Dynamic, Model-based Reconfiguration for Flexible Robotic Assembly Lines

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Abstract—**The European industry is becoming more customer centric in an approach to meet the varying customers' demand and minimize the costs of large inventories. The optimized production capacity that is achieved by the fixed production model can no longer guarantee the sustainability inside a fluctuating market that constantly requests new models. This creates the need to deploy flexible production systems exploiting the capabilities of multiple resources including both robots and human operators. Motivated by this need, this paper introduces the usage of mobile dual arm robots that are able to autonomously navigate in different workstations to undertake multiple operations, acting as assistants to human workers. A digital world model infrastructure for enabling this dynamic performance achieving process level reconfiguration, through robot's behavior adaptation is discussed. This system is based on a multiple sensor data synthesis mechanism that facilitates the real time shopfloor status digital representation. Static objects and moving obstacles, as well as human presence are identified inside this model enabling the robots' behavior adaptation through reasoning upon them. The suggested infrastructure has been deployed and tested in a case study from the automotive industry.**

Keywords-Mobile robots; flexibility; perception; digital world; sensor data synthesis.

I. INTRODUCTION

Robots have been considered as a major enabler for autonomous assembly systems. However, in current robot-based production systems, flexibility [1] and reconfiguration are still constrained due to [2]: a) the rigidity of the used stationary robotic units, b) the use of fixed and product model dedicated equipment, c) the use of fixed robot control logic and d) the absence of perception abilities that would allow the robots to dynamically adapt their behavior to the production needs.

Overcoming these limitations may be realized through the introduction of flexible robot workers enabling autonomy and collaboration between all production resources (including human operators and robot resources). Mobility both in resources and product level can play a vital role towards the realization of such production concepts as discussed in [3]. To this end, a hybrid and dynamically reconfigurable shopfloor is suggested employing mobile dual arm workers, namely *Mobile Robot Platforms (MRP)*, and *human operators*.

The last decades, extensive research has been made in the field of mobile robotic systems, either in the field of mobile robot manipulators or simple mobile platforms [4]. However, existing applications have limited perception capabilities not allowing real time adaptation of the system and robot behavior to dynamic environments [5][6]. Most of the manipulators are restricted to performing off-line programmed tasks only when they are in fixed positions, thus not fully exploiting their mobility.

On the other hand, digital representation and simulation of the production environment and process have emerged over the last decades as a means of partially handling the optimization of the production system performance [6]. In this era of digitalization in manufacturing, the Digital Twin concept has gained a lot of attention given the advantages that it may offer in terms of system autonomy [7]. The main principle of this concept relies on the digital representation of the physical world using multiple data input formats, such as Computer aided design – CAD files or other unified formats [8] as well as real time update of the virtual world based on real-time data (e.g., shopfloor/resource sensors, process related data, etc.). This is a very promising approach for providing perception and cognition abilities towards more autonomous and intelligent robotic systems [9].

Existing applications of dynamic robot control based on digital modelling and sensor data for ensuring collision free paths are based on the functionalities provided by Robot Operating System (ROS) [10]. The latter provides a rich content of data types and formats to virtually represent various hardware devices and multi-sensor data as well as a network of services and topics for broadcasting the captured knowledge. However, existing infrastructures are not mature enough to support the representation of the discussed hybrid production paradigm given the complexity of the various automated devices used, such as multiple mobile dual arm workers and products as well as human operators.

To overcome the existing limitations, this paper introduces a Digital World model infrastructure for supporting the effective introduction of MRPs in assembly environments. A unified semantic representation of the geometrical and the workload state on top of the ROS provided data structures is proposed so for the model to be able to support real time planning and MRP behavior optimization based on the shopfloor status.

The paper is organized as follows: Section II discusses the MRPs structure and capabilities while section III is focusing on the Digital World model description. In Section IV, the implementation of the robot's behavior adaption in different levels is presented. The performance of the system is analyzed on an automotive case study in Section IV. The last section is dedicated to drawing the conclusions and providing an outlook towards future work.

II. Mobile Robot Platforms (MRPs)

The present work considers as flexible robotic assembly lines the production paradigm presented by Kousi et al. [3]. Under this paradigm, mobile dual arm workers are introduced as the main enables for the flexibility of the system. These so-called MRPs can autonomously navigate inside the shopfloor localizing themselves into different workstations for a) performing multiple assembly operations, such as handling, insertion, screwing, drilling, etc. and b) acting as assistants to human operators. Figure 1 presents MRPs' hardware structure.

The main hardware components integrated under the MRPs can be summarized as follows:

- Two collaborative robot arms undertaking the assembly tasks execution;
- An omnidirectional mobile platform enabling the autonomous navigation;
- A torso adding two degrees of freedom to the robot arms in terms of rotation and elevation;

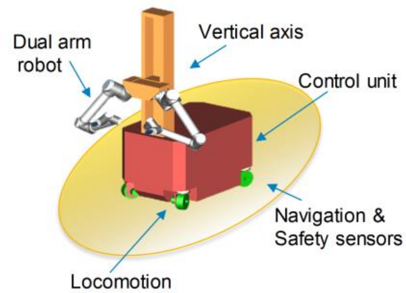

Figure 1. Mobile Robot Platforms (MRPs).

- Safety certified 2D laser scanners allowing the single plan obstacle detection, and
- Depth sensors allowing the 3D environment understanding.

These components aim to provide the hardware infrastructure allowing the safe navigation and localization of the robot into the different workstations as well as flexibility in terms of the process by dynamically identifying the product variants that need to be processed.

III. Dynamic digital world model

To enable the dynamic behavior and communication among these MRPs, the discussed Digital World model aims to provide the infrastructure for enabling the shopfloor data acquisition as well as combine them in a common representation to be consumed by the different decision-making mechanisms involved in the execution. A continuous feedback from the actual shopfloor (using resource and sensor data) will enable the dynamic update of digital twin involving two main functionalities:

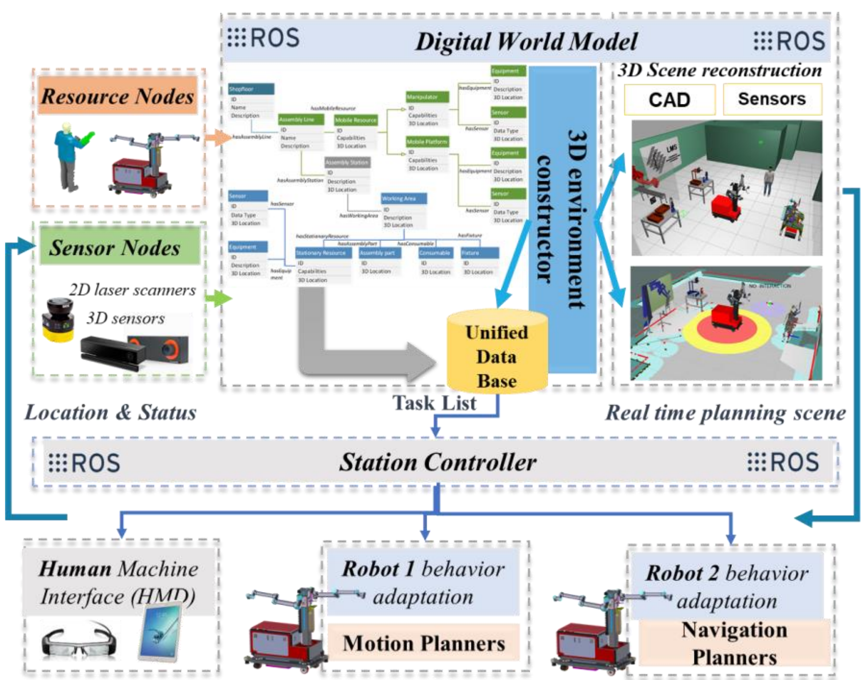

Figure 2. Digital World model-based system.

- Virtual representation of the shopfloor using multiple sensor data combination and CAD models. The digital shopfloor is rendered in the 3D environment using the capabilities provided by ROS.
- A unified data model will be implemented in order to semantically represent the geometrical as well as the workload state. This data model should be generic enough in order to be able to address multiple cases as well as to be consumed by multiple components inside execution system.

The overall system structure is presented in Figure 2.

A. 3D environment constructor – sensor data synthesis

The 3D environment constructor, composed by a set of sub-components, is responsible for registering the various entities included in the assembly, such as resources, parts, equipment, sensors, etc. A dedicated monitoring mechanism records the online location of these entities. These locations are used for constructing the complete working environment under a global world frame. This construction is performed based on the ROS Tf library [11] as visualized in Figure 3. The involved software components were developed on top of ROS provided functionalities enabling the scalable network communication and easy integration with existing robotic applications. In more detail, existing ROS interfaces for various robot models and sensor types make the developed infrastructure re-usable in multiple robotic systems.

During the set-up phase, the configuration of the resources, sensors and static objects takes place. In particular, the Resource configuration sub-component is managing the registration of the existing resources in the system. A set of attributes describing the resources have been defined as a universal resource model, such as transform configuration (.urdf format), path (.yaml format) and motion (.srdf format) configuration, payload, velocity, location, etc. These are populated for each resource instance introduced in the system. In a similar way, the involved Sensors are registered in the system through interfacing with the ROS drivers and recording their configuration data. The multiple

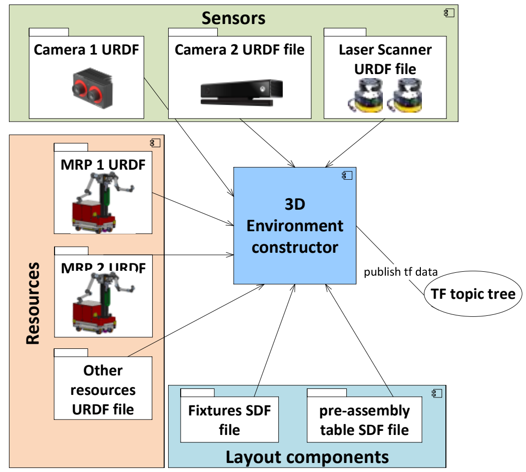

Figure 3. 3D environment constructor.

sensor data are shared with the robots' motion and path planners though dedicated topics following a predefined naming convention for each new sensor. Collecting the data from the available sensors, a data synthesis mechanism is responsible for publishing the 2D–3D combined sensor data. In that way, the 3D scene is reconstructed based on the sensors and this scene is consumed as a cost map for the standards motion and path planning algorithms (e.g., gmapping, amcl, ompl). The static objects, are loaded in .sdf that is uses by robot simulators, such as GAZEBO [12].

During the real-time execution phase, a Resource location and status monitoring sub–component is deployed for regularly publishing this online information on the digital twin. These data are retrieved through dedicated interfaces in each resource controllers. Nevertheless, apart from the static parts whose position is defined at the configuration phase, there are also moving objects and obstacles whose position is not well fixed and need to be identified during the execution.

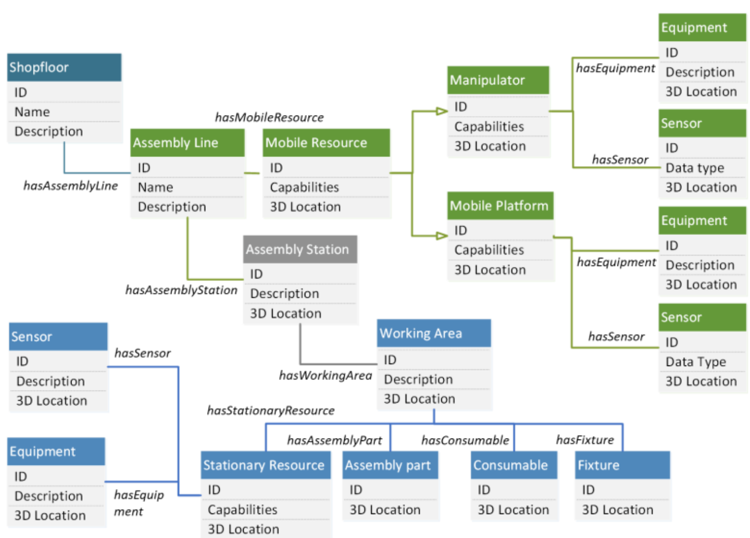

Figure 4. Unified semantic world model.

B. *Unified semantic model*

To handle the complexity of hybrid production systems, this study suggests a structured way to model the process and the environment following the principles of hierarchical modelling as shown in Figure 4.

IV. ROBOT BEHAVIOR ADAPTATION

Under this study robot behavior is specified as the set of low-level actions, such as *navigation*, *move arm* actions that the robot needs to perform for performing a task such as *pick and place* of an object. Thus, the concept of adapting robot behavior relies on the realization of ad-hoc changes in the MRP's planned navigation and motion paths so that it may perform the high-level task successfully.

A lot of research has been done related to the avoidance of collisions among resources and unmapped obstacles inside the shopfloor environment. Exploiting existing algorithms, the Digital twin provides interfaces with robot's path and trajectory planners, to achieve online re-planning based on fused real-time information from shopfloor. The MRP structure has been modelled through a ROS based description file describing the link the inter-robot connections among the robot arms, the platform and the torso. Thus, inter-robot conflicts such as collision of the robot with itself are not allowed.

A. *MRP platform online path planning*

MRP online path planning is implemented based on ROS navigation stack for mobile robots, thence, is essential the use of ROS Topics for sending transforms using tf, publishing odometry information, publishing sensor data. Digital World model resource manager handles the appropriate information for the correct configuration of each MRP unit as follows:

- Transform configuration: The transform tree for every coordinate frame of each resource is described inside the .urdf file. Worlds model's repository contains all the URDF files for each resource.
- Sensor and Odometry Information: Resource manager is responsible for defining which sensors are used by each robot.
- Map: Inside world model's repository 2D and 3D maps of the shopfloor are stored. In case of simple 2D navigation as visualized in Figure 5, the map_server node publishes periodically the map data in */map2d* topic.
- Planner Configuration: For the MRP's navigation two planners are responsible based on the ROS 2D SLAM navigation module. The first is the global planner and is responsible for finding a minimum cost plan from a start point to an end point. The second is the base local planner, which is responsible for computing velocity commands to send to the mobile base of the robot given a high-level plan from global planner.

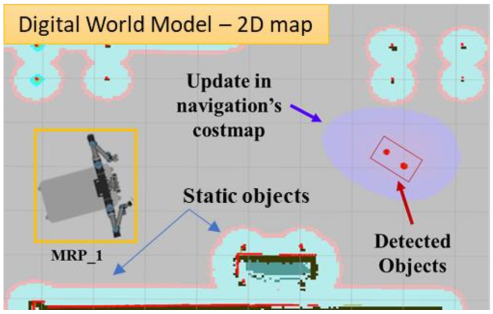

Figure 5. Digital World Model – 2D map.

B. *MRP robot arm online motion planning*

For the motion planning and controlling of the MRP arms ROS MoveIt! [13] is used. MoveIt! communicates with the MRP through ROS and it requires the existence of a dedicated ROS package for its configuration. The resource manager for the registration of a robot, such as MRP needs three type of information in order to setup the motion planning and export the MoveIt! package.

- Robots Universal Robot Description File (URDF);
- Robots Semantic Robot Description Format (SRDF) file created from MoveIt! setup assistant tool, and
- MoveIt! configuration files including among others joint limits, kinematics, motion planning, perception.

The digital world model through the Sensor Manager provides to MoveIt! the configuration for the occupancy 3D map created in occupancy grid using the OctoMap library as represented in Figure 6. This map is used as cost map with real time obstacles. Enhancing the environment knowledge with the occupancy map, the online motion planning component is aware of the existing objects / obstacles and uses this knowledge to ensure a collision-free trajectory planning.

V. CASE STUDY

The proposed Digital World model infrastructure has been implemented and tested through a case study coming from the automotive sector. In particular, the pilot case scenario involves the assembly of a passenger's vehicle suspension. This assembly scenario involves a set of assembly operations in three different workstations: a) the damper pre-assembly area, b) the damper compression area and c) the damper assembly on the disk area.

Following the analysis made in [3], an MRP is introduced in this assembly line, navigating among these

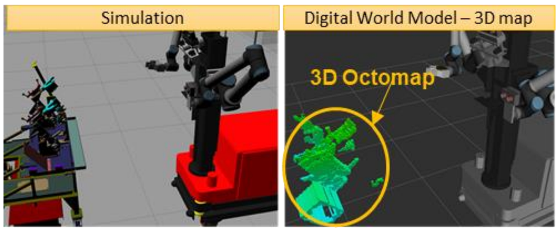

Figure 6. Digital World model – 3D map.

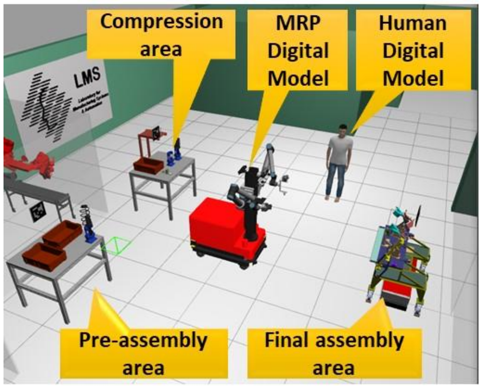

Figure 7. Assembly enviroment simulation.

workstations for performing a) the transferring of the damper from the pre-assembly to the compression area, b) small parts assembly on the compression area and b) the assembly of the compressed damper on the disk. In parallel, one human operator is working on the same workspace performing the pre-assembly of the damper as well as a set of cabling operations on the disk assembly area.

To be able to test the application in a realistic robotics set up in terms of 3D layout, a GAZEBO ROS-based simulation was set up replicating the assembly environment as shown in Figure 7. The digital models of the MRP (URDF) and human (CAD) where added in the simulation integrating the human side interface and robot controller in the backend. Figure 8 visualizes the Digital World model of the assembly environment based on the sensor data: a) two laser scanners located in the mobile platform of the MRP and b) one Kinect located on its torso. A Station Controller mechanism is responsible for dispatching the assigned tasks to the MRP, as well as the human operator and monitoring their progress so to coordinate the execution.

For the efficient execution of the scenario, the MRP needs to perceive the: a) damper and working tables to compensate the localization errors that cannot be foreseen offline, using a Kinect depth sensor, b) static obstacles and moving humans / obstacles for ensuring collision free navigation, using 2D laser scanner data.

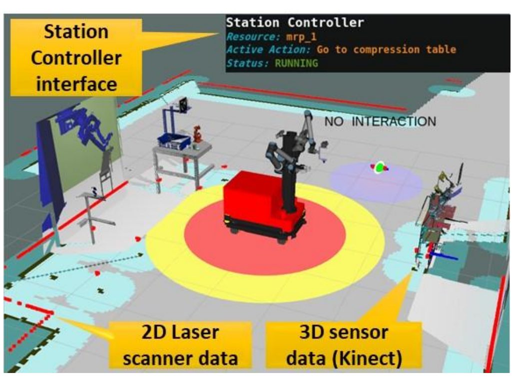

Figure 8. Digital World model visualization.

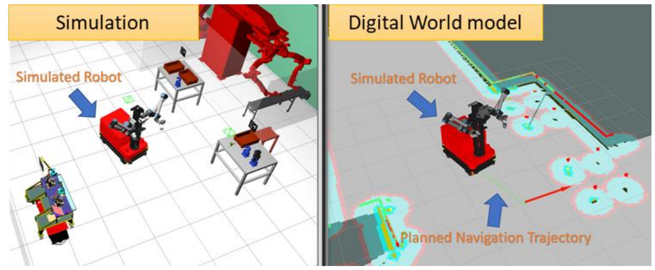

Figure 9. MRP 2D SLAM navigation.

Each time the robot is re-located by the Station Controller to a different workstation it needs to autonomously navigate from its current location to the new one. 2D SLAM based navigation is an existing solution for resolving the path generation aspects as visualized in Figure 9.

In this specific use case, the Digital World model provides the 2D map based on the combined sensor data from the two laser scanners located on the MRP platform. This map includes the static obstacles existing during the map creation procedure. Nevertheless, as mentioned in Section II, apart from the static obstacles recorded during the map creation procedure, during actual execution several other moving obstacles may be in conflict with MRP's navigation path. The dynamic nature of the Digital World model allows the real time update of the planning scene, so for the navigation planners to consider in the local plan generation the new, unmapped obstacles. Figure 10 presents an instance where the human operator interferes to MRP's planned path. The respective visualization of the Digital World model instance during this case is also presented.

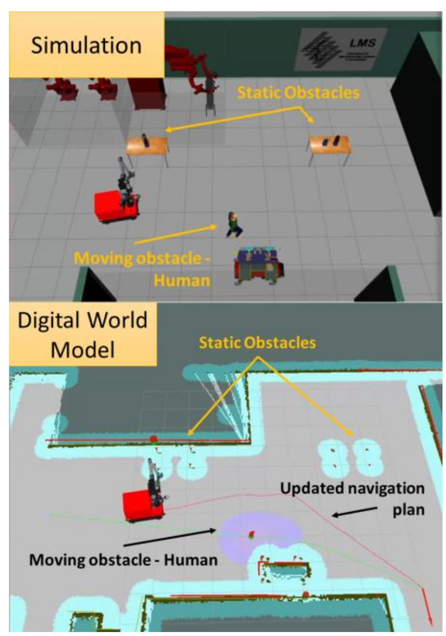

Figure 10. Collision avoidance with moving obstacles – humans.

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In that way, the MRP may avoid collision with humans in a dynamic way while both are in motion.

VI. CONCLUSIONS AND FUTURE WORK

Shopfloor uncertainty is a key aspect that limits the flexibility potential of nowadays manufacturing systems. Modular robotic systems are considered as a main enabler for production system reconfigurability. However, their fixed control logic, based on pre-programmed operations, does not allow the effective exploitation of their capabilities. Robots' perception abilities and reasoning upon the perceived environment so to adapt their behavior are key prerequisites for overcoming the existing limitations. To this end, this work, introduces the deployment of a dynamic Digital World model enabling the a) multiple sensor data synthesis into a common scene and the online update of the scene based on the real time data, b) the integration of the involved resources and hardware components allowing the robots to understand the real time environment and apply cognition techniques to transform the sensor based scene into useful information for optimizing their behavior.

The discussed infrastructure has been tested in an assembly case study form the automotive sector, employing one MRP and one human operator. The deployment of the Digital World model allowed the reconfiguration of robot behavior by compensating the real – world uncertainty. Combining 2D and 3D sensor data information increases shopfloor's real time knowledge and eventually leads to higher accuracy in robot actions.

Considering a production system with more workstations and more humans and MRPs the complexity and unpredictability of the system increases a lot. In these cases, the suggested Digital World model may have a greater impact when applied in the completed manufacturing system. To achieve that, technical issues such as the computational requirements for processing big amounts of data need to be overcome as a future step. In addition, under the era of Industry4.0 data security is an important aspect to be addressed. Future version of this platform needs to be enhanced a secure communications framework that can ensure that connections between resources and systems are private (or secure) by using approaches such as symmetric cryptography.

Nevertheless, the validation of the developed infrastructure under a physical set up involving the actual MRP is already an ongoing work by the authors. Future work should also focus on the integration of a higher-level decision-making mechanism that will be able to dynamically re-distribute the work among the available robot and human resources based on their capabilities and the production needs.

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