Handling with AI-enhanced Robotic
Technologies for flexible ManUfacturing

D4.1
ASSEMBLY DATASET

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HARTU Consortium

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1	Tekniker	FUNDACION TEKNIKER (TEK) 20600 Gipuzkoa | Spain	Contact: Iñaki Maurtua inaki.maurtua@tekniker.es
2	dfki Deutsches Forschungszentrum für Künstliche Intelligenz German Research Center for Artificial Intelligence	DEUTSCHES FORSCHUNGSZENTRUM FUER KUENSTLICHE INTELLIGENZ GMBH (DFKI) 67663 Kaiserslautern | Germany	Contact: Vinzenz Bargsten vinzenz.bargsten@dfki.de
3	aimen	ASOCIACIÓN DE INVESTIGACIÓN METALÚRGICA DEL NOROESTE (AIMEN) 36418 Pontevedra| Spain	Contact: Jawad Masood jawad.masood@aimen.es
4	eng	ENGINEERING INGEGNERIA INFORMATICA S.P.A. (ENG) 00144 Rome| Italy	Contact: Riccardo Zanetti riccardo.zanetti@eng.it
5	TOFAŞ	TOFAS TURK OTOMOBIL FABRIKASI ANONIM SIRKETI (TOFAS) 34394 Istanbul | Turkey	Contact: Nuri Ertekin nuri.ertekin@tofas.com.tr
6	PHILIPS	PHILIPS CONSUMER LIFESTYLE BV (PCL) 5656 AG Eindhoven | Netherlands	Contact: Erik Koehorst erik.koehorst@philips.com
7	ULMA	ULMA MANUTENCION S. COOP. (ULMA) 20560 Gipuzkoa | Spain	Contact: Leire Zubia lzubia@ulmahandling.com
8	deepblue	DEEP BLUE Srl (DBL) 00193 ROME | Italy	Contact: Erica Vannucci erica.vannucci@dblue.it
9	FMI ImProvia	FMI HTS DRACHTEN B.V. (FMI) NL-4622 RD Bergen Op Zoom, Netherlands	Contact: Floris goet floris.goet@fmi-improvia.com
10	TECNOALIMENTI	TECNOALIMENTI S.C.p.A (TCA) 20124 Milano | Italy	Contact: Marianna Faraldi m.faraldi@tecnoalimenti.com
11		POLITECNICO DI BARI (POLIBA) 70126 Bari | Italy	Contact: Giuseppe Carbone giuseppe.carbone@poliba.it
12	OMNIGRASP	OMNIGRASP S.r.l. (OMNI) 70124 Bari | Italy	Contact: Vito Cacucciolo vito.cacucciolo@omnigrasp.com
13	ITRI Industrial Technology Research Institute	INDUSTRIAL TECHNOLOGY RESEARCH INSTITUTE INCORPORATED (ITRI)	Contact: Curtis Kuan curtis.kuan@itri.org.tw
14	INFAR INFAR INDUSTRIAL CO., LTD.	INFAR INDUSTRIAL Co., Ltd (INFAR) 504 Chang-hua County | Taiwan	Contact: Simon Chen simon@infar.com.tw

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Executive Summary

The overall topic of the HARTU project is to develop robotic technologies which allow a more flexible robotic automation of manufacturing and logistics tasks. One element towards achieving this goal is the application of data-driven machine learning approaches. In the course of the method development in the project, multiple datasets related to robotic assembly have been created for this purpose. This document describes a dataset of user demonstrations for learning and generalizing robotic assembly skills, a dataset of measurements of a novel type of force sensor using fiber optics, as well as image datasets of the objects being handled in various containers. The datasets have been published on Zenodo and are accessible at the links listed in the Summary chapter. The deliverable described by this document is part of work package WP4 of the HARTU project, which deals with *Learning and control of contact-rich assembly skills* and also includes some datasets generated in "*WP2 Common software infrastructure for integration, simulation and perception*".

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Acronyms

List of the acronyms	
HARTU	Handling with AI-enhanced Robotic Technologies for flexible manufactUring
PbD	Programming by Demonstration
FBG	Fiber Bragg Grating
DOF	Degrees of freedom

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1. Introduction

1.1. Purpose and scope of the datasets

The overall topic of the HARTU project is to develop robotic technologies which allow a more flexible robotic automation of manufacturing and logistics tasks. To achieve this goal, machine learning methods play a major role, since they allow the use of data-driven solutions instead of solutions hand-crafted by experts for specific applications. More specifically, one of the tasks which has been defined to achieve the goals of the HARTU project is *Learning assembly operations through demonstrations.* In more general terms, this is also known as *Programming by Demonstration (PbD)*: the idea is to allow users of a robotic system such as a manipulator arm to teach the motions it has to do for certain task and to avoid a software-based programming. Simplify such that configuration of a systems is less reliant on expert programming skills. In HARTU, contacts and generalization are considered in the problem. However, for these methods respective data are required. Therefore, a dataset containing a variety of recordings of a user demonstrating assembly operations to a robotic manipulator arm is described and published with this document.

Since assembly relies on locating, grasping, and sensing the objects, the scope of this deliverable has been extended: it is not limited to the assembly operations itself, but also includes related datasets that have been created in the first period of the project.

Specifically, the accurate sensing of forces and contacts is crucial for a robotic system to fulfill the assembly and handling, in particular grasping, of parts. For this purpose, a fiber optic-based sensor is developed, which can be integrated into gripper pads and suction cups. The corresponding dataset of the measurements of such sensor elements is described in this document.

The last type of datasets described in this document are segmented and labelled virtual images of the objects being handled in the HARTU project, such as automotive parts, barrels, and vegetables located in different type of containers or palletized. These images can be used, for example, to develop machine-learning-based grasp strategies or object pose estimation methods. We have expanded the deliverable's scope to encompass not just assembly operations but also other pick-and-place operations. This expansion includes additional datasets we've developed during this period.

1.2. Outline of the document

The document is outline as follows. Each dataset published with this deliverable is described in a separate chapter: Chapter 2 describes the dataset related to the assembly demonstrations, Chapter 3 describes the dataset related to the development of a fiber optic force sensing method, and Chapter 4 describes multiple image datasets with objects being handled within HARTU. Chapter 5 summarizes the published datasets.

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2. Assembly Dataset for Learning from Demonstration of Contact Based Tasks (DFKI)

This dataset is a detailed collection of motion and visual data during kinesthetic demonstration gathered for the HARTU project, specifically for two use cases:

- PCL: assembly of plastic shaver housing parts
- TOFAS Assembly: assembly of metal automobile axle and brake parts

The dataset supports research and development of methods for learning from demonstrations of contact based tasks in robotics, focusing on motion planning, control, and computer vision applications related to contact based assembly tasks.

This dataset has been uploaded to ZENODO. It has been assigned the following DOI as unique identifier and is accessible at this address:

https://doi.org/10.5281/zenodo.12513790

2.1. Description of the data acquisition process

2.1.1. Experimental setup

The experimental setup consists of a manipulator arm with 7 degrees of freedom (KUKA LBR iiwa 14 R820), an end-effector force torque sensor (Robotiq FT-300), a two-finger gripper (Robotiq 2F-140), and RGBD camera (Intel Realsense D455). The manipulator arm is mounted vertically, onto a metal column, which is mounted on a table. At the front of the table, the parts to be assembled are located. The general setup is shown in the following figure:

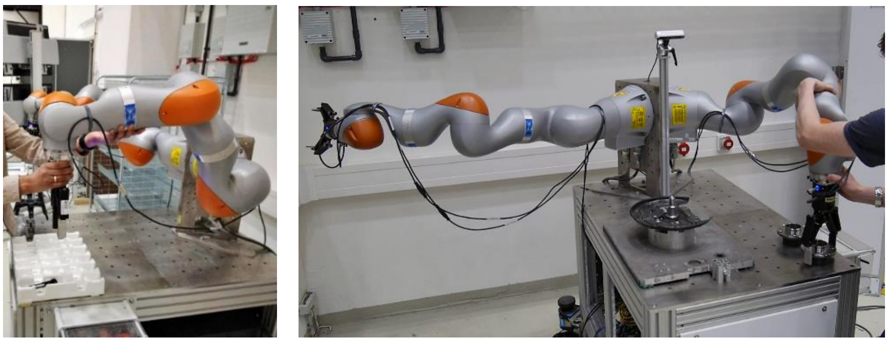

Figure 1. The experimental robotic setup used to acquire the user demonstrations

2.1.2. Data collection

The robotic manipulator arm is controlled in a gravity compensating mode such that it can be moved freely by external forces. A human operator then guides the end-effector of the

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manipulator with his hands into the target positions and orientations of the segments defined by each task. Thus, a task is composed of a sequence of these demonstrations.

During this procedure, joint torques, joint velocities, joint positions, end-effector positions, forces and torques, as well as RGBD camera images are recorded in the HDF5 format and simultaneously in rosbag format using the tool rosbag2.

2.2. Dataset Contents

2.2.1. Demonstration Subsets

The following demonstrations of the assembly tasks have been recorded:

a) Use case PCL, part 1
   i) The complete assembly procedure
      (1) Trial 1
      (2) Trial 2
   ii) The procedure sub-divided into 4 separately recorded assembly steps
      (1) Trial 1
      (2) Trial 2
b) Use case PCL, part 2
   i) The complete assembly procedure
      (1) Trial 1
      (2) Trial 2
   ii) The procedure sub-divided into 3 separately recorded assembly steps
      (1) Trial 1
      (2) Trial 2
c) Use case TOFAS, part 1
   i) The complete assembly procedure
      (1) Trial 1
      (2) Trial 2
   ii) The procedure sub-divided into 3 separately recorded assembly steps
      (1) Trial 1
      (2) Trial 2
d) Use case TOFAS, part 2
   i) The complete assembly procedure
      (1) Trial 1
      (2) Trial 2
   ii) The procedure sub-divided into 3 separately recorded assembly steps
      (1) Trial 1
      (2) Trial 2

In summary, 34 individual recordings are included in this dataset.

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2.2.2. Data in each recording

Each recording contains the following data:

- Motion data
  The motion data provides detailed information about the movement and operation of the dual arm KUKA robot. This includes:
  - Cartesian Positions: The positions of the robot's end effectors in 6D Cartesian coordinates, position in 3D (x, y, z) and orientation represented as quaternion (x,y,z,w)
  - Joint Positions: The joint angles or positions of each joint in the robot's arms
  - Velocity: The speed of movement in both, Cartesian space and joint space

- Camera data
  The visual data is captured using an RGB-D camera, which provides both colour and depth information for each frame. This includes:
  - RGB Data: Colour images captured during the demonstrations, providing visual context for the robot's actions
  - Depth Data: Depth images that represent the distance of objects from the camera, useful for 3D reconstruction and spatial analysis

- Force data
  - Force/Torque: The forces and torques experienced by the robot's end effectors during the demonstrations measured using the 6-DOF force/torque sensor and torques measured from joints

- Gripper actions
  - Information about the actions performed by the robot's grippers during assembly operation, such as open and close

2.2.3. File format and directory structure

The dataset is stored in HDF5 files, a hierarchical data format that allows for efficient storage and retrieval of large datasets. Each HDF5 file contains the data listed in 2.2.2. In addition, ROS-typical rosbags are recorded during each demonstration, capturing all the relevant ROS topics published during the demonstrations for easy playback and analysis.

The dataset is organized into directories corresponding to individual demonstrations for each use case. As listed above, each use case is recorded for complete execution and step wise execution. Each directory contains the following files:

1. demo.hdf5: An HDF5 file containing motion and camera data recorded during demonstration
2. rosbag2*: A ROS bag folder containing metadata and a db3 file capturing required ROS topics during the demonstration

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2.3.Data processing

Resources for working with HDF5 and ROS Bags

1. HDF5 Resources
    a. HDF5 Viewer: HDFView is a tool for browsing and editing HDF5 files
    b. Python Library: h5py is a Python library for interacting with HDF5 files

2. ROS Bag Resources
    a. ROS Bag Tutorials: ROS Wiki
    b. rqt_bag: A GUI plugin for visualizing ROS bag files

This dataset can be used for Learning-from-Demonstration applications, including but not limited to:

- Robotics motion planning: Developing and testing algorithms for controlling dual arm robots in industrial assembly tasks
- Robot vision: Training and evaluating models for object recognition, tracking, and 3D reconstruction in assembly processes
- Force control: Studying the interaction forces between the robot and its environment during assembly tasks.

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3. Fiber Optic Force Sensor Experiments for Suction and Finger Grippers (AIMEN)

This dataset has been collected in the development of fiber optic force sensors for suction and finger grippers. This dataset has been uploaded to ZENODO. It has been assigned the following DOI as unique identifier and is accessible at this address:

https://doi.org/10.5281/zenodo.11387093

3.1. Experimental setup

Two setups are considered:

1. Suction cup

The experimental setup consists of a suction cup with some fibre optic sensors embedded. The suction cup is then attached to a static holder. The vacuum was obtained by using an external vacuum generator

2. Tactile fingers

The experimental setup consists of a silicone patch with some fibre optic sensors embedded. The patch is there attached to a steel plate and a robotic arm has been used for pressing in different points of the patch.

3.2. Data collection and description of files

1. Folder Suction cup

FILE: test1.h5

GRIPPER: suction cup with embedded fibre/ distributed measurements by Rayleigh Scattering

PROCESS: Decreasing vacuum by an external vacuum generator with different weights. Weights are 250 g, 470g, 511 gr, 750g and 1000g. The vacuum decreases from 700 mbar in 50 mbar steps.

FILE: test2.h5

GRIPPER: suction cup with embedded fiber / distributed measurements by Rayleigh Scattering

PROCESS: Manually approaching a weight to the suction cup with the vacuum switched on for three times, holding and releasing the vacuum, letting the part to fall. Then increasing the weight and repeat that cycle. Weights are 250, 500,750, 1000,1250 and 1500 grams.

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GRIPPER: suction cup with embedded fibre/ punctual measurements in three different points by FBGs

PROCESS: Manually approaching a weight to the suction cup with the vacuum switched on for three times, holding and releasing the vacuum, letting the part to fall. Then increasing the weight and repeat that cycle. Weights are 250, 500, 750, 1000 and 2000 grams. Lifting performed at 170 mbar.

2. Folder TactileFingers

FOLDER:test3

FILES: wrenches3.txt is the file for the force's sensor (SCHUNK FTN-Mini-40) and attached to the ABB robot tcp (ABB IRB2600 20kg 165) with six columns (Fx, Fy, Fz, Tx, Ty, Tz) in S.I units and test3.h5 contains the FBG signal.

PATCH: patch of 42 mm x 42 mm x6 mm with misaligned FBGs and patch of 42 mm x 42 mm x6 mm with aligned FBGs. Positions of the fibre are shown in FigurePatch1 and FigurePatch2 in the parent folder

PROCESS: Pressing the patch in 40 different positions by using a square probe of 5 mm x 5 mm and indenting the patches for 3 mm. Probe moves doing a matrix as shown in FigureMatrixTest3, moving 8 mm in the fibre array direction (X) and 5 mm in the orthogonal direction (Y). After finishing a column in the y direction, it returns to the original Y position moves in the X direction and perform again the movement in the Y direction. After finishing with patch#1 it goes to patch#2 and do the same process. Then it goes to a third patch whose data it is not collected in *.log file. This whole process is repeated for three cycles. In addition, the force measurements are recorded from the force/torque sensor and registered in the file wrenches3.txt.

INFO: indicesChannelsP1=[0,1,2,3,4,5]; indicesChannelsP2=[14,15,10,11,6,7]

FOLDER:test6

FILES: wrenches6.txt is the file for the force's sensor (SCHUNK FTN-Mini-40) and attached to the ABB robot tcp (ABB IRB2600 20kg 165) with six columns (Fx, Fy, Fz, Tx, Ty, Tz) in S.I units and test6.h5 contains the FBG signal.

PATCH: patch of 42 mm x 42 mm x6 mm with misaligned FBGs and patch of 42 mm x 42 mm x 6 mm with aligned FBGs. Positions of the fibre are shown in FigurePatch1 and FigurePatch2in the parent folder

PROCESS: Pressing the patch in 24 different positions by using a cylindric probe of 20 mm x 3 mm and indenting the patches for 3 mm. Probe moves doing a matrix as shown in FigureMatrixtTest6

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in the parent folder, moving 12 mm in the fibre array direction (X) and 3 mm in the orthogonal direction (Y). After finishing a column in the y direction, it returns to the original Y position moves in the X direction and perform again the movement in the Y direction. After finishing with patch#1 it goes to patch#2 and do the same process. Then it goes to a third patch whose data it is not collected in *.log file. This whole process is repeated for three cycles. In addition, the force measurements are recorded from the force/torque sensor and registered in the file wrenches6.txt.

INFO: indicesChannelsP1=[0,1,2,3,4,5]; indicesChannelsP2=[14,15,10,11,6,7]

FOLDER:test9

FILES: wrenches9.txt is the file for the force's sensor (SCHUNK FTN-Mini-40) and attached to the ABB robot tcp (ABB IRB2600 20kg 165) with six columns (Fx, Fy, Fz, Tx, Ty, Tz) in S.I units and test9.h5 contains the FBG signal.

PATCH: patch of 42 mm x 42 mm x6 mm with misaligned FBGs (#6) and patch of 42 mm x 42 mm x 6 mm with aligned FBGs(#6). Positions of the fibre are shown in FigurePatch1 and FigurePatch2 in the parent folder

PROCESS: Pressing the patch in 24 different positions by using a cylindric probe of 20 mm x 3 mm and indenting the patches for 3 mm. Probe moves doing a matrix as shown in FigureMatrixTest9, moving 12 mm in the fibre array direction (X) and 3 mm in the orthogonal direction (Y). After finishing a column in the y direction, it returns to the original Y position moves in the X direction and perform again the movement in the Y direction. After finishing with patch#1 it goes to patch#2 and do the same process. Then it goes to a third patch whose data it is not collected in the *.log file. This whole process is repeated for three cycles. In addition, the force measurements are recorded from the force/torque sensor and registered in the file wrenches9.txt.

INFO: indicesChannelsP1=[0,1,2,3,4,5]; indicesChannelsP2=[14,15,10,11,6,7]

3.3. Data processing

Data obtained by Rayleigh scattering measurement equipment provides data for time (in seconds), distance (in meters) and a 2D-matrix of data (strain (µe) which rows are time evolution of data, and the columns are related to the distance or location of the sensor. For processing data of Rayleigh scattering measurements from Python, data can be extracted by using:

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```
import h5py hf = h5py.File('test1.h5', 'r')
list(hf.keys())
datos = hf.file['Datos'][:,:]
tiempo = hf.file['Tiempo'][:]
distancia = hf.file['Distancia'][:]
hf.close()
```

Data obtained by FBGs interrogator only includes time and nD-array of data. The number of columns on the nD-array will depend on the number of sensors used. In the same way than before data can be extracted using:

```
import h5py
hf = h5py.File('test3.h5', 'r')
list(hf.keys())
h5_data = hf.file['Sensores']
y21= h5_data[:,:]
h5_tiempo = hf.file['Tiempo']
x21 = h5_tiempo[0:]
hf.close()
```


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4. Images dataset (TEKNIKER)

This dataset contains rendered images of multiple objects from the HARTU use cases in different containers. The initial datasets generated in the project have been uploaded and shared to ZENODO, HARTU community. In all cases the datasets have been created with the tools developed in WP2, i.e., using the simulation environment and CAD of parts provided by end-users and others publicly available.

The datasets have been assigned a DOI as unique identifier:

- HARTU AUTOMOTION DATASET: https://doi.org/10.5281/zenodo.12155482

  This dataset is created using CAD models of different automobile parts. There are four distinct datasets: part1, part2, mosaic and carboard boxes. For each image, the location of each part is provided at the box level with labels in YOLO format. Each dataset is divided into training, validation and test subsets.

- HARTU PALLETIZING AND BOXING DATASET: https://doi.org/10.5281/zenodo.12155351

  This dataset is created using different objects CAD models. There are two distinct datasets: palletizing and multiobject boxing. For each image, the location of each object is provided at the box level with labels in YOLO format. Each dataset is divided into training, validation and test subsets.

- HARTU VEGETABLES DATASET: https://doi.org/10.5281/zenodo.12155113

  This dataset is created using vegetables CAD models. There are three distinct datasets: tomatoes, eggplants, and zucchinis. For each image, the location of each fruit is provided at the box level with labels in YOLO format. Each dataset is divided into training, validation and test subsets.

For the development of the dataset, the tools developed in T2.3 have been used, which offers three interfaces: one for defining the visual appearance of the parts, a second one for defining the scenes and a third one for defining the dataset. For more details, see “D2.3 Simulation infrastructure for handling component training”.

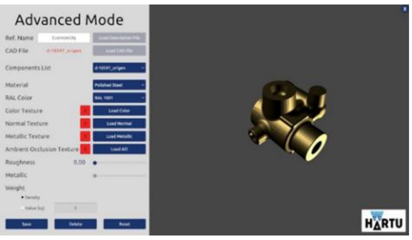

Figure 2. Interface for defining the visual appearance and physical characteristics of parts

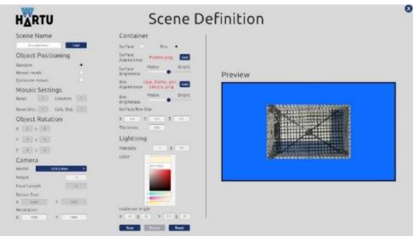

Figure 3. Interface to define a scene

Figure 4. Interface to define the dataset of images to be generated

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5. Summary

To summarize, the following datasets have been published with this deliverable:

Dataset	DOI
Assembly demonstrations	https://doi.org/10.5281/zenodo.12513790
Fiber-optic force sensor measurements	https://doi.org/10.5281/zenodo.11387093
Image dataset, automotive parts	https://doi.org/10.5281/zenodo.12155482
Image dataset, palletizing and boxing of parts	https://doi.org/10.5281/zenodo.12155351
Image dataset, vegetables	https://doi.org/10.5281/zenodo.12155113

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