirement of motion control at high precision. Joint encoders, however, are explicitly based on rigid-body dynamics and are unable to directly record structural deflection, backlash, or external force on the manipulator. Consequently, encoder-based sensing can cause large estimation errors when performing a contact-intensive task or when operating under heavy external forces.

In order to augment position sensing, force/torque sensors are usually attached to robotic manipulators, typically the wrist or base. Such sensors are used to measure interaction forces and moments that exist between the manipulator and its surroundings, and can be represented as:

$$\mathbf{w} = [F_x, F_y, F_z, \tau_x, \tau_y, \tau_z]^T \quad (2)$$

where F_x, F_y, F_z represent Cartesian forces and τ_x, τ_y, τ_z represent corresponding torques. The application of force/torque sensing allows robotic arms to sense a contact event, estimate the forces of interaction, and apply compliant control when manipulating an object. These competencies are required when it comes to work involving dealing with objects, surface tracking, or any physical interaction between humans and robots. However, force/torque sensors do not give much information regarding the world pose or kinematic position of the manipulator and react to noise, temperature variation, and calibration issues.

The exteroceptive information is the vision sensors, such as Red-Green-Blue (RGB) cameras and depth sensors, that are beyond the robot. Visual sensing is useful in task-level perception and error correction as it can estimate object position, end-effector position, and geometry of the environment to aid in their localisation. Multi-sensor robotic systems also commonly compensate for accumulating kinematic errors that happen due to encoder drift or unmodeled mechanical influences using vision. However, measurements made visually are indirect in nature, and they are subject to environmental errors like changes in lighting, occlusions, and inaccuracies in camera calibration.

Considering the shortcomings of single sensory functions, the current robotic manipulators would often incorporate the multi-sensor designs where joint encoders, force/torque sensors, and vision sensors are incorporated at the system level. Joint-level sensors are used to solve the situation of internal state, end-effector sensors are used to sense the dynamics of interaction, and vision sensors are used to give the global context information. When these complementary sources of information are added, robotic arms are given a richer and stronger picture of their condition. These multisensor architectures constitute the sense basis of high-resolution manipulation, compliant engagement, and secure operation in unstructured and manmade environments.

3. Experimental studies and quantitative performance analysis of multi-sensor applications

3.1 Multi-sensor teleoperation for motion accuracy and stability

Yang et al. proposed a multi-sensor remote manipulation system to enhance the quality of motion and interaction performance of an anthropomorphic robotic arm with a dextrous hand [1]. Their system combines vision sensors, force sensors, and motion capture devices, which have different purposes in the teleoperation loop. Motion capture sensors give the high rate data on the joint movements of the human operator, vision sensors give the pose of the end-effector globally, and force sensors give the forces at interfaces when doing contact tasks.

The accuracy of robot teleworking and the smoothness of its movements are the main metrics in this system to assess the quality of teleoperation. The experiments described by Yang et al. included the finding that the multi-sensor set-up with the lowered average Cartesian tracking error of about 5.3 mm in the vision-only control and 4.7 mm in the encoder-only control dropped to about 1.6 mm during fused sensing. The instantaneous tracking generally decreased by nearly 911 mm to about 3 mm, and the standard deviation of the trajectory error of the continuous motion tasks was reduced by over half. Moreover, oscillations (velocity variation) at the joints were observed to be significantly damped after which the highest amplitude oscillations were cut by about 40 percent, and the system continued to run steadily in real-time at control update rates exceeding 100 Hz during teleoperation experiments [1].

Besides the accuracy of space motion, the joint velocity profiles and continuity of trajectories were also tested. The hybrid sensor system generated more horizontal joint paths and fewer oscillations, especially when passing through free-space movement and contact. Such enhancements were attained without reducing the quality of real-time performance, and this indicates that multi-sensor fusion can augment the quality of teleoperation without adding computationally demanding delays.

3.2 Proprioceptive multi-sensor force estimation and contact localization

To determine the contact forces and localize the contact points with high accuracy with the limited amount of sensing information, Han and Kim examined a proprioceptive multi-sensor design applied to robotic manipulators [2]. Their technique combines the measurements of joint torque sensors with a base-mounted force/torque sensor and allows for determining the interaction states without the need for external measurements like vision.

The essence of the relation that is utilized in their study is the mapping of the external forces to the induced joint torques, whereby it is in the form:

$$\boldsymbol{\tau}_{ext} = \mathbf{J}^T(\mathbf{q})\mathbf{F}_{ext} \quad (3)$$

where τ_{ext} represents the externally induced joint torques, $\mathbf{J}(\mathbf{q})$ is the manipulator Jacobian, and $\mathbf{F}_{ext}$ denotes the external contact force. The proposed approach can eliminate ambiguities caused by the single proprioceptive sensor use because of joint-level torque data, plus base force/torque measurements, help the proposed approach to resolve the ambiguities.

Experiments on a 7-degree-of-freedom robotic arm by simulation showed that the success rate of single-contact localization is about 99.96% on average [2]. Also, the measured error of the force estimation was stated to be under sub-newton when using a normal interaction load. A notable benefit of the suggested framework is that it can be computationally efficient (similar to 2200 Hz update frequencies), which is good enough to control forces and monitor contacts in real-time.

These findings support the experimental outcomes in a quantitative way by showing that multi-sensor proprioceptive fusion is capable of giving much better results compared to single-sensor force estimation methods in terms of accuracy, robustness, and responsiveness.

3.3 Multi-sensor-based safety evaluation in physical human-robot interaction

Haddadin et al. performed systematic crash-testing of collaborative robotic manipulators to make physical human-robot interaction safer and measure the dynamics of the collision [3]. In the case of their study, they performed a joint encoder measurement with the force and torque sensing to examine the collision dynamics and the risk of injury in the case of unintended human-robot contact.

One of the indicators of their analysis is the impact force at the time of collision, which can be estimated as the momentum change in the contact period:

$$F_{impact} \approx \frac{\Delta p}{\Delta t} \quad (4)$$

In which Δp denotes the change in robot momentum, and Δt is the collision duration. This system could identify contact events in 5-10 ms because the system operated using multi-sensor feedback, allowing quick intervention to control the system [3].

It was also experimentally demonstrated that the use of a multi-sensor-based collision detection and compliance control scheme resulted in a reduction of the maximum impact forces by as much as half of those obtained with encoder-based detection schemes alone [3]. The result of this decrease is directly proportional to the fact that it leads to enhanced safety margins in the case of human-robot interaction. The paper presents the quantitative data that multi-sensor configurations are crucial in attaining safe and responsive behavior in collaborative robotic systems that operate within the close range of human beings.

4 Challenges, limitations, and future development in multi-sensor integration

4.1 Challenges and limitations

Despite the many benefits of multi-sensor integration, such as increased positioning accuracy and safety of interaction, it is still plagued by a number of practical issues that still limit its implementation at large scale in robotic manipulators. The former settles on the accuracy of calibration. Multi-sensor fusion needs the ability to provide accurate intrinsic and extrinsic calibration to provide spatial agreement between coordinate frames. Any slight sensor-frame mismatch can cause systematic errors that are passed on by the kinematic computation and control loops. According to Qiu et al., the multi-modal calibration performance suffers as time goes on when the exposure is dynamic and under varying environmental conditions, and thus, the accumulation of pose deviation is observed [4]. In a similar vein, Haq also pointed out that conventional methods of static calibration are not suitable for long-term use in industrial applications, particularly to operate in vibrating and thermal drift conditions [5].

Multi-sensor fusion is further overcome by temporal inconsistency and heterogeneous noise characteristics. Generally, robotic manipulators are engineered to combine high-frequency encoder data with low-frequency visual sensing; i.e., asynchronous measurements. Time differentiations between sensor streams may worsen state estimation without accurate synchronization. Huang et al. showed that a hybrid EKF RNN fusion model is more robust in asynchronous and noisy conditions [6], but this would also raise the computational cost. Moreover, vision sensing tends to have non-Gaussian noise distributions, invalidating the statistical assumptions of classical Kalman filters, and limiting the accuracy of estimation where objects are moving out of view, or the scene is being controlled by new light sources [7].

Other than the feeling of accuracy, there is another limitation of increased system complexity. The multisensory approach leads to costs in addition to hardware, communication bandwidth, and software synchronization. Rossi et al. observed that tightly coupled fusion designs can make industrial robotic systems more latent and less maintainable. Disturbances in the environment are also one of the issues [8]. As experimental works on collaborative robots show, there are still light effects, vibration, and thermal effects that deteriorate the sensing stability despite sophisticated filtering techniques [9]. These results indicate that even in a controlled laboratory environment, multi-sensor systems are effective, but a serious engineering issue is in the robustness and scalability of their implementation in a real environment.

4.2 Future development

Aspects of the development of multisensor robotic manipulators in the future will involve adaptive calibration, robust fusion algorithms, and scalable system architectures. Instead of the fixed offline calibration, new directions are on online self-calibration that can compensate for mechanical deformation and environmental drift effects throughout its operation. Compensation based on

learning has shown good outcomes in sustaining sub-millimeter inaccurate positioning accuracy in the long-term [5], [10].

Progress in probabilistic modeling and mixed strategies of fusion is expected to deal with asynchronous multi-rate sensing and non-uniform noise distributions as well. This can be enhanced by combining physics-based estimators and data-informed correction layers to achieve balance in robustness and retaining interpretability and stability [6], [7]. Also, there is a current effort to explore modular and distributed fusion architectures to improve fault tolerance as well as lower the coupling of the system [8]. Predictive impact modeling and accelerated collision detection systems, based on the foundations of crash-testing systems and techniques, including those described in [3], are expected to take centre stage in next-generation cooperative robotic systems in safety-critical applications.

5 Conclusion

Integration of multiple sensors has already become a hallmark of state-of-the-art robotic manipulators, in such tasks as high precision and compliant interaction with other objects and operational safety. This paper has investigated some representative works in the field of research dealing with teleoperation control, contact localization, and physical human-robot interaction, which show that the integration of joint encoders, force/torque sensors, and vision sensors greatly improves the performance of the systems. The systematic results presented in the literature indicate that every experimental result indicates superior tracking accuracy, less error in force estimation, quicker collision detection, and greater stability with multiple sensor configurations than a single-sensor set-up. These quantitative findings show that the use of multi-sensor systems is a more accurate and complete demonstration of the state of the manipulator when performing dynamic tasks.

Even with these benefits, the development of multi-sensor robot systems is more of an engineering challenge upon their practical implementation. The uncertainties that come with the calibration accuracy, time synchronization, nonuniform noise distribution, and augmented computational needs can negate the performance improvements. Physical world conditions also increase these challenges by introducing mechanical drift, vibration, temperature fluctuations, and unexpected disturbances. Long-term reliability is also an issue when dealing with tightly coupled multi-sensor architectures due to their scalability and maintainability.

Future research should be aimed at adaptive and online strategies of calibration that can be used to counterbalance the dynamic changes in the environment. There should also be the presence of strong multi-rate fusion models that specifically deal with non-Gaussian noise models and asynchronous sensing. Also fault-tolerant and modular system architecture can help ease the complexity and enhance the system's resilience. Further combination between model-based estimation and data-driven correction methods is the key to the development of the next generation of robotic manipulators.

On the whole, even though multi-sensor systems show recorded and substantial manipulation in robots, further study of the system is needed before it can be incorporated in large-scale industrial applications. The future effect of multi-sensor robotics technologies will be dependent on sustainable, adaptive, and computationally efficient integration strategies.

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