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

Publication of I.AM. dataset (update D1.1)

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Control sheet

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ABBREVIATIONS

Abbreviation	Definition
D1.4	Deliverable 1.4
EC	European Commission
FE	Franka Emika
I.AM.	Impact-Aware Manipulation
M36	Month 36
PU	Public
TU/e	Technische Universiteit Eindhoven
WP	Work Package

EXECUTIVE SUMMARY

This deliverable D1.4 "Publication of I.AM. Dataset (update D1.1)" aims at providing an updated overview of the current status of the database generated in WP1 (I.Model) and D1.1. This deliverable builds upon D6.3 "Data Management Plan", D1.1 "Publication of I.AM.Dataset", and consequently on the H2020 On-line Manual on Data Management Plan and deals with the topics of FAIR data. The deliverable provides an in-depth description of the updated version of the Impact-Aware Robotics database, including an overview of the data currently stored in the database. Furthermore, this deliverable describes the technical implementation of the database, including the created software architecture to collect and store the data, and the developed web application to display the data on a dedicated website.

1 INTRODUCTION

1.1 I.AM. Project Background

Europe is leading the market of torque-controlled robots. These robots can withstand physical inter-action with the environment, including impacts, while providing accurate sensing and actuation capa-bilities. 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 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.

I.AM. integrates these research areas to bring robots to an unprecedented level of manipulation abil-ities. By incorporating this new technology in existing robots, I.AM. enables shorter cycle time (about 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 applica-tion demonstrating object tossing, a bin-to-bin application for fast object boxing, and a case depalletizing scenario demonstrating object grabbing.

1.2 Purpose and Background of the Deliverable

This deliverable D1.4 "Publication of I.AM. dataset (update D1.1)" is an update to D1.1 "Publication of I.AM. dataset" and is summarizing (i) information about the software written to collect and store the data in a structured way, (ii) information about the dedicated website that is created to disseminate the data, and (iii) information about the collected datasets, i.e., the datasets that are currently stored in the database and related to the three validation scenarios (TOSS, BOX, GRAB) of the I.AM. project.

Deliverable D1.4 paves the way to reaching the following milestones:

- MS14 "Robot-object-environment impact laws" (TU/e) – M42 (June 2023)

- MS15 "Impact motion learning" (EPFL) – M42 (June 2023)

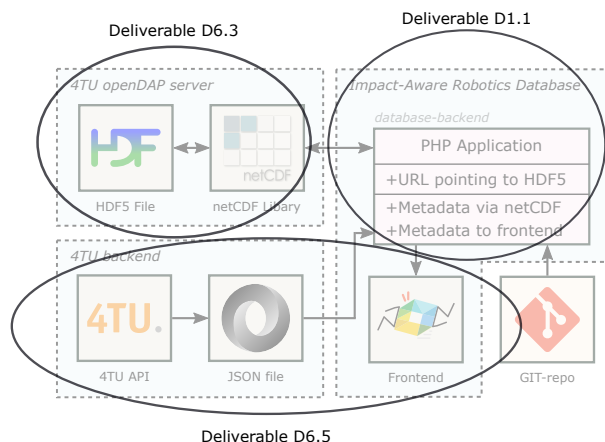- MS18 "Scenario 3 (GRAB)" (EPFL) – M42 (June 2023)

Figure 1: Current architecture of the impact-aware robotics database, highlighting how earlier deliverables contributed to the different parts.

Earlier, related to this deliverable, the following deliverables were published: deliverables D1.1 "Publication of I.AM. dataset" (describing in detail the impact-aware robotics database structure and taxonomy), D6.3 "Data Management Plan" (which is updated in M25 as D6.5 and will be updated in M40 as D6.6) and related deliverables on ethics, being D8.1 "H - Requirement no.1" and D8.4 "POPD – Requirement no.2". The topics of FAIR data and data privacy are already described in these deliverables and therefore the reader is asked to read these documents for further details on these topics. Figure 1 shows an overview of the structure of the database (which will be detailed in Section 2), where we indicate the information covered in previous deliverables. These previous deliverables have already contributed to achieving the following milestones, by providing a data repository, specific dataset regarding 2 scenarios as well as a methodology for uploading and using the data:

- MS3 "Object-environment impact laws" (TU/e) – M18 (June 2021)

- MS8 "Scenario 1 (TOSS)" (TU/e) – M24 (December 2021)

- MS9 "Robot-environment impact laws" (TU/e) – M30 (June 2022)

- MS13 "Scenario 2 (BOX)" (Smart Robotics) – M36 (December 2022)

In this deliverable (D1.4), we will detail the overview of the whole database structure as a result of D1.1, D6.3 and D6.5, therefore covering the full picture of Figure 1.

1.3 Intended Audience

The dissemination level of D1.4 is 'public' (PU) – meant for members of the Consortium (including Commission Services) and the general public.

1.4 Associated Scientific Paper

To share the database and the software written for data collection and storage with the scientific community, this deliverable is paired with a scientific paper. A preprint of this paper [1] can be accessed openly on the European open science repository HAL.

1.5   Structure of the Report

In Section 2, we will detail how the data can be accessed via the developed web interface and we will describe the structure of this web interface. In Section 3, we will describe how someone can contribute to the Impact-Aware Robotics Database and we describe the software developed for collecting and storing data in a structured way. In Section 4, we will give an overview of datasets that are currently stored in the database. The conclusions and recommendations for future work are given in Section 5.

2 ACCESSING THE DATABASE

In this section, we first discuss how the datasets can be viewed and downloaded via a custom developed web interface, and then provide more details about the architecture that is behind this web interface.

The current version of the database contains 16 datasets. These datasets are published on the service 4TU.ResearchData as part of the Impact-Aware Robotics Archives collection [3], and can be viewed and downloaded via the web interface of 4TU.ResearchData [4]. 4TU.ResearchData is an international data repository and offers dataset curation, sharing, long-term access, and preservation services. As discussed in Deliverable D1.1 [5], 4TU.ResearchData is chosen to host our datasets, as it guarantees the data to be stored long-term (at least 15 years) and it allows the datasets to be stored as widely-used netCDF [6] or HDF5 [7] open-format files. Furthermore, the 4TU.ResearchData service is comparable with the European initiative Zenodo [8], already mentioned and described as one possible option for data storage in D6.3 "Data Management Plan".

Figure 2: Screenshot of the frontend of the Impact-Aware Robotics Database, see [2].
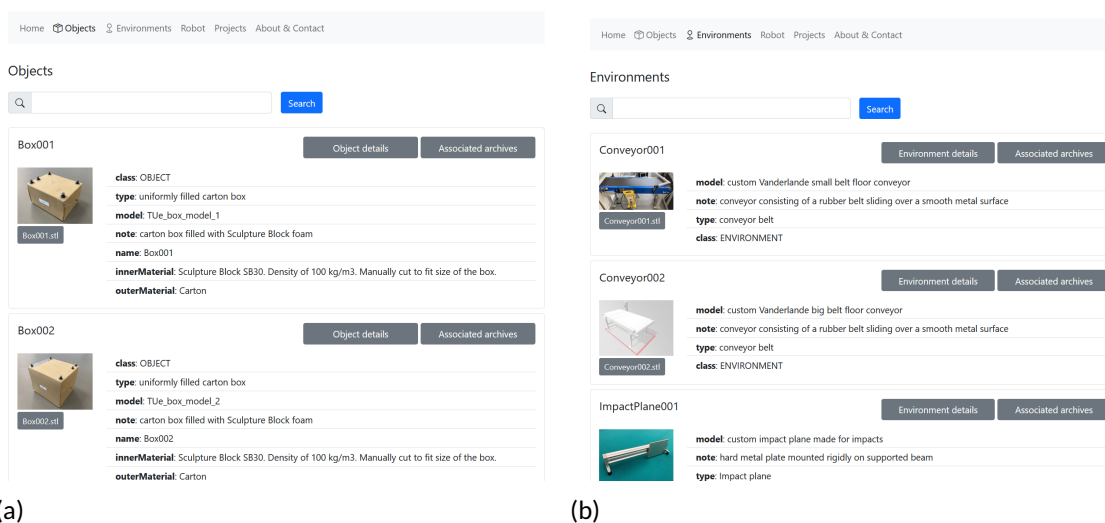
Figure 3: Screenshots of webpages dedicated to display the objects (a) and environments (b) used in the recorded experiments stored in the database.

Although the website of 4TU.ResearchData [3] gives access to view and download the datasets, it does not provide the option to search for specific metadata tags (related to objects, robots, environments, sensors, and the contact transition taxonomy) that are stored within the datasets. This makes it difficult for users to understand the content of a dataset without having to download the dataset first. Therefore, we developed a web interface [2] that provides a platform to search for and download impact-aware-robotics-related datasets from the database.

Figure 2 shows a screenshot of the frontend of the Impact-Aware Robotics Database that has been created within the I.AM. project. A user is able to see an overview of the datasets and is able to search for specific datasets via metadata tags under the "Search" field. In this search field, the user can search on metadata tags of Object, Robot, Environment, Transition, Purpose, or Sensor. The possible search tags are also shown in a drop-down menu which is displayed when the user clicks on the specific search field. The user can also search for datasets via visible properties metadata, such as description, project, institution, note, author, and keywords. Once a search is executed, the frontend will display all datasets that contain the metadata on which the user searched and the datasets can be downloaded via a download button (shown on the top-right of every dataset shown in Figure 2). The previews of the datasets, as partly shown in the bottom of Figure 2, also show these metadata tags.

Figures 3a and 3b show the Objects and Environments page, respectively. On these pages, all objects and environments are shown that are used in the datasets. A client can view detailed information about the objects and environments, or search for all datasets that contain that object/environment. This allows the client to understand the meaning of the various metadata tags.
Furthermore, the client can also search for a combination of keywords, such as **Object: Box006** and **Environment: Conveyor002**. The separate Object and Environment page can then be used to view detailed information about Box006 and Conveyor002.
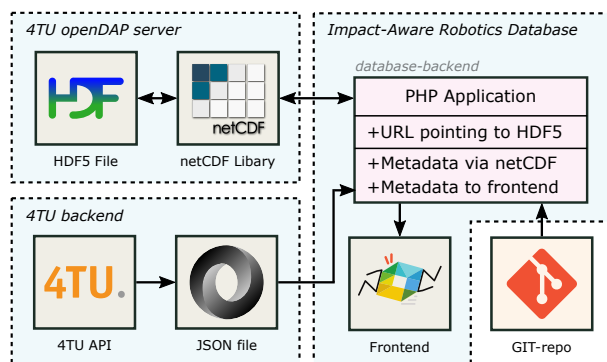
Figure 4: Overview of the backend structure of the database. A PHP application crawls information from the 4TU backend about the datasets stored under the Impact-Aware Robotics archive collection and retrieves metadata from these datasets stored on the 4TU openDAP servers via a netCDF library. This information is then displayed on the database frontend, together with metadata on the objects, robots, and environments retrieved from an external Git-repository.

Figure 4 shows an overview of the database web application. A PHP application crawls information about the datasets stored under the Impact-Aware Robotics archive collection from the 4TU backend via a JSON file. This JSON file contains the URL pointing to the HDF5 files stored on the OpenDap [9] servers of 4TU. A request for metadata or content of the HDF5 file can then be made by issuing an HTTP request to the OpenDAP server via the NetCDF [6] library, allowing us to display all information on the frontend of the database, see [2]. It then displays this information, together with all metadata of the objects, robots, and environments retrieved from an external Git-repository (lower right corner of Figure 4), on the frontend of the database.

A clear path has been laid out to continue the development of the web interface in the coming year. Some examples of pages that will be added are given below:

- "Robots" page - containing information about the robots used in the experiments (similar to Objects and Environments page)

- "Projects" page - containing information about the projects under which the datasets are created

- "About and Contact" page - containing general information about the database, how to contact the developers, and instructions on how to contribute to the database.

3   CONTRIBUTING TO THE DATABASE

In this section, we will describe the developed software architecture for collecting and storing experimental data according to the structure discussed in Section 2.3 of Deliverable D1.1. The structure of a dataset is also shown in Figure 5, which is an updated version of Figure 2 from Deliverable D1.1 and shown here for ease of readability. Within this software architecture, we distinguish between *data collection* (e.g., controlling the experimental setup and collecting raw sensor data) and *data storage* (e.g., post-processing raw sensor data to enhance human and machine interpretability, providing metadata, and storing the data in a structured way). In the following subsections, we will detail our approach on data collection and storage. We share the software online[1], which provides an example and possibility for other researchers that want to contribute to the Impact-Aware Robotics Database.

3.1   System Overview

Figure 6 provides an overview of the developed software architecture. A host PC controls the experimental setup and logs the incoming data from the sensors via the *data collection* application, which also stores the data of each experiment in separate recording folders. Next, via the *data storage* application, the raw sensor data is processed and stored together with the associated metadata in datasets. These datasets are uploaded to 4TU.ResearchData [4] OpenDAP servers as part of the Impact-Aware Robotics Archive Collection [3]. The custom web application, as discussed in Section 2, extracts information from the 4TU servers, which is then displayed on the front-end web interface.

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[1]The software written to collect and store data according to the Impact-Aware Robotics database structure is made publicly available and can be found on `https://gitlab.tue.nl/robotics-lab-public/impact-aware-robotics-database`.
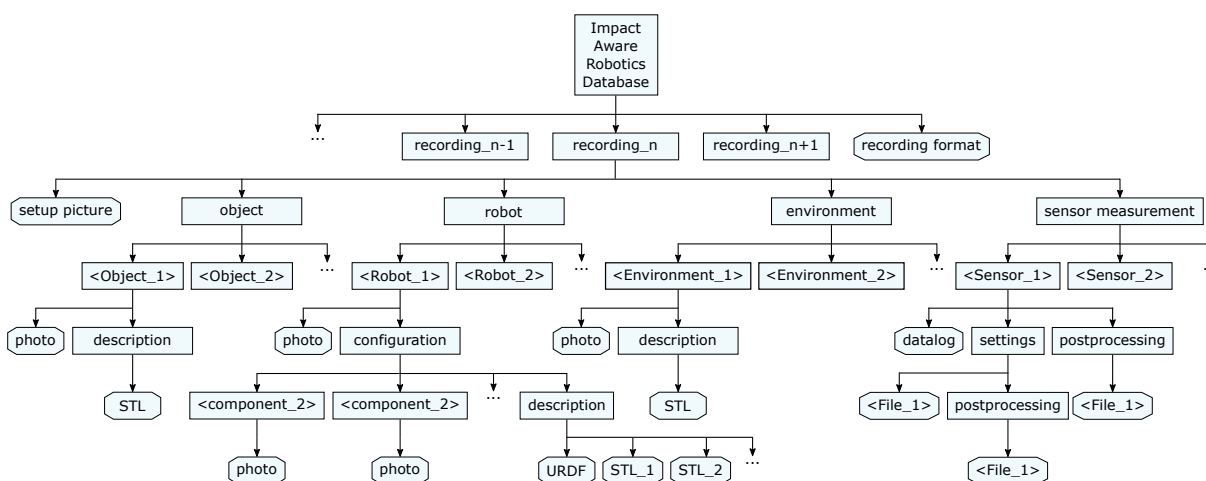

Figure 5: Structure of an dataset. Each dataset contains a set of recordings, as well as a description of the recording format. Each recording is subdivided into object, robot, environment, and sensor measurement subfolders and contains a picture of the setup used during the data recording. This figure is an updated version of Figure 2 from Deliverable D1.1.
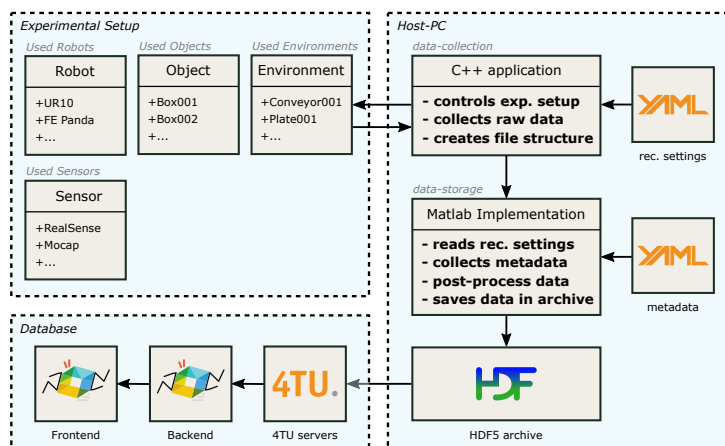
Figure 6: Overview of the software architecture. The host PC contains the data-collection application that takes the recording settings from a configuration YAML file (top right corner) to control the experimental setup, collects the data from the recording, and stores the data in a session/recording file structure. The data-storage application takes this raw data and stores it, together with the associated metadata imported from an external Git-repository (middle right), to an HFD5 dataset file. This file is then uploaded to the 4TU servers from which we display the datasets on the front-end.

3.2 Data Collection

Within the I.AM. project, data is collected at different experimental setups. At the TU/e, two different setups are used for the BOX, TOSS, and GRAB scenarios. At Franka Emika, a setup is used to test intentional impacts (details in deliverable D5.2) related to the GRAB scenario. At other partners, secondary local setups for the GRAB scenario are created. Because experimental data is collected at all these setups, it is important that the software to collect this information is modular, such that the collected data always has the same structure, even though it is recorded on different setups. Furthermore, it is important to document all metadata about the setup, the robot (with its configuration), the objects, and the environment used during the recording of an experiment. Important information to record is also the geometric (dimension, shape) and dynamic (mass, inertia, material) properties of the robot(s), object(s), and environment involved in the experiments, in order to allow for the reproduction of the experimental conditions. For commercial products (robots, end-effectors, consumer objects), it is requested to describe the exact model/type of product.

To allow the software to deal with this high variety of objects, robots, environments, and sensors, a simple C++ application has been written that can control the setup (e.g., starting/stopping of sensor recordings, turning on/off a conveyor) and collects the raw sensor data. The application contains various functions that each control and record data of a specific sensor. The structure of this application is modular to ensure that new functions corresponding to new sensors added to the setup, can easily be added to the application without interfering with the existing structure. Next to these functions, the application contains a configuration YAML file (top right of Figure 6) that contains the recording settings (e.g., to decide what sensors will be used to record the experiments) and initializes and configures a recording of a specific experiment. Furthermore, this configuration YAML file contains metadata describing what objects, robots, and environments are used in the recordings, and contains information about the setup, the author(s), and a short description of the experiment. The configuration YAML file

is then stored with the raw sensor data in the folder created for that specific experiment. This ensures that all information about one recorded experiment is stored together in one dedicated folder.

3.3 Data Storage

The purpose of the data storage application is to post-process and store the recorded (raw) data files together with the associated metadata in a single dataset according to the structure shown in Figure 5. From the recording configuration YAML files is known for each recording what objects, environments, robots, and sensors are used. This information is used to retrieve the associated metadata (e.g., pictures, STL files, robot configuration files) from an external Git repository (middle right of Figure 6), and store this information in the dataset together with the raw and post-processed data. Storing the metadata together with the sensor data ensures the datasets are stand alone and the data can be interpreted by both humans and machines. Once a dataset is created in the form of a HDF5 file, it can be added to the Impact-Aware Robotics Database, for which we detail the procedure in the next section.

3.4 Adding Datasets to the Impact-Aware Robotics Database

The current version of the database contains datasets that are collected during the I.AM. project. However, the database is intended to continue and grow beyond this project and to provide a platform for data storage for any experiment related to impact-aware robotics. To this end, we stimulate researchers in the field of impact-aware robotics to contribute to the database by providing the option to upload datasets to the database. In Sections 3.2 and 3.3, we discussed the open software we have created that can be used to collect and store the experimental data in a predefined structure used for the Impact-Aware Robotics Database. This software provides the end-user with the tools to create a dataset that can be uploaded to the database. At this stage, the procedure to do so is as follows, but the reader is referred to the database website [2] for the latest information about contributing to the database.

To upload a dataset, the end-user must create an account on 4TU.ResearchData [4]. This can be done either through an institutional login (if the institution the end-user is connected to is a partner of 4TU) or via an eduID[2], which can be created using an email address and name. End-users that are not connected to an institution that is partnered with 4TU can get up to 5GB of free storage, and after that, they have to pay 4.5 euro per gigabyte[3]. End-users that are connected to a partner institution can upload more data, depending on the partner status (either gold, silver, or bronze member). Datasets can then be uploaded under different licenses and linked to the Impact-Aware Robotics Archive Collection [3] on 4TU.ResearchData by adding a metadata tag pointing to this collection. All datasets currently stored in the database are publicly available under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC-BY-NC-SA 4.0) license. We recommend using this license, but authors are free to choose differently. Best practice is to contact a TU/e contact mentioned on the website [2] for advice or support on data conversion and upload. After the dataset is uploaded, a data curator from the TU/e evaluates the dataset before it is added to the collection. Once the dataset is part of the collection on 4TU, it is automatically displayed on the website of the Impact-Aware Robotics Database.

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[2]An eduID is an account that allows to login into several services connected to Dutch educational and research institutions, meant for users that are not connected to any of those institutions. More info can be found at `https://eduid.nl/en/`.

[3]More information can be found at 4TU.ResearchData, see `https://data.4tu.nl/info/en/about-4turesearchdata/membership-prospectus`.

4 DATA COLLECTION PLAN AND COLLECTED DATASETS

In Deliverable D1.1, the following expectations regarding the data collection plan were stated.
Responsible Partner:

- TOSS and BOX scenarios, mainly TU/e, with input from TUM, FRANKA EMIKA, CNRS, and EPFL.

- GRAB scenario: mainly EPFL and CNRS for providing equipment (dual arm KUKA robot, dual Panda arms, sensor I/O logging), support for hardware and acquisition software, performing of experiments; TU/e for setting up experimental conditions and storage of collected data in agreed format with inputs from TUM, CNRS, and EFPL.

Expected recording time:

- First year: TOSS/BOX

- Second year: BOX/GRAB

- Third year: GRAB

The current version of the Impact-Aware Robotics Database contains a total of 16 datasets related to all three different scenarios as a continuous effort of all partners in the project. The database is still growing and a complete overview of the (current) uploaded datasets is shown in Table 1. In total, at the time of writing this deliverable, these datasets have been viewed 5622 times and are downloaded 2135 times, and these numbers are growing rapidly, see also Table 2. This shows that the database is used extensively. Most of the datasets uploaded to the database are related to the I.AM. project, except for

Nr.	Name	Creation Date	Size	Scenario
1	First version of an Impact Aware Manipulation (I.AM.) archive	25/09/2020	1.9GB	TOSS
2	Impact Aware Manipulation (I.AM.) archive containing suction cup recordings	18/11/2021	1.96GB	TOSS
3	Impact Aware Manipulation (I.AM.) archive containing box impact recordings	03/12/2021	2.48 GB	TOSS
4	Impact Aware Manipulation (I.AM.) archive containing suction cup release experiments	22/08/2022	1.02GB	TOSS
5	Impact Aware Manipulation (I.AM.) archive containing box-drop experiments for Parameter Identification of Box006	07/09/2022	1.95GB	TOSS
6	I.AM. archive containing box-drop experiments for Velocity Based Parameter Identification of Box007	24/10/2022	2.46GB	TOSS
7	I.AM. archive containing box-drop experiments for Velocity Based Parameter Identification of Box009	24/10/2022	2.41GB	TOSS

Nr.	Name	Creation Date	Size	Scenario
8	I.AM. archive containing box-drop experiments for Trajectory Based Parameter Identification of Box006	24/10/2022	1.1GB	TOSS
9	I.AM. archive containing box-toss experiments with Box005 for repeatability analysis	24/10/2022	3.73GB	TOSS
10	I.AM. archive containing box-toss experiments with Box005 for sensitivity analysis	25/10/2022	6.78GB	TOSS
11	I.AM. archive containing long range box-toss experiments with Box005 and Box006 for validation of impact models	26/10/2022	2.75GB	TOSS
12	Archive containing experiments with a drone impacting a rigid wall with the purpose of parameter identification	26/10/2022	821.02MB	-
13	I.AM. archive containing long range box-toss experiments with Box006, Box007, and Box009 for validation of impact aware object tracking	26/10/2022	308.44MB	TOSS
14	I.AM. archive containing dual-arm grabbing experiments	14/11/2022	115MB	GRAB
15	I.AM. archive containing experiments of stacking boxes in totes, relevant for the BOX scenario.	01/12/2022	947MB	BOX
16	I.AM. archive containing impact experiments with a Franka Emika Panda robot	01/12/2022	452MB	GRAB

Table 1: Overview of the uploaded datasets to the Impact-Aware Robotics database, updated on 15/12/2022

archive number 12 (see Table 1), which contains impact experiments with a drone. These experiments were executed in collaboration with DTU and show that the database has already been used outside of the I.AM. project for storage of experimental data related to impact-aware robotics. Some uploaded datasets are also used to support publications, such as dataset number 4, which is a dataset supporting the publication in [10]. Other datasets, such as dataset 3 and 5, will be used in publications as well. As the datasets themselves have their own DOI, they can always be found and referred to in scientific

#Archives	#Recordings	Total #Views	Total #Downloads	Total size
16	2174	5622	2135	31.13GB

Table 2: Overview of the size, the number of views and the number of downloads of the database, updated on 15/12/2022

publications, encouraging researchers to upload their datasets to the Impact-Aware Robotics database.

To further disseminate the web interface and service we have created, we are already in contact with the community manager of the 4TU.Research Data[4] and we aim to promote our work at least nationally by participating, e.g., in 2023 at the FAIR Data in Science and Engineering event hosted by 4TU.ResearchData.

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[4]See also the press release at `https://community.data.4tu.nl/2022/01/06/one-year-of-the-4tu-researchdata-community-reflections-achievements-and-looking-ahead/`

5   CONCLUSION AND FUTURE WORK

This deliverable provides an update with respect to Deliverable D1.1 and comes with a scientific paper, of which a pre-print can be found online [1]. This report describes the procedure for accessing the data via the web interface and describes how data can be collected (via a data-collection application), stored (via a data-storage application), and uploaded to the database. A web interface has been created that allows users to search through the database efficiently via provided metadata tags, and software has been written to collect and store experimental data in the proper format. Furthermore, this report gives an overview of the current status of the database showing that datasets for all three scenarios have been made as a continuous effort by all partners. The project will continue till M48 (December 2024) and new datasets will be added to the database related to the TOSS, BOX, and GRAB scenarios. Furthermore, the web interface will be updated as well with new information and webpages. After the I.AM. project, the database will be able to grow beyond the I.AM. project as the modular structure allows researchers from all over the world to upload their experimental data (conform the Impact-Aware Robotics database structure) to the database.

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