Artificial Intelligence supported Tool Chain in Manufacturing Engineering

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Work package 2

Extraction of knowledge and process information from experience and data

Deliverable 2.3

Preparation of processes & equipment by applying knowledge

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Executive Summary

This report highlights the advancements made in WP2 of the AITOC project, showcasing how these developments support the industrial operations by enhancing efficiency and decision-making in key areas. Central to the WP2's progress are applications focusing on the creation and use of digital twins, the strategic management of mobile robots, advancements in quality inspection processes, and the prediction of tool wear in manufacturing settings. One of the report's main focuses is the development of a real-time digital twin system under WP2. This system, leveraging advanced sensor technology, plays a crucial role in accurately monitoring factory environments. Its primary application lies in optimizing the operations of mobile robots within industrial spaces, ensuring their navigation is both efficient and safe amidst a dynamic working environment. Additionally, WP2's work includes integrating deep learning techniques to improve the navigation capabilities of mobile robots. This involves predictive odelling that enables robots to effectively circumnavigate both stationary and mobile obstacles, thereby increasing operational safety and efficiency.

The integration of comprehensive image process'ng methods is also a key achievement of WP2. These methods are instrumental in enhancing quality inspection processes, particularly in the detection of product defects and irregularities, exemplified in scenarios like printed circuit board inspections. Furthermore, WP2's contribution to the AITOC project extends to the application of data analysis and AI algorithms for predicting tool wear in CNC machining. This predictive approach is vital for preventive maintenance, allowing for timely interventions that prevent machinery damage and reduce downtime.

This report underscores WP2's contributions to the AITOC project as not merely technical achievements but as practical solutions that significantly improve the efficiency, safety, and overall productivity of industrial operations.

Content

1 Introduction

In this report we summarize some of the advances from WP2 regarding digital twins, and using information collected during operations to make decisions about mobile robots, quality inspection and to predict tool wear. The integration and application of advanced technologies in industrial environments are rapidly transforming how we approach manufacturing and logistics. This report presents a comprehensive overview of developments within WP2 of AITOC addressing distinct aspects of industrial operation and efficiency. The sections cover a range of topics, from the creation of digital twins using vision systems to methods for quality inspection and tool wear estimation.

Vision supported digital twins: This section delves into the development of a real-time digital twin system, a collaborative effort between Chalmers and AB Volvo. Utilizing optical sensors, such as ceiling-mounted cameras, this system effectively tracks the dynamic environment of a factory setting. The focus here is on how this digital representation can enhance the planning and operation of mobile robots in industrial spaces, ensuring efficient and collision-free navigation. Building on the concept of digital twins, this section explores advanced strategies for dynamic obstacle avoidance in mobile robots. It emphasizes the integration of vision-based deep learning for Multimodal Motion Prediction (MMP) with Model Predictive Control (MPC) for trajectory tracking. This approach is important in enabling robots to navigate effectively in environments where both static and dynamic obstacles are present.
Integration of WP4 AIM Pipeline for Image Processing: The WP4 AIM platform's capabilities in handling both time series data and images are the focus here. The section discusses the integration of image processing methods into a unified tool, enhancing its application in various machine vision scenarios, such as worker support systems and quality inspection processes.
Quality Inspection in Tactotek's Use Case: This part examines the application of vision-based techniques for the quality inspection of printed circuit boards (PCBs). It details the process of using design plans and machine learning algorithms to detect faults in PCBs, highlighting the role of different types of data in this process.
Ford Otosan's Use Case with Tool Wear Estimation: The final section addresses the challenge of tool wear in CNC machining, focusing on the 'Remaining Useful Life' use case. It presents an approach that combines data collection, AI model training using LSTM algorithms, and real-time tool wear prediction to prevent damage to the machining process and tools.

Each section contributes to a broader understanding of how technology can be applied in industrial settings, enhancing efficiency, safety, and productivity.

2 Vision supported digital twins

With the increasing presence of mobile robots operating alongside human workers in warehouses and industrial settings, their interaction becomes inevitable. This necessitates the need for real-time updates of a digital twin, which could be instrumental in planning how the robots should function. In a collaboration between Chalmers and AB Volvo, a system for real-time updating of a digital twin has been developed. This system utilizes optical sensors, such as cameras mounted in the ceiling over a factory area, to track the current state of the environment. As illustrated in Figure 1, the architecture of the system is presented. The cameras are strategically placed in the ceiling to monitor the state of the factory, including the positions of various entities like human operators and manually driven forklifts. A typical view from the cameras are shown in Figure 2. Based on this data, a map-manager is updated in real-time. This map-manager, representing the digital twin, shows the current positions of all dynamic obstacles and classifying the free and occupied areas on the factory floor, see Figure 3. Moreover, the digital twin offers the capability to predict future states of the system by forecasting the movements of these dynamic actors. This predictive information, in conjunction with data from the MES system, is used to schedule a fleet of mobile robots to complete tasks according to the orders received. The integration of information from the digital twin and the ordering system enables the generation of collision-free trajectories for the mobile robots.

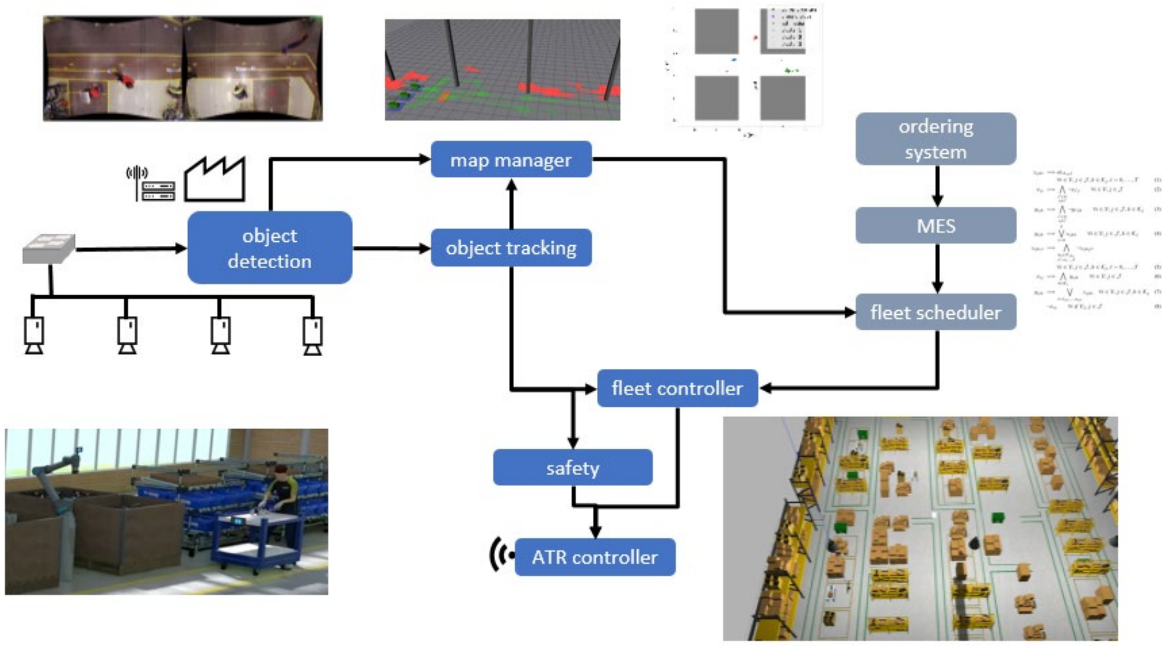

Figure 1: Architecture of a digital twin for a logistic application using optical sensors.

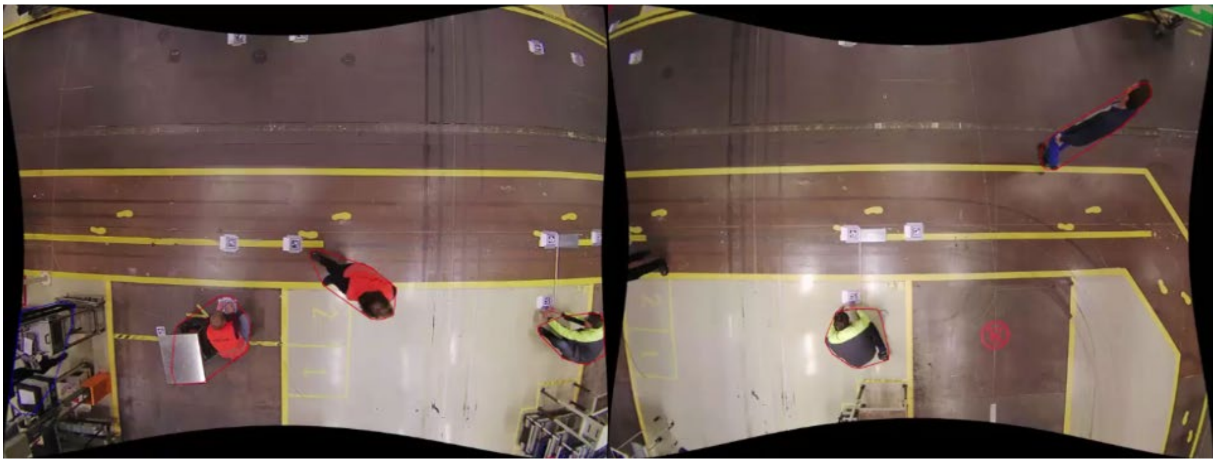

Figure 2. The view from two ceiling cameras. Semantic segmentation is used to differentiate between non-drivable areas (equipment, humans), and drivable areas (free and permitted to drive areas).

Obstacle avoidance for mobile robots is a natural necessity since the emergence of general mobile robots. Static obstacle avoidance is well-developed whereas dynamic obstacle avoidance is still challenging, mainly due to the uncertainty of obstacles' future positions. For example, industrial Automated Guided Vehicles (AGVs) are normally equipped with sensors detecting nearby obstacles and decelerate until stopping if their paths are blocked. Some techniques allow AGVs to detour from planned routes. However, most detour strategies are passive and do not make a distinct difference whether the obstacle is static or dynamic. With the emergence of Autonomous Mobile Robots (AMRs), more proactive approaches to dynamic obstacle avoidance became prominent. Humans are proficient at sidestepping dynamic obstacles due to their capacity to discern the motion intentions of others, anticipate possible scenarios, and initiate evasive manoeuvres. Nevertheless, future motions are difficult to predict due to the inherent uncertainty. A simple prediction assumes a constant velocity or a constant turning rate of the target object. The reality is more intricate since the environment constrains how humans move. Hence, a motion predictor should encode the environmental information and generate multiple estimations of the future position of the target object. The term *multimodal* emphasizes the estimation of multiple alternative future positions, like a pedestrian at an intersection possibly moving straight, turning left, or turning right. In industrial environments, workers normally move in repetitive patterns, which can be exploited to improve the estimation of future positions.

After obtaining predictions, a mobile robot can approximate its own future states according to its motion model and steer clear of areas that might be occupied by static or dynamic obstacles. This means the trajectory planner considers both the robot's future states and other dynamic obstacles' possible future positions.

In [2], we present a combination of vision-based deep learning for iterative Multimodal Motion Prediction (MMP) with Model Predictive Control (MPC) for trajectory tracking to perform prescient dynamic obstacle avoidance of a mobile robot in factories or warehouses.

To focus on integrating motion prediction with trajectory tracking, several assumptions are made:

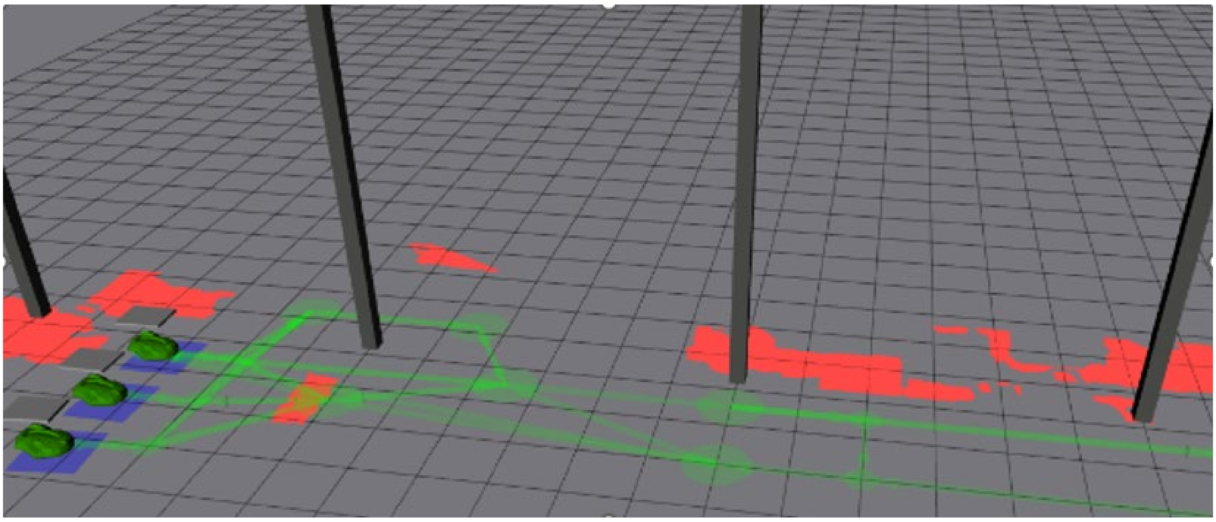

Figure 3. Digital twin of the factory. Positions of obstacles and robots are updated in real-time using vision. The digital twin is used for trajectory planning.

- The primary sensor is a ceiling-mounted camera system with overlapping views. Feeds from cameras merge into a single bird's-eye-view of the relevant area.
- The occupancy grid map is given using semantic segmentation that is generated using machine learning, see more details in [1].
- Dynamic obstacles are captured by the vision system and tracked.

The main contribution of this work is:

- Real-time update of the digital twin using vision data. Integration of tracking and forecasting of dynamic actors.
- Integrating of iterative MMP with MPC trajectory tracking to perform collision-free navigation of mobile robots in dynamic and stochastic environments.
- Processing of MMP results to formulate MPC problems.
- Evaluating the proposed integration in robot-warehouse scenarios and providing a comparative analysis.

The approach has also been implemented, the forecasting and control modules are available at [5]. The real-time update of the digital twin is presented in [1], the forecasting and control in [2], the planning and scheduling in [3] and [4].

3 Integration of WP4 AIM Pipeline for Image Processing

The WP4 AIM platform is designed to handle not only time series data but also images. An image processing pipeline is crucial for all machine vision applications. In this project, these applications are primarily realized through WP3 efforts, which focus on a worker support system, as well as Tactotek's use case for a quality inspection application. Since many methods in image processing are commonly used across different use cases, combining them into a single tool is very handy. The whole process of layout extraction from vision is divided to small building blocks that can be reused in other applications. The core activity of WP2's and WP4's collaborative work involves the integration of open libraries for image processing into the general pipeline. This integration includes the development of a data marketplace for data storage, as well as for the storage of models and pipelines, and the addition of a user interface.

4 Quality Inspection in Tactotek's Use Case

Quality inspection of printed circuit boards (PCB) is based on vision. The input to the system is the plan design, that contains vector graphics representing the final layout of the PCB traces. This input is converted to raster graphics so that it can be compared with camera images of the PCB film after printing process that creates conductive traces. There are two types of knowledge that this quality inspection process needs to utilize. First of all, the required design provided as vector image, secondly, the design constraints, which are trace parameters, spaces between traces, relation between trace shape and resistance. Based on those two sets of parameters, faults in the product are identified. Finally, a relation between faults and printing parameters will be established to allow for automatic machine tuning based on detected flaws in the process.

5 Ford Otosan's Use Case with Tool Wear Estimation

CNC machine tools experience wear during machining. Using worn tools can lead to significant damage to both the process and the machine. This damage manifests in various phenomena such as chatter vibrations, chipping (where chip materials adhere to the tool's surface), and tool breakage. To prevent these anomalies, the use case 'Remaining Useful Life' focuses on estimating tool life based on machine and sensor signals. The following describes how it is implemented and how it links to WP2 activities.

As the tool wears down, machining the workpiece becomes more challenging due to the tool's diminished sharpness. This effect can be observed through force, torque, spindle current, and other related machine signals. To identify the trend of tool wear, drilling experiments were conducted using a carbide tool and a steel workpiece. During these experiments, high-frequency CNC machine data were collected using an industrial edge device. Simultaneously, cutting force and torque data were gathered using a rotary dynamometer mounted on the spindle motor. Additionally, tool wear measurements were performed using a microscope.

The data acquisition pipeline is shown in the figure 4, below:

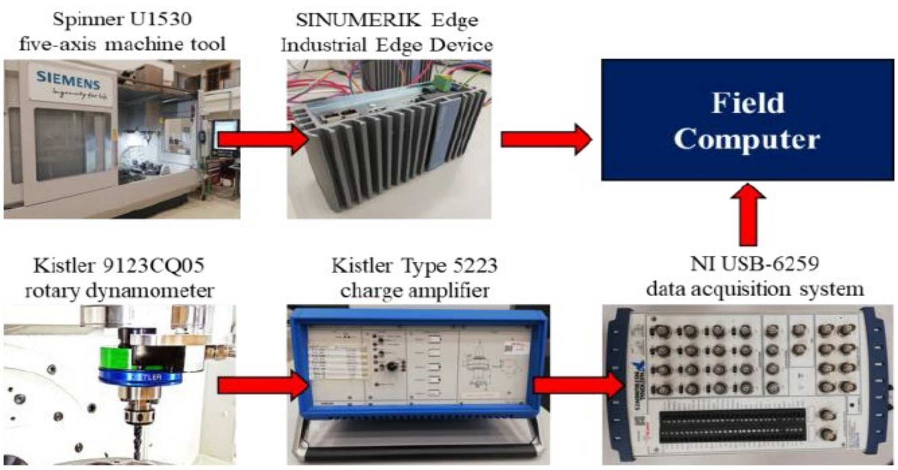

Figure 4: Test setup used in flank wear experiments to collect data [6].

After the data collection step, the data was processed to prevent the development of misleading AI models. This included applying cutting region detection and feature extraction methods. To train an AI model capable of predicting the 'remaining useful life' of the machine tool based on machine and sensor signals, LSTM (Long Short-Term Memory) deep learning algorithms were utilized. The LSTM model is designed to predict tool wear in real-time for each hole drilled. The fundamental structure of the model is presented below.

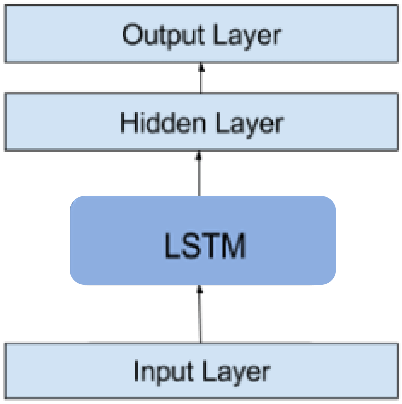

Figure 5: Fundamental model architecture.

Each hidden LSTM layer is represented by an LSTM block in our model. The final layers are dense layers, which are used to predict tool flank wear and the remaining useful life based on this predicted wear. The structure of the model should be updated when there are changes in the machining system, such as the use of different workpieces and tool pairs.

Details of this use case is presented in [6]. For this specific use case, our article titled '*Tool Flank Wear Prediction using High-Frequency Machine Data From Industrial Edge Device*' has been published. This work is a collaborative effort between Koç University's Manufacturing & Research Center and TUBITAK BILGEM Information Technologies Institute. It was presented at the 16th CIRP International Conference on Intelligent Computation in Manufacturing Engineering, held from July 13-15, 2022.

6 Summary and conclusions

In conclusion, this report outlines advancements in industrial technology, focusing on improving operational efficiency and safety. The development of a real-time digital twin system using optical sensors illustrates a step forward in integrating mobile robots into industrial settings, enhancing task planning and execution. The application of Multimodal Motion Prediction and Model Predictive Control in mobile robotics addresses the challenge of navigating around obstacles, both static and dynamic. This approach aims to improve robotic navigation in complex environments. The consolidation of image processing methods within the WP4 AIM platform represents an effort to streamline machine vision applications, relevant in areas like worker support and quality inspection. Additionally, the use of vision-based techniques for quality inspection in printed circuit board manufacturing highlights a move towards more automated inspection processes. This method aims to maintain quality standards through advanced processing techniques. Lastly, the report discusses the use of LSTM algorithms for tool wear estimation in CNC machining, an approach that falls under predictive maintenance. This method is intended to help prevent machinery damage and optimize the machining process. Overall, these developments reflect an ongoing shift towards integrating more advanced technologies in industrial processes, aiming for improvements in efficiency and safety.

7 References

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