Impact-Aware Manipulation by Dexterous Robot Control and Learning in Dynamic Semi-Structured Logistic Environments

I.AM.

I.Sense report

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Reviewer 2	26/09/2023	Alessandro MELONE

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ABBREVIATIONS

Abbreviation	Definition
EC	European Commission
PU	Public
WP	Work Package
GA	Grant Agreement
IMU	Inertial Measurement Unit
KF	Kalman Filter
EKF	Extended Kalman Filter
SFDI	Sensor Failure Detection and Isolation

EXECUTIVE SUMMARY

I.Sense's primary goals were centered around revolutionizing impact detection and classification in the field of robotics. More specifically, a robust impact monitoring pipeline is desired that integrates prior knowledge and validated models, alongside an adaptive reflex framework, to effectively handle faults, recover from them, and ensure successful completion of tasks. By addressing these key aspects, it is sought to overcome the limitations and challenges faced by existing systems, thus contributing to the advancement of impact-aware manipulation.

TUM, in collaboration with partners, has successfully developed innovative methodologies and techniques to improve collision detection accuracy, payload identification, material discrimination, and end-effector velocity measurements. These advancements align with the work package objectives and demonstrate valuable contributions to the field. Through extensive research, TUM identified momentum observer as a reliable approach for impact detection. However, to enhance its speed and accuracy, a new approach was introduced, incorporating Inertial Measurement Units (IMUs) to monitor and reject modeling errors. This improvement enabled better collision detection and reduced the reliance on complex hardware. Furthermore, TUM developed a collision monitoring framework that distinguished intentional and unintentional impacts, providing sensitivity tuning and improving post-impact behavior classification. Overall, TUM has made significant strides in enhancing impact detection and classification in robotics.

1 INTRODUCTION

1.1 I.AM. project background

Europe is leading the market of torque-controlled robots. These robots can withstand physical interaction with the environment, including impacts, while providing accurate sensing and actuation capabilities. I.AM leverages this technology and strengthens European leadership by endowing robots to exploit intentional impacts for manipulation. I.AM focuses on impact aware manipulation in logistics, a new area of application for robotics which will grow exponentially in the coming years, due to socio-economical drivers such as booming of e-commerce and scarcity of labour. I.AM relies on four scientific and technological research lines that will lead to breakthroughs in modeling, sensing, learning and control of fast impacts:

1. I.Model offers experimentally validated accurate impact models, embedded in a highly realistic simulator to predict post-impact robot states based on pre-impact conditions;
2. I.Learn provides advances in planning and learning for generating desired control parameters based on models of uncertainties inherent to impacts;
3. I.Sense develops an impact-aware sensing technology to robustly assess velocity, force, and robot contact state in close proximity of impact times, allowing to distinguish between expected and unexpected events;
4. I.Control generates a framework that, in conjunction with realistic models, advanced planning, and sensing components, allows for robust execution of dynamic manipulation tasks.

This integrated paradigm, I.AM brings robots to an unprecedented level of manipulation abilities. By incorporating this new technology in existing robots, I.AM enables shorter cycle time (10%) for applications requiring dynamic manipulation in logistics. I.AM will speed up the take-up and deployment in this domain by validating its progress in three realistic scenarios: a bin-to-belt application demonstrating object tossing, a bin-to-bin application object fast boxing, and a case depalletizing scenario demonstrating object grabbing.

1.2 DELIVERABLE TOPIC background

The primary focus of I.Sense is to develop an impact monitoring pipeline that incorporates pre-existing knowledge of impact and release motions. The pipeline will be developed in two stages, starting with intentional impacts and then progressing to differentiate between intentional and unintentional contact forces. Additionally, the Grant Agreement (GA) highlights the formalization of robot reflexes, enabling an adaptive reflex framework that learns optimal reactions to faults over time. The validation of the reflex framework will take place in a grabbing validation scenario, demonstrating its effectiveness in recovering from unwanted contact losses. The GA also specifies performance benchmarks for each subobjective. For OBJ3.1, the time required for detecting changes in contact situations will be benchmarked, along with real-time performance evaluation using ground truth data from impact simulations. OBJ3.2 aims to minimize misses and errors in detecting, isolating, and identifying contact events compared to existing methods. Finally, OBJ3.3 focuses on assessing the ability to recover from faulty conditions and disturbances through reflex activation, ultimately increasing the success rate of task completion.

1.3 Purpose of the deliverable

This deliverable is a comprehensive impact monitoring pipeline incorporating a-priori knowledge and validated models, along with a formalized adaptive reflex framework for fault recovery and task completion.

1.4 Intended audience

The dissemination level of D3.1 is ‘public’ (PU) – meant for members of the Consortium (including Commission Services) and the general public. This document is intended to also serve as an internal guideline for the entire I.AM. Consortium and provide the consortium’s implementation plans regarding data management.

2 Deliverable Summary

2.1 I.AM. WP3 objectives

We recall that I.AM. project objectives related to WP3 (Sensing) are:

1. OBJ3.1: Development of intentional impact monitoring pipeline.
2. OBJ3.2: Discrimination between intentional and unintentional contact forces/impacts.
3. OBJ3.3: Formalization of robot reflexes for adaptive fault recovery and task completion.

2.2 Explanation of the work carried towards WP3 objectives

In the first period of the I.AM. project, TUM focused on advancing impact detection and classification in robotics. A literature review was conducted, highlighting the Momentum Observer as a well-established method for impact detection, albeit with a delay due to its nature, demonstrating a first-order filter behavior. To improve the detection speed, we introduced a regressor-based observer that monitors and rejects modeling errors, enhancing collision detection accuracy using IMUs [4]. Additionally, we explored a method for a real-time multi-contact detection, isolation and identification algorithm for tree-structured floating base robots based on generalized external forces and (optional) external wrenches measured by force/torque sensors within the kinematic chain [5]. During the second period, TUM expanded on the previous work and investigated discrimination between intentional and unintentional impacts. As a result, a collision monitoring framework that encoded desired impact motion using a rigid robot model and an inelastic impact map was introduced. This framework utilized a momentum observer for impact detection and an online causal envelop filter for classification, enabling sensitivity tuning for expected and unexpected post-impact behaviors. We also explored the use of IMUs for material identification and enhancing end-effector velocity measurements [6]. In another work, we introduced an innovative collision monitoring framework based on causal envelop filter, which distinguishes between expected and unexpected post-impact behaviors in robotic manipulation (see Fig. 1). This framework offers tunable sensitivity for various impact scenarios and has been validated through simulations and preliminary experiments, representing a crucial step towards robust impact-aware robotics monitoring [9]. Additionally, methods for estimating inertial parameters of held objects and improving the robot model were investigated [7]. Overall, we demonstrated different applications aligned with I.Sense from enhancing collision detection accuracy, payload identification, material discrimination, to link velocity and acceleration estimations for task space control systems.

Based on the results obtained in the first two periods, accurate estimation of link velocity and acceleration in robot manipulators is crucial for various high-tech tasks and control applications. However, traditional methods rely on mathematical models and measurements, but these models may contain variables that cannot be directly measured, and the number of available measurements may be limited. Robot manipulators link velocity and acceleration can be estimated using nonlinear observers. This is typically achieved by model-based fusion of inertial measurement units (IMUs) with the robot motor encoders. As shown in the first two periods, this method has been proven to be light, generally applicable (broad bandwidth), and easily implementable. However, due to technical difficulties, the full potential of this observer has never been evaluated. In this period, we investigated the observer performance installing seven IMUs on a robot manipulator [1]. Although the sensor noise, as well as mechatronics challenges, may degrade the overall performance, there exist methods to maintain the estimation accuracy to acceptable levels. We also review and evaluate some of these methods, which come in the following.

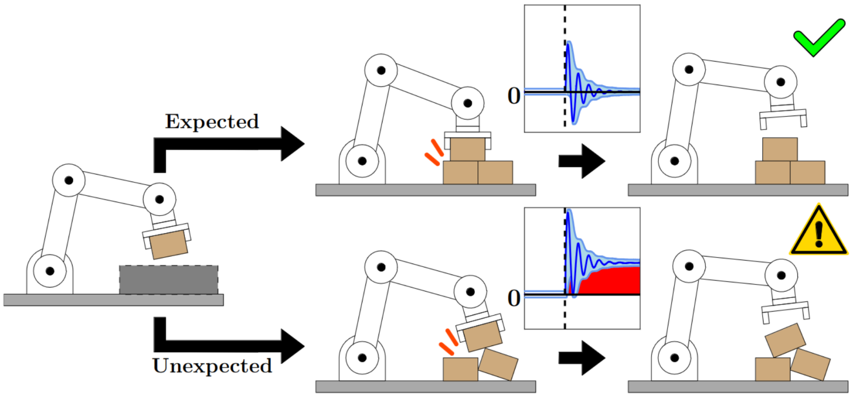

Figure 1: The proposed aim-aware collision monitoring method in action. Using the error between the predicted and measured impact response, a signal envelope is generated. If the region inside the envelope (shaded light blue) envelops 0, the impact sequence is classified as expected. If it does not (the difference is shaded red), the impact sequence is classified as unexpected.

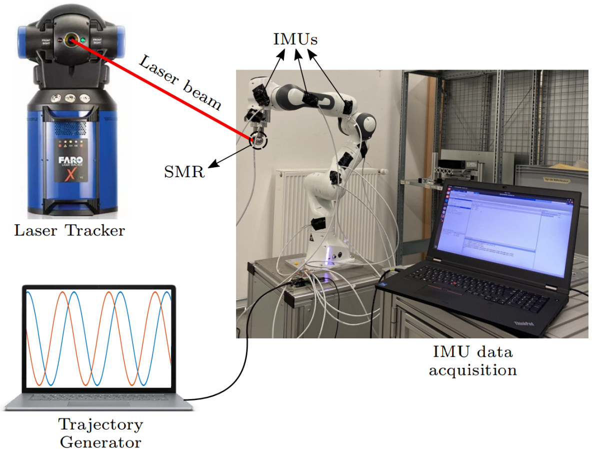

Figure 2: Schematic of the proposed experimental IMU fusion setup, with 7 IMUs installed on all robot links.

We have mainly used families of Kalman filters for estimating the robot link velocity and acceleration so far. While successful in aerospace programs in the 60s, Kalman filter has been facing challenges in industrial applications due to inaccurate modeling and limited budgets [8]. Different approaches, such as online adaptation of noise covariance, have been proposed to overcome these limitations. In collaboration with EPFL, we introduce a noise covariance adaptation algorithm based on maximum likelihood, combined with the extended Kalman filter (EKF) [2]. However, tuning EKF requires substantial measurement samples and is sensitive to sensor changes. Also, the stability of adaptive Kalman filter has been a major issue in the literature. To address these issues, we presented a stable method for adapting noise covariance, aiming to reduce tuning efforts and enhance estimation robustness in the context of link velocity and acceleration estimation.

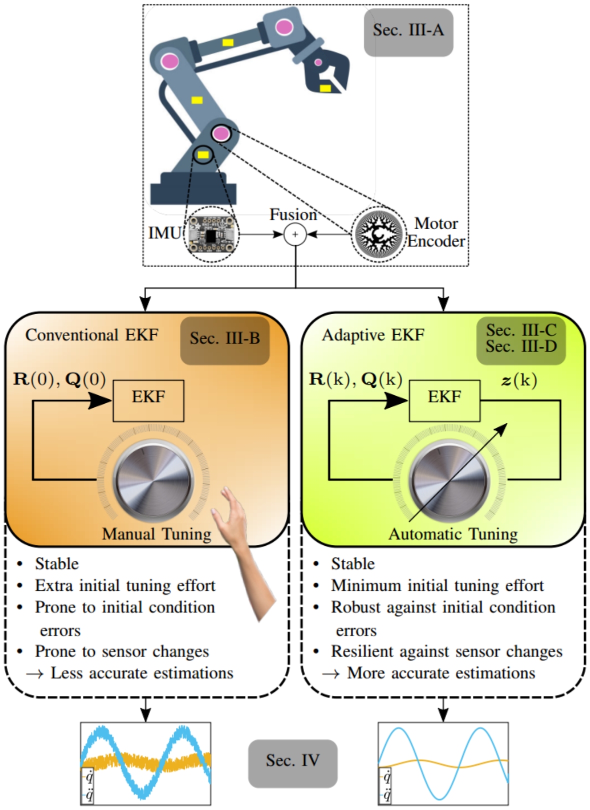

Figure 3: Comparison of conventional versus adaptive Kalman filter introduced in [2].

In another work recently submitted to the International Journal of Robotics Research (IJRR), several significant contributions are presented for estimating link velocity and acceleration in robotic systems [3]. Firstly, the previous scheme for rigid robots is generalized to include flexible-joint robots, allowing for the application of the method in modern collaborative and tactile robots with lightweight structures and elastic joints. This expansion addresses challenges associated with harmonic drives, shaft windup, and bearing deformation. Secondly, the optimal placement of inertial measurement units (IMUs) in the link structure is analyzed to optimize the signal-to-noise ratio (SNR) using the Fisher information matrix (FIM). This analysis enables the quantification and optimization of the IMU's effect on link-side variable estimation, with potential improvements in applications such as IMU-based collision monitoring. Thirdly, the paper explores the fusion of multiple IMU sensors per link using both centralized and decentralized architectures, evaluating their respective performance. Lastly, a sensor failure detection and isolation (SFDI) algorithm is introduced to enhance the proprioceptive sensor system, allowing for robust state estimation even in the presence of sensor failures. These contributions advance the field of link velocity and acceleration estimation in robotic systems, addressing challenges related to flexibility, optimal sensor placement, sensor fusion, and robustness.

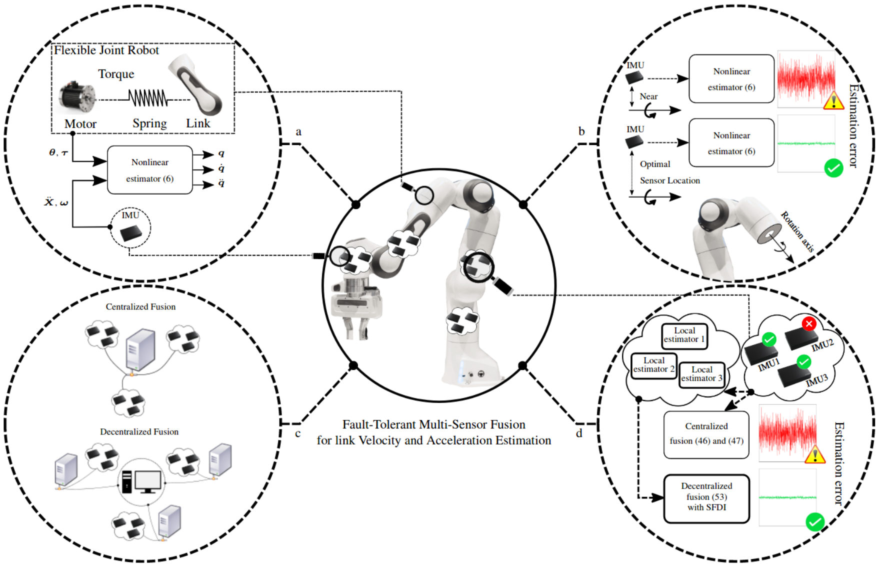

Figure 4: Summary of the contributions made in [3]: a. Estimating link-side velocity and acceleration by fusing IMUs installed on the robot links with proprioceptive sensing. b. Placing IMUs on the link surface for maximum estimation accuracy. c. Designing different architectures for multiple-IMU fusion. d. Tackling sensor failures in the setup.

3 CONCLUSION

In conclusion, TUM has made significant progress in the field of impact detection, classification, and link-side, as well as task-space variables estimation in robotic systems. Through collaboration with our project partners, we have successfully achieved the objectives outlined in the GA. Firstly, we have developed a regressor-based observer that enhances collision detection accuracy using IMUs and rejects modeling errors consistent with OBJ3.1. This method has demonstrated improved collision detection speed and sensitivity. Secondly, we have extended our collision monitoring framework to distinguish between intentional and unintentional impacts, incorporating an inelastic impact map and an online causal envelop filter, aligning with OBJ3.2. This framework allows for the classification of impact motions and sensitivity tuning for expected and unexpected post-impact behaviors. Additionally, we have explored the use of IMUs for material identification and enhancing end effector velocity measurements, contributing to the overall goal of the project. Furthermore, we have maintained consistency with the GA by benchmarking the performance of our methods and evaluating them against state-of-the-art approaches. The results have demonstrated the effectiveness and applicability of our techniques in enhancing collision detection accuracy, payload identification, material discrimination, and robot kinematics (both in joint- and task-space) estimation. Our findings have been documented in several research papers and have been submitted to renowned conferences and journals in the field.

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