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

I.AM.

Human Safety in Impact Aware Manipulation

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Control sheet

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ABBREVIATIONS

Abbreviation	Definition
EC	European Commission
PU	Public
WP	Work Package
SMU	Safe Motion Unit
HRI	Human-Robot Interaction
EMU	Expectable Motion Unit
MPC	Model Predictive Control

EXECUTIVE SUMMARY

Ensuring both physical and psychological well-being of human coworkers in the vicinity of robots is a critical aspect of logistics automation. Although the main focus of the I.AM. project is autonomous task execution, it is crucial to demonstrate that the entire framework is compatible with state-of-the-art robot control systems that prioritize human safety. For this, we provide a comprehensive overview of the research and development work that has been undertaken to emphasize the human safety aspects of the impact-aware manipulation pipeline.

During impact-aware manipulation tasks, there is a possibility of unintentional contact between the robot and the human operator/coworker. In such contact cases, it is essential to ensure the safety of the human operator from a biomechanical pain/injury perspective. This safety consideration needs to be addressed across various components of the I.AM. technology (i.e., learning, sensing, control). Leveraging pain/injury biomechanics data, the robot must be controlled in a manner that minimizes the severity of any unforeseen contact. To achieve this, we employ the so-called Safe Motion Unit (SMU), which utilizes a scheme based on pain and injury biomechanics to establish a link between basic impact datasets, robot reflected dynamics, and intrinsically safe robot velocities. The SMU calculates the instantaneous safe velocity based on the robot's inertial properties (particularly, its reflected mass), surface curvature, and potential collision points with human body parts. This safe velocity threshold is used for real-time control to mitigate the impact of contacts. Moreover, in terms of psychological safety, we introduced the concept of the Expectable Motion Unit (EMU). The EMU ensures that the occurrence of involuntary motions during typical human-robot interactions does not exceed a certain probability threshold. This is achieved by establishing a mapping between robot velocity, robot-human distance, and the relative frequency of involuntary motion occurrences through experimental observations. In fact, real-time motion plans can be generated that adhere to the threshold for involuntary motion occurrence. By combining the EMU and SMU concepts, we develop a holistic, data-driven safety framework that addresses both physical and psychological aspects of human-robot interaction. In this deliverable, we provide detailed insights into the developments made within this comprehensive safety framework for robot task and motion control, that can be utilized to safely guide the execution of I.AM. dynamic manipulation tasks in shared workspaces with humans.

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. Developments in the context of I.AM. project leverages this technology and strengthens European leadership by endowing robots with the ability to exploit intentional impacts for manipulation. I.AM. focuses on impact-aware manipulation in logistics, a new area of application for robotics that will likely grow exponentially in the coming years, due to socio-economic drivers such as booming e-commerce and scarcity of labor. I.AM. relies on four scientific and technological research areas 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 during and after impact, 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.

With this integrated paradigm, I.AM. aims to bring robots to an unprecedented level of manipulation abilities. By incorporating this new technology in existing robots, I.AM. enables shorter cycle time ($\sim$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 for fast object **BOXING**, and
- a case depalletizing scenario demonstrating object **GRABBING**.

1.2 Background of the deliverable

Manufacturing processes can be made more efficient, faster, and more cost-effective when humans and robots are brought to work side-by-side in close proximity to work on them together. Although I.AM. is mainly focused on the autonomous operation of robots, the ultimate aim of its research is to facilitate the possibility of seamless human-robot collaboration while the robot is performing impact-aware manipulation tasks. Extending I.AM. technological developments, in terms of modeling, learning, sensing, and control (WP1 – WP4), with the possibility of workspace sharing and collaborative operation alongside humans imposes additional safety challenges that must be tackled while executing impact aware manipulation tasks. For this, tailored implementation choices are needed in order to ensure human safety while maintaining efficient human-robot collaboration, which translates especially into not reducing the robot speed more than necessary. As the I.AM. framework is expected to reduce cycle time by 10% compared to state-of-the-art manipulation on socio-economic relevant logistics scenarios such as, e.g., tossing, boxing, grabbing, (OBJ5), reliable safety measures can be introduced while preserving competitive overall performance. To emphasize how this deliverable contributes to I.AM. roadmap towards addressing the market needs from the logistics domain, we recall the shown snippet in Figure 1, which was adopted from the standard V-cycle approach (with blue color representing 'solutions' and purple for 'technology').

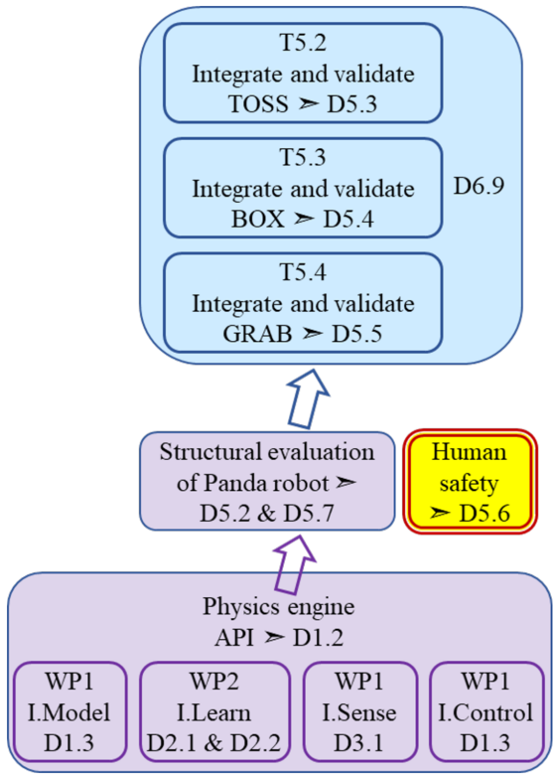


Figure 1: V-cycle snippet indicating the role of D5.6 (highlighted in yellow) within the overall I.AM. roadmap.

1.3 Purpose of the deliverable

The purpose of this deliverable is to elucidate the advancements made in ensuring human safety during the execution of impact-aware manipulation tasks using the technological developments of I.AM. These developments are to be validated in three logistics scenarios: Tossing, boxing, and grabbing.

1.4 Intended audience

The dissemination level of this report is "public" (PU) - meant for members of the Consortium (including Commission Services) and the general public.

2 Human safety in impact aware manipulation

2.1 I.AM. WP5 objectives

We recall that I.AM. project objectives related to WP5 (Integration and Scenario Validations) are:

OBJ5.1 Provide guidelines to ensure a smooth integration of the impact aware manipulation software, developed as modeling, learning, sensing, and control components in WP1, WP2, WP3, and WP4.

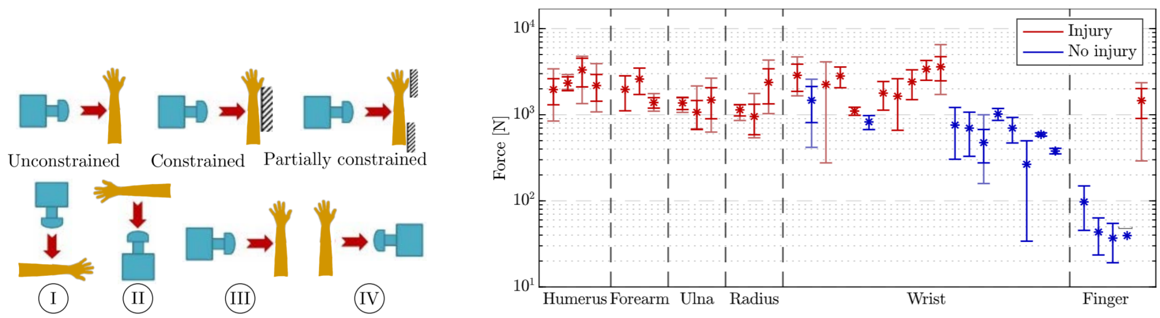
OBJ5.2 Validate the impact aware manipulation software on the three validation scenarios, first by means of numerical simulation and then physically on the consortium robot manipulators.

2.2 Explanation of the work carried towards WP5 objectives

From the perspective of human-robot interaction, it is crucial to avoid any unintentional collisions between humans and robots. However, it is necessary to investigate the scenarios in which such collisions may be unavoidable, potentially leading to human injuries. Consequently, it is imperative to control the robot in a manner that minimizes the likelihood and severity of unforeseen contact, aligning with biomechanical data on pain and injury. To achieve this, a unified safety framework called the safe motion unit (SMU) has been previously developed to ensure human safety in case of robotic collisions [1]. The SMU imposes limitations on the robot's velocity, ensuring it always remains below a safe level during contact phases. These limitations are based on the robot's impact properties (such as reflected inertia, collision points' geometry, and velocity) as well as data from a human pain/injury database [2].

A significant challenge associated with utilizing the SMU is the limited availability of comprehensive pain/injury datasets for various human body parts [3, 4]. In the context of the I.AM. project, fixed-based manipulators are commonly employed in activities such as, e.g., tossing, boxing, and grabbing. When humans are introduced to collaborate with robots while executing their impact-aware manipulation tasks, there is a potential risk of collision between the robot and human upper extremities. To address this issue, TUM conducted an extensive literature review in order to gather relevant data from various sources regarding the upper extremities of the human body. This information was then compiled into comprehensive injurious/safe impact datasets. Additionally, the corresponding experiments were classified based on testing setups, impact scenarios, and collision cases involving the upper extremities. Each category was represented by a minimal set of test arrangements, which standardized the description, storage, reporting, and comparison of experimental settings and results. This approach enables easy categorization and comparison of any new impact test or incident against others within the developed digital database. As an illustration, Figure 2 demonstrates the categorization of arm/hand impact scenarios and testing setups, along with selected results from the literature review on injuries related to the upper extremities of the human body.

On the other hand, the I.AM. project utilizes dynamic manipulation techniques, which may involve higher robot velocities. In order to ensure the safety and efficiency of its impact-aware technology in shared workspaces with humans, it is crucial to avoid imposing conservative velocity limits. This objective can be accomplished by reducing the robot's reflected mass and activating the SMU only when absolutely necessary. The robot's reflected mass is influenced by its configuration and can be optimized, particularly in the case of kinematically redundant robots. Considering that humans may enter the shared workspace from different directions, it is computationally advantageous (however, maybe conservative)



(a) (b)

Figure 2: (a) Standard hand/arm impact scenarios encountered in biomechanics and principal test setups abstraction for impact experiments. (b) Synopsis plots of the reported force values versus injury in reviewed experimental impacts with the human upper extremities.

to minimize the reflected mass in all possible directions. To address this, TUM has introduced a novel metric known as the *Mean Reflected Mass* (MRM) [5]. The MRM is a configuration-dependent measure that represents the average reflected mass in all directions, enabling the assessment and optimization of the robot's posture in terms of safety. Importantly, the MRM can be directly correlated with human pain/injury data. Furthermore, our experimental studies have demonstrated that optimizing the robot's MRM leads to a reduction in the mean collision force. A visual representation that illustrates the MRM-based safety concept for posture optimization is depicted in Figure 3, where the reflected mass is visualized using belted ellipsoids.

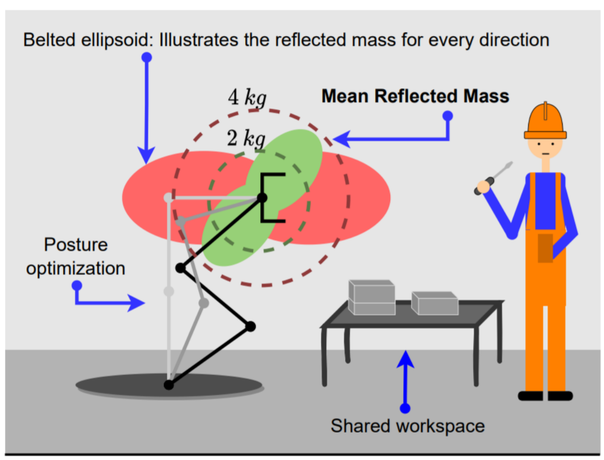


Figure 3: A visual illustration of the MRM concept. This physically interpretable metric can be used for safety assessment and optimization of the robot's posture for all possible robot-to-human impact directions during physical HRI phases.

Regarding the safe operation of collaborative robots, the current ISO/TS 15066 standard emphasizes the significance of dynamic properties, particularly reflected mass, and presents a model for estimating it. TUM has conducted further research to investigate the accurate estimation of reflected mass and compare it with the ISO model [6, 7]. The results have revealed a disparity between the simplified ISO model

and the state-of-the-art dynamic model. Not only is the ISO model excessively conservative in most cases, but it can also underestimate potential hazards, thereby jeopardizing human safety in human-robot interaction (HRI) applications. For instance, we have already demonstrated that the estimated reflected mass value obtained from the two-mass ISO model can be lower than the actual reflected mass, which we measured independently.
In situations where a human coworker approaches the robot closely, the SMU can enforce velocity constraints to prevent injuries in the event of an undesired collision. To enhance efficiency and avoid an unnecessary reduction in velocity, a novel concept called *robot functional mode switching* has been introduced to ensure human safety during collaborative tasks [8]. This concept encompasses different human-robot interaction modes (cf. Figure 4), such as coexistence and collaboration. In the coexistence mode, human and robot share the same workspace but does not have a shared task objective. Therefore, even if the presence of a human around the robot is detected, it is not necessary to decrease the robot's velocity, and it can continue its impact-aware manipulation task. Furthermore, research has been conducted on a smooth velocity shaping method, allowing seamless transitions between various safety regimes and evaluating this shaping technique based on different criteria.

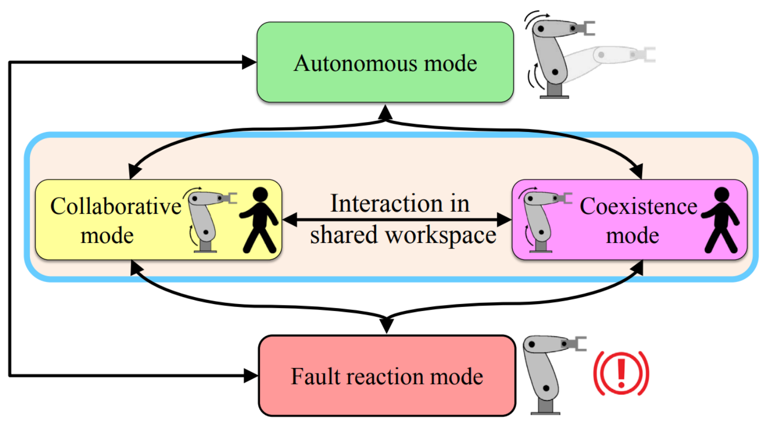


Figure 4: Robot's safe and functional mode switching concept. Different modes of operations are suggested for robot, depending on whether it operates autonomously with complete isolation from humans or there is a probability of physical interaction in a shared workspace.

In dynamic manipulation tasks like tossing within the I.AM. project, the robot may need to achieve higher velocities even when humans are present. Despite extensive research on physical safety in interaction scenarios, the consideration of expectations and psychological state of humans in such scenarios is often overlooked. To address the psychological safety of humans working around/with robots, an experimental setup was devised to examine the influence of robot velocity and robot-human distance on the occurrence of rapid involuntary motion (IM) caused by startle or surprise [9]. The relative frequency of IM occurrences served as an indicator of potentially unsafe psychological situations for humans. The findings from these experiments were utilized to develop the Expectable Motion Unit (EMU). The EMU ensures that the occurrence of rapid involuntary motion remains within a certain probability range in typical human-robot interaction (HRI) settings, thereby preserving psychological safety. This EMU is integrated into a comprehensive safety framework that combines psychological safety insights with the physical safety algorithm of the Safe Motion Unit (SMU) (see Figure 5). In a subsequent study, the efficiency of this psychologically-based safety approach in HRI was further enhanced through the implementation of Model Predictive Control (MPC). This MPC-based approach optimizes both the Cartesian path and speed simultaneously to minimize the time taken to reach the target pose [10].

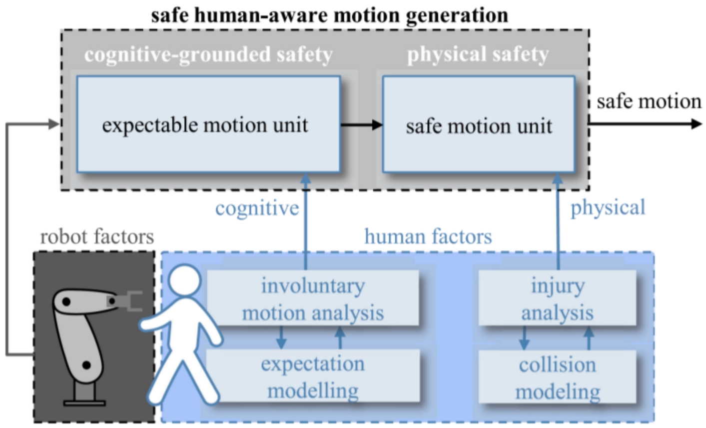


Figure 5: The EMU-SMU framework for safe and human-aware robot motion generation. It builds upon an experimental model of human involuntary motion occurrence, and further combines cognitively-grounded safety aspects and well-established physical safety considerations to prevent potentially dangerous robot motions during HRI.

To further investigate the impact of robot motion and individual characteristics on users' perceived safety in HRI, a study was conducted involving a total of 44 participants [11]. The objective was to determine whether significant effects of human factors could be observed on startle and surprise reactions (see Figure 6). The results of the study, analyzed using a generalized linear mixed model, revealed that direct human factors such as gender, age, profession, intention, technology anxiety, or curiosity to use did not have a significant influence on the occurrence of startle and surprise reactions. However, a noteworthy habituation effect was observed, indicating that participants became accustomed to the robot's motions over time. Additionally, the presence of a training sequence between trials seemed to have an impact on the occurrence of startle and surprise reactions. Furthermore, the study confirmed the influence of velocity and instantaneous distance between humans and robots on the observed reactions. Overall, this investigation shed light on the interplay between robot motion, personal traits, and users' perceived safety in HRI, highlighting the importance of habituation and experimental design considerations.

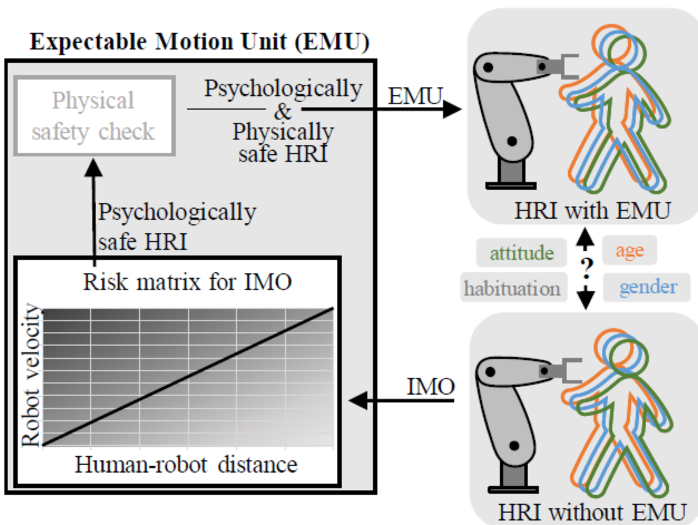


Figure 6: Testing the generalizability of the EMU concept for the broad population by comparing the influence of robot motion scaling of the EMU against possible influences of users' human factors.

3 CONCLUSION

This deliverable is a technical report that describes how human safety can be ensured within the I.AM. software framework. The goal of all the technical developments described in this report is to ensure human-safe operation while executing I.AM. impact-aware manipulation tasks. It includes implementation details of safety modules on a robotic manipulator arm that are compatible with the three main impact-aware dynamic manipulation scenarios: Tossing, grabbing, and boxing. To achieve this, we proposed a unified framework that combines both physical and cognitive safety aspects for HRI. Furthermore, we extended this framework to simultaneously consider human factors and personal traits, such as age, profession, or technology affinity. These factors may potentially influence humans' perceived safety with respect to varying robot factors.

4 REFERENCES

[1] Sami Haddadin, Simon Haddadin, Augusto Khoury, Tim Rokahr, Sven Parusel, Rainer Burgkart, Antonio Bicchi, and Alin Albu-Schäffer. On making robots understand safety: Embedding injury knowledge into control. *The International Journal of Robotics Research*, 31(13):1578–1602, 2012.

[2] Technical Univesrity of Munich. Report on human injury data for autonomous mobile systems. Technical report, Deliverable 4.4, ILIAD project, 2020.

[3] M. Hamad, A. Kurdas, S. Abdolshah, and S. Haddadin. Experimental injury biomechanics of human body upper extremities: Anatomy, injury severity classification, and impact testing setups. In *2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR) 2021 Mar 4*, pages 310–315. IEEE, 2021.

[4] M. Hamad, A. Kurdas, S. Abdolshah, and S. Haddadin. A robotics perspective on experimental injury biomechanics of human body upper extremities. In *2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR) 2021 Mar 4*, pages 316–320. IEEE, 2021.

[5] Thomas Steinecker, Alexander Kurdas, Nico Mansfeld, Mazin Hamad, Robin Jeanne Kirschner, Saeed Abdolshah, and Sami Haddadin. Mean reflected mass: A physically interpretable metric for safety assessment and posture optimization in human-robot interaction. In *2022 International Conference on Robotics and Automation (ICRA)*, pages 11209–11215. IEEE, 2022.

[6] Robin Jeanne Kirschner, Nico Mansfeld, Guillermo Gómez Peña, Saeed Abdolshah, and Sami Haddadin. Notion on the correct use of the robot effective mass in the safety context and comments on iso/ts 15066. In *2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR)*, pages 6–9. IEEE, 2021.

[7] Robin Jeanne Kirschner, Nico Mansfeld, Saeed Abdolshah, and Sami Haddadin. Experimental analysis of impact forces in constrained collisions according to iso/ts 15066. In *2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR)*, pages 1–5. IEEE, 2021.

[8] Petr Svarny, Mazin Hamad, Alexander Kurdas, Matej Hoffmann, Saeed Abdolshah, and Sami Haddadin. Functional mode switching for safe and efficient human-robot interaction. In *2022 IEEE-RAS 21st International Conference on Humanoid Robots (Humanoids)*, pages 888–894. IEEE, 2022.

[9] Robin Jeanne Kirschner, Henning Mayer, Lisa Burr, Nico Mansfeld, Saeed Abdolshah, and Sami Haddadin. Expectable motion unit: Avoiding hazards from human involuntary motions in human-robot interaction. *IEEE Robotics and Automation Letters*, 7(2):2993–3000, 2022.

[10] Moritz Eckhoff, Robin Jeanne Kirschner, Elena Kern, Saeed Abdolshah, and Sami Haddadin. An mpc framework for planning safe & trustworthy robot motions. In *2022 International Conference on Robotics and Automation (ICRA)*, pages 4737–4742. IEEE, 2022.

[11] Simone Nertinger, Robin Jeanne Kirschner, Saeed Abdolshah, Abdeldjallil Naceri, and Sami Haddadin. Influence of robot motion and human factors on users' perceived safety in hri. In *2023 IEEE International Conference on Advanced Robotics and its Social Impacts (ARSO)*. IEEE, 2023.