Demonstration Projects

Call for Ideas to Boost the Competitiveness of the Estonian Manufacturing Industry

Final Report

Please fill in the Final Report in English *The content of the Final Report is published also in [AIRE GitHub]* *To be filled by the Lead of the Development Team*

Demonstration Project Title

Digital twin for development and validation of AI-based motion planning and control for robot-assisted processing of curved surfaces

Company

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Development Team

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Objectives of the Demonstration Project

The primary goal of this project was to develop and evaluate an open-source, modular software pipeline to enable surface-conforming Cartesian motion planning and execution, with a specific focus on robotic cutting and welding applications. The project aimed to create a digital twin of a robot-assisted process for curved surfaces, which could be used to test, validate, and benchmark motion planning algorithms. The developed digital twin pipeline seeks to bridge the gap between expensive, proprietary commercial systems and the more limited open-source alternatives by providing an integrated, robot-agnostic solution using the ROS 2 and MoveIt frameworks. A key objective was to create a platform that could facilitate the integration and testing of new AI-based motion planning algorithms, thereby supporting flexible manufacturing with parametric programming.

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Activities and results of the Demonstration Project

Challenge addressed (i.e. whether and how the initial challenge was changed during the project, for which investment the demonstration project was provided)

The project addressed a significant challenge in manufacturing automation: the processing of complex, curved surfaces with robot manipulators, such as in milling and welding. Existing solutions are often proprietary, costly, and tied to specific hardware, creating a high barrier to entry for smaller companies and researchers. Open-source tools, while available, lacked a comprehensive, integrated, and geometry-aware pipeline for planning and executing trajectories on such surfaces. When automation is not feasible due to mathematical complexity or kinematic constraints, these tasks are performed manually by human workers. This project aimed to create an accessible, open-source solution to this problem. The initial challenge remained the central focus throughout the project.

Activities implemented and results achieved

The project's activities were centered around two main goals: 1) developing a process-specific, universally scalable digital twin, and 2) creating a framework to validate and benchmark motion planning approaches.

- Activities: The project developed a physics-based digital twin for the use-case of processing cylindrical objects, which involved customizing off-the-shelf robot models, creating models for the end-effector tool and the workpiece, and integrating these into a simulation environment. A baseline pipeline was established to benchmark different motion planning components.
- Results: The primary technological result of the project is a process-specific but universally scalable digital twin for robot-assisted processing of curved surfaces, along with a corresponding motion planning pipeline. This integrated solution delivers a modular method for generating, projecting, and executing geometry-aware Cartesian trajectories on complex surfaces. The package successfully integrates surface processing, path projection from 2D contours, inverse kinematics feasibility checking, and robot-agnostic trajectory execution by leveraging the ROS 2 and MoveIt frameworks. As planned, the solution is universally scalable. Its effectiveness and robot-agnostic nature were demonstrated and quantitatively benchmarked through simulated cutting and welding tasks, specifically validating the pipeline on four distinct robot models: the Universal Robots UR5 and UR20, the Fanuc m10ia, and the Kuka iiwa14. This benchmarking specifically compared the performance of three different motion planning back-ends integrated into the pipeline: the standard MoveIt ComputeCartesianPath interpolator, the Pilz Industrial Motion Planner, and MoveIt Servo.

Data sources (which data was used for technological solution)

The technological solution utilizes a 3D model of the workpiece. In industrial applications, these models typically originate from Computer-Aided Design (CAD) files or 3D scans. For this demonstration project, the following specific data was used:

- 3D mesh models of pipe geometries created in Blender.
- Point cloud data with estimated surface normals, generated from the meshes using the Open3D library.
- Robot kinematic models (URDF descriptions) for the four validation platforms: Universal Robots UR5, UR20, Fanuc m10ia, and Kuka iiwa14.
- Motion execution data (joint states and end-effector poses) collected at 100 Hz during simulations for performance evaluation and benchmarking.

This data is processed by the system to project a user-defined 2D path onto the 3D surface, generating a precise sequence of waypoints that is passed to the motion planner to create the final robot trajectory.

Description and justification of used AI technology

The project developed a digital twin and a motion planning pipeline designed to integrate, test, and benchmark various motion planning approaches, including AI-based methods like diffusion policy and learning from demonstration. The core technology is the robot-agnostic framework built using ROS 2 and the MoveIt 2 motion planning library.

This approach was justified by the lack of cohesive, open-source tools capable of handling the entire workflow from path projection on curved surfaces to feasible execution. The project focused on creating and validating the essential infrastructure that enables the safe testing and deployment of novel AI algorithms. The pipeline leverages established robotics techniques such as inverse kinematics (IK) solvers (e.g., KDL, IKFast), and the solution was validated and benchmarked using several motion planners: the MoveIt Cartesian Interpolator, the Pilz Industrial Motion Planner, and MoveIt Servo. This framework provides the baseline for comparing AI-based motion planners in a standardized environment.

Results of testing and validating of the technological solution

The technological solution pipeline was rigorously validated in a simulation environment with four distinct robot models: the Universal Robots UR5 and UR20, the Fanuc m10ia, and the Kuka iiwa14. The evaluation benchmarked the performance of three motion planning back-ends based on Cartesian position error, motion smoothness (jerk), and velocity consistency (Figure 1).

The key findings were:

- Accuracy: The back-ends implementing the MoveIt ComputeCartesianPath and Pilz Industrial Motion Planner demonstrated excellent path-tracking accuracy, achieving average translational errors below the millimeter level (approx. 55-57 micrometers).

- Error: The MoveIt Servo back-end, while offering real-time control, exhibited significantly higher translational and angular errors compared to the other two planners.
- Smoothness: The back-end using ComputeCartesianPath produced the smoothest trajectories, with the lowest average jerk in both Cartesian and joint space.
- Velocity Control: MoveIt Servo proved far superior in maintaining a consistent end-effector velocity, a critical factor for processes like welding.

These results provide a valuable quantitative benchmark, highlighting the trade-offs between accuracy, smoothness, and velocity control for different planners in surface-conforming tasks.

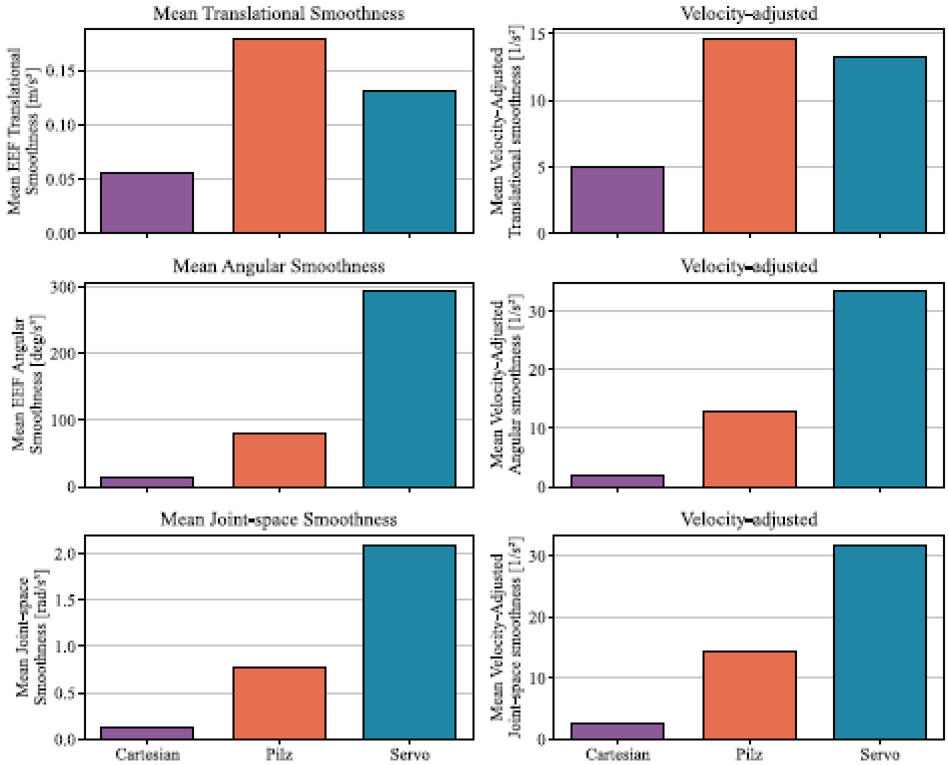


Figure 1. *Mean smoothness scores averaged across robots and runs. Lower is smoother.*

Technical architecture of the technological solution (presented graphically, where can also be seen how the technical solution integrates with the existing system)

The technological solution is architected as a modular ROS 2 pipeline (Figure 2). Its workflow is as follows:

1) Input: The process starts with a 3D mesh of the workpiece (e.g., a pipe from a CAD program like Blender) and a 2D reference path (e.g., a circle defining the desired cut).
2) Waypoint Generation: A core module projects the 2D reference path onto the 3D mesh surface. This is achieved by transforming the workpiece's point cloud into the local 2D frame of the path and performing an efficient nearest-neighbor search using a KD-tree to find the corresponding 3D points and their surface normals.

3) Feasibility Analysis: The generated 3D waypoints (poses) are checked for kinematic feasibility. This is done using the integrated Reach tool for reachability analysis and a custom-developed "Seed State Finder" algorithm, which iteratively searches for a valid initial robot joint configuration that allows for a continuous and successful trajectory execution.
4) Trajectory Planning & Execution: The feasible poses are passed to a MoveIt execution back-end. The system supports multiple planners—ComputeCartesianPath, Pilz Industrial Motion Planner, and MoveIt Servo—which can be used interchangeably. This back-end plans the final, time-parameterized trajectory and sends it to the robot's controllers for execution in the simulated environment.
5) Visualization: The entire process, including the robot, the workpiece (as a collision object), and the executed path, is visualized using RViz, a standard ROS tool.

The architecture is robot-agnostic by design, capable of working with any manipulator that has a standard MoveIt configuration package.

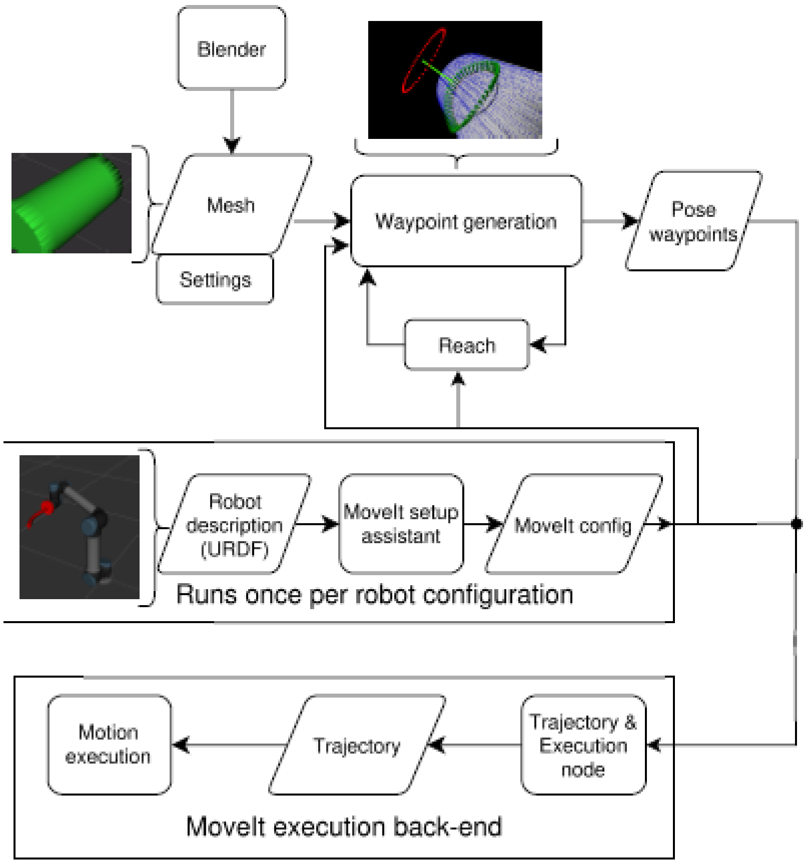


Figure 2. *A high-level overview of the system architecture and information flows.*

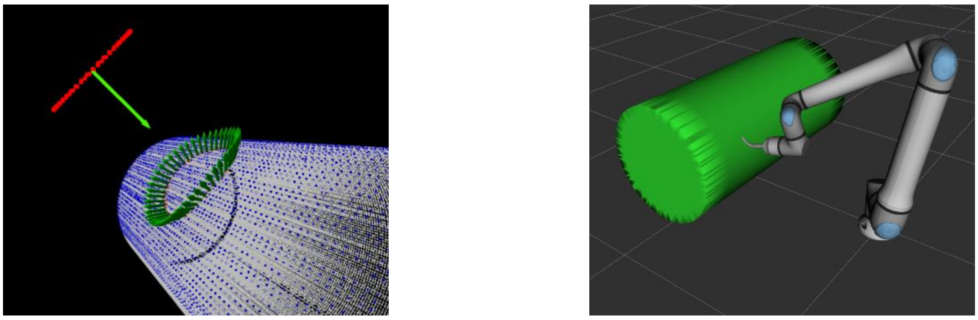
Potential areas of use of technical solution

While the project's primary focus and demonstration were on robotic pipe cutting and welding, the SurfMotion framework is broadly applicable to any robotic task that requires an end-effector to precisely follow a path on a complex or curved surface. Potential application areas across the manufacturing industry include:

- Milling
- Painting and Depainting
- Sandblasting
- Polishing
- Arc Welding
- Automated Quality Control and Inspection

Description of User Interface (i.e. How does the client 'see' the technical result, whether a separate user interface was developed, command line script was developed, was it validated as an experiment, can the results be seen in ERP or are they integrated into work process)

The system includes a graphical user interface (GUI) designed specifically for positioning the 2D reference path (the "stencil" for the cut or weld) in relation to the 3D workpiece model (Figure 3a). This GUI allows the user to precisely place the contour and provides a live-updating preview of the final projected path on the object's surface, aiding in setup and visualization. The primary interface for monitoring the overall process, including the robot's motion, the environment, and the planned trajectory, is RViz, the standard 3D visualization tool for ROS (Figure 3b). The technological result is the physical (or simulated) motion of the robot arm executing the planned path. The solution was validated as an experiment in a simulation environment and is not integrated with an ERP system.



(a) (b)

Figure 3. *(a) GUI for projecting the path on the curved surface. (b) Rviz-based visualization of the robot and its movements*

Follow-up activities and plans for future (e.g. developments, potential for scalability, creation of spin-offs aso)

The project outcomes have significant potential for future development and commercial application. The partner company plans to integrate the developed framework directly into its service offerings for customized automation solutions. The digital twin pipeline is designed with scalability as a core principle and has been released as an open-source package to foster wider adoption and community contribution.

Future development plans for the digital twin pipeline include:

- Improving Planner Back-ends: The driver nodes that interface with MoveIt will be enhanced, particularly the MoveIt Servo back-end, to improve its path accuracy while retaining its excellent velocity control.
- Enhanced Velocity Control: Implementing better and more standardized velocity control across all supported planners is a key priority.
- Greater Parameterization: Increasing the use of runtime ROS parameters will allow users to adjust settings like velocity or planner-specific options on the fly, without needing to modify the source code.
- Smarter Seed-State Finding: The seed-state finding algorithm will be improved to not only find a successful starting pose but also to optimize for desirable characteristics, such as minimizing total joint movement, and to cache good states for reuse.

This framework's open and transparent nature is intended to accelerate the validation and deployment of novel AI-based motion planning technologies in industrial settings.

Lessons learned

i.e. assessment whether the technological solution actually solved the initial challenge

The project successfully solved the initial challenge by creating a functional, robot-agnostic, open-source pipeline for programming complex, surface-conforming robotic tasks like welding and cutting. This work effectively fills a documented gap in the open-source robotics toolset.

Key lessons learned from the project include:

- No One-Size-Fits-All Planner: The detailed benchmarking revealed a clear trade-off between different motion planning strategies. Planners like ComputeCartesianPath and Pilz provide superior path accuracy, which is crucial for precision milling, whereas MoveIt Servo excels at maintaining consistent velocity, a critical requirement for weld quality. This indicates that the choice of planner must be tailored to the specific application's most important constraints.
- The Importance of a Good Start: The custom-developed "Seed State Finder" algorithm proved to be highly effective and almost essential for ensuring successful trajectory generation, reliably overcoming the non-deterministic behavior of some inverse kinematics solvers.
- Jerk vs. Accuracy: The smoothest motion, in terms of lowest jerk, was achieved by the ComputeCartesianPath back-end, which also had high accuracy. This suggests that for tasks sensitive to vibration, it is a strong candidate.
- Complexity of Integration: The project underscored that even with powerful frameworks like ROS 2 and MoveIt, significant, dedicated engineering effort is required to integrate components into a cohesive, validated, and user-friendly pipeline for advanced industrial applications.

Projekti lühikirjeldus (AIRE kodulehele, eesti keeles)

Projekti pealkiri, millist väljakutset lahendati, projekti eesmärk, millist tehisintellekti tehnoloogiat valideeriti, projekti tegevused ja tulemused, kuni 10 lauset

Digikaksik AI-põhise liikumise planeerimise ja juhtimise arendamiseks kumerate pindade tõõtlemisel roboti abil

Tootmises on palju automatiseerimise valdkondi, mida ei saa automatiseerida või on automatiseerimise maksumus väikeste ja keskmise suurusega tootmisettevõtete jaoks äärmiselt kõrge. Üheks selliseks probleemiks on materjali töötlemine robotmanipulaatoritega, kus objektil on keeruline ja potentsiaalselt muutuv vorm. Näiteks on objektil kumerad pinnad ja roboti mõjur-tööriist peab ülesande, nagu lõikamine, täitmiseks täpselt seda kõverat pinda järgima. Antud projekti eesmärk on välja töötada digitkaksik kõverate pindade roboti abil töötlemiseks. Digikaksikut kasutatakse seejärel liikumise planeerimise algoritmide testimiseks, valideerimiseks ja võrdlemiseks, et saavutada mõjuri täpne liikumine mööda mistahes eeldefineeritud rada piki kõverat pinda ja kokkupõrkevaba liikumine.

Project description (to be published on AIRE webpage, in English)

Project title, what challenge was addressed, aim of the project, what AI technology was validated, project activities and results achieved, max 10 sentences

Digital twin for development and validation of AI-based motion planning and control for robot-assisted processing of curved surfaces

There are many areas of automation in manufacturing that cannot be automated, or the cost of automation is extremely high for small and medium-sized manufacturing companies. One such problem is material processing with robot manipulators where the object has a complex and potentially changeable form. For instance, the object has curved surfaces, and the robot’s end-effector tool needs to precisely follow this curved surface to complete a task such as milling. The goal of this project is to develop a digital twin of robot-assisted processing of curved surfaces. The digital twin will then be used to test, validate, and benchmark motion planning algorithms to achieve an accurate arbitrary path following for the end-effector along a curved surface and collision-free motion.