AUTONOMOUS CONTROL OF AN INDUSTRIAL ROBOT BASED ON FORMALIZED PROCESS DESCRIPTION FOR CABIN ASSEMBLY

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Abstract

Envisioning advance assembly concepts in Aircraft manufacturing are essential for sustaining the competition and acquiring customers. In this paper we focus ourselves on describing an approach that offers adaptable process flow, reliable assembling methodology that provides faster cycle time along with safety to human workers. Further we also introduce the methodologies to program robot control from different sources which could be of interest to the Aerospace manufacturers. The process planning associated with deployment of robots and communication between the robots using external sensors are described here. Based on existing assembly model for cabin, the initial assembly instructions are written with Ontology. Time consuming activities during such assembly work are identified and interactions are reframed such that the overall assembly time is optimized. This is achieved by collecting and storing the meta-data of the robot motion which may describe the different process times, and associated robot motions. Feasibility on preempting the failure through live visualization of robot data (such as joint current, joint temperature) is studied along with analyzing and improving process by visualizing robot motions in Blender.

1. INTRODUCTION

The size of aircraft mobility is increasing at high rate that by 2036, there would be around 7.8 billion passengers travelling per year (source: IATA[1]). To match up the growing market requirements and to sustain competition, aircraft manufacturers tend to provide reliable assembling of Aircraft components with greater degrees of flexibility. To avert huge backlogs due to the modification requests from various customers and to focus on safety of the human workers robot based cabin assembly is gaining importance in aerospace industry. Flexibility is described with regard to freedom of customization in which the customers are provided with pre-qualified optional equipment, and traditional assembly process together with customization resulted in cost shoot-up along with increased lead-times. Also the degree of freedom with respect to time is well described in flexible automation, where customers are able to successfully make “Last minute customization” and manufacturers are able to implement those changes with the help of adaptable process models.

This work is intended to digitalize cabin assembly process, thereby generating a digital thread from cabin design until assembly. Focusing on automating aircraft cabin assembly tasks by utilizing the latest generation robots, sensors, control and information system, this project demonstrates the digitalization of cabin assembly. This paper identifies some of the essential part of this overall thread, where the information is transferred between the Process plan and robots and instructing robots based on different inputs. Process models are built with Ontology where the flexibility of the process plan is viable and the specific instructions for the robot are devised based on the decision that is inferred from the rules of Ontology. Instruction to robot is contributed from two sources: 1. Ontology model which holds target information, Ex: location at which the side-wall panel should be attached. 2. Feedback from Sensor (Camera) that is from dynamic environment to enable the co-design, ex: to pick and place a component for sub-assembly process.

To achieve autonomous robot control, it is necessary to measure the performance of robots [7]. Some of the measures are: 1. Resolution, 2. Accuracy, 3. Repeatability, 4. Operational speed 5. Payload ability and 6. Positional error. As described in [7], minimizing the positional errors under loaded conditions is the major obstacle and robots should perform accurate motion within working envelop for any number of repetitive operations. To this end, meta-data from the whole process execution is important for analyzing and improving the performance of the process. For making effective decisions, quality of the data plays important role for gaining effective outcome of the associated tasks [5]. For analyzing performance of robot tasks, different data from robot such as joint angles, joint currents play vital role in understanding the robot performance. This work leverages the use of HDF5 format for storing the meta-data information.

This paper is constructed in following manner: Section 2 speaks about existing State-of-Art work employing robots followed by reasoning the Last minute customization, which is described in section 3. Section 4 describes the important modules constituting the automated assembly process. Section 5 describes simple demonstration use-case followed by visualization of robot motion in section 6. Conclusion forms section 7 followed by future work description in section 8.

[1] International Air Traffic Association : https://www.iata.org/en/pressroom/pr/2017-10-24-01/

doi:10.25967/530315

2. RELATED WORK

Employing robots in aerospace manufacturing began in 1990s, due to low accuracy of industrial robots [4] that were mostly designed for automobile industry. Initial applications in aerospace employed robots for drilling holes on medium sized components, ex: nose fuselage structures. Recently robots are proving to be effective in the Aircraft manufacturing process, where manufacturers are able to meet customer demands with the aid of robots. One such outcome is demonstrated by Airbus for its A320 production, where the robots drilled 2800 holes on fuselage in order to join the two halves in an ergonomic manner [3]. Future aircraft industry demonstrated in ACCLAIM[2][9] project, focused on employing robots for assisting human workers in combination with autonomous aircraft interior inspection. Process plan is streamlined using SIMFAL[3][9] for analyzing and optimizing the automated assembly tasks, thereby classifying the tasks that are suited for automation by simulating different scenarios and collaborations (complete autonomous or human assisted). Application of robots in aircraft assembly operations are: drilling and fastening, welding, countersinking and applying sealants.

The proposed method encapsulates all the necessary steps for autonomous assembly process. It employs ontology for process planning and optimization simulates the robot motions with available industrial packages, programs the robot based on different constraints and finally validates the real time robot motion with feedback from Sensors. Use-cases related the cabin assembly such as installation of Side-wall panels, cabin-linings and hat-racks are explored.

This work concentrates more about measuring and improving robot performances with a desire to optimize robot utilization. Through analysis of robot performances by monitoring the real-time data, performance metrics is computed for different mode of operations for different load conditions. Debra *et.al* [6] has used Mean Time to Intervene (MTTI) as measure that depicts the average time spent on overcoming anomalies that interrupt the scheduled robot tasks. With this measure, the time spent on unplanned interventions is minimized. 2. Productive time is the time for the robot to execute the planned tasks. 3. Overhead time describes the time that the robot is idle waiting for other resources. 4. Work efficiency index which is computed as the ratio of productive time to overhead time.

3. THE NEED FOR LAST MINUTE CUSTOMIZATION

This term is plays vital role in cabin assembly, as this portion of Aircraft largely interacts with the end-users of the Aircraft. The end-users are the passengers and the experience on the cabin is variable on person-to-person basis and this constitutes main input for the customization. This is not coming from single-source and manufacturers cannot envisage the time of arrival. This dynamic nature propels the necessity for flexible customization.

Due to the dynamic nature of the inputs from different sources, “Last minute customization” is gaining importance, and to leverage all the inputs at different time points, there should be an agile mechanism available with Aircraft manufacturer that can enforce those changes “just before” assembly time. Modifying the existing process plan based on the changes with time flexibility averts the requirement of process re-planning and thereby reducing the assembly cycle time.

4. COMPONENTS FOR CUSTOMISABLE AND AUTOMATED ASSEMBLY PROCESS

For implementing digital thread on Cabin assembly process, the following components are essential: 1. Process plan for customizable cabin assembly process is conceived using ontology 2. Implementation of process plan with respect to robot is developed by simulation and feasibility analysis is made 3. To validate the functioning of digital thread related to robot motion, i.e., successful translation of information from ontology to robot control is validated using the feedback information relevant to robot motion from sensors, such as cameras or motion sensors.

4.1 Simulating cabin assembly

Simulation plays an important role in realizing the plan for digital thread related to the role of robots in cabin assembly and to optimize the cycle time of the process. Simulating the kinematics of the robot combining the robot dynamics results in robot motions that is viable in real time. In this work is an adaptable process with robots is demonstrated to highlight the idea behind autonomous cabin assembly. In this use-case, it is possible to define the type of desired panel, and the location to fix the panel is inferred from ontology. Plausibility checks are made so that the appropriate number of panels based on their type is inferred.

4.2 Cabin ontology

For encompassing agility for responding to last minute customization, ontology plays vital role in reframing the process plan. The Ontology model specifies the cabin and it associates rules for the relationship between the components. Customization of the cabin assembly would be based on inferring the Ontology model and validating the customer requirements.

The ontology defines the whole cabin assembly. The relationship between the components are defined and inferencing of indirect relations based on the described relations are computed. For example, if Cabin *has some* relation to hat-racks and hat-racks *has some* relation to handles, then appropriate relation between Cabin and handles are derived.

4.3 Ascertaining robot motion

Based on the ontology semantics, robot is fed with necessary information about assembly; such as pick-and-place sidewall panel. The robot is expected to perform the operation in real time and to validate the successful implementation, feedback from sensors (cameras) are captured. Based on the feedback information, further improvements on robot planning and motion is envisioned. Generic image processing flow is shown in FIGURE 1. Flow of image classification algorithm is depicted where the classifier is trained with set of images and used in real time application.

[2] Automated Cabin and Cargo Lining and Hatrack Installation Method
[3] SIMulation of an aircraft Final Assembly Line

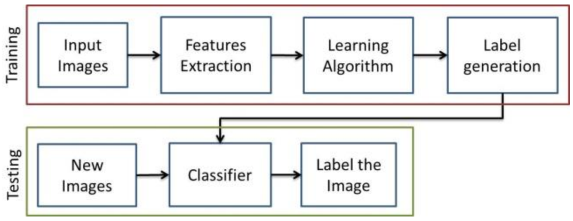


FIGURE 1: FLOW DEPICTING THE 2D IMAGE PROCESSING

4.4 Robot paradigm for cabin assembly

For implementing the robot control to achieve the automated assembly process for cabin, robot controls are written in modules such that dynamically triggering a particular module is viable from ontology. On receiving a customized user's input, ontology reframes the process plan after validating the user's request. To this end, modular programming serves better for robot control as the sequence of operations is dynamic. The different robot control programs are written in modules, such that the operation sequence is formulated by combining different modules. Modularity of program serves better for formulating meta-data from the information of robot, as inferencing from a large dataset without tags won't yield useful results.

4.5 Storing metadata for feedback control

To ensure the effectiveness of implementing digital thread with configurable process plan and automated robot control, measurement information regarding the robot motion is required to be stored. With this information, different process parameters could be evaluated. For example, to understand the robot motion for picking a component, the whole set of joint parameters are required to be evaluated such that the optimized process plan could be devised.

5. USE CASE DESCRIPTION

In this project is demonstrated an use-case with robots performing the expected planned motions based on Ontology modeling. Use-cases for the essential components for customized and automated Cabin assembly such as Ontology, Robot control algorithms and sensor feedback are in process of implementation. This section elucidates the planned implementation of the above modules.

5.1 Simulating the Robot motion

Blender is used for initial demonstration of the automated Cabin assembly process. In Industry, open-source software is seldom used and users always prefer to use the existing environment. Industrial simulation packages are effective for deploying the robot directly in real time industrial environment. Real time simulation is carried out with *3DExperience*, since aerospace industries largely use Dassault products for production planning and controlling, it would be easy for them to adapt the new function in existing framework. Offline programming of robot by translating the code to robot specific language yield the benefit of programming the robot from computer. Simulation in 3DExperience is shown in FIGURE 2.

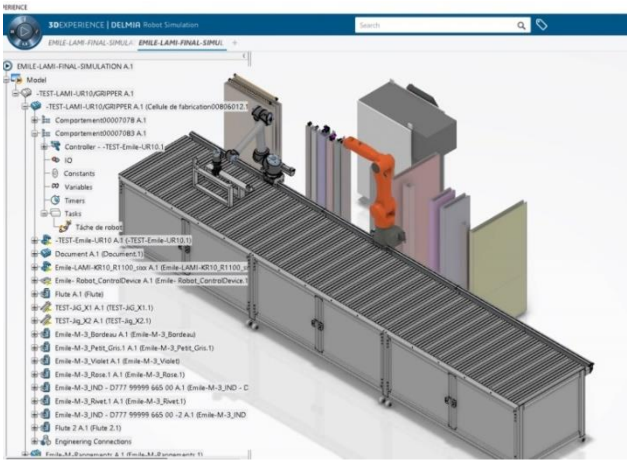


FIGURE 2: SIMULATION IN DASSAULT SYSTEMS - 3DEXPERIENCE

5.2 Ontology model for Cabin assembly process with robots

Ontology relevant to cabin contains the location information of the components defined, for example it contains information regarding the mounting locations of the sidewall panels on cabin. The *instances* of the side wall panel contain the exact information regarding where they are mounted on cabin. From FIGURE 3, it can be seen that there are four different panels on cabin. Each of the Panels could have assembly location information stored. Like sidewall panels could be assembled at certain locations in cabin (list of $\{x_a, y_a, z_a\}$). There are different types of sidewall panels available and those types are available as *instances* bundled with location information.

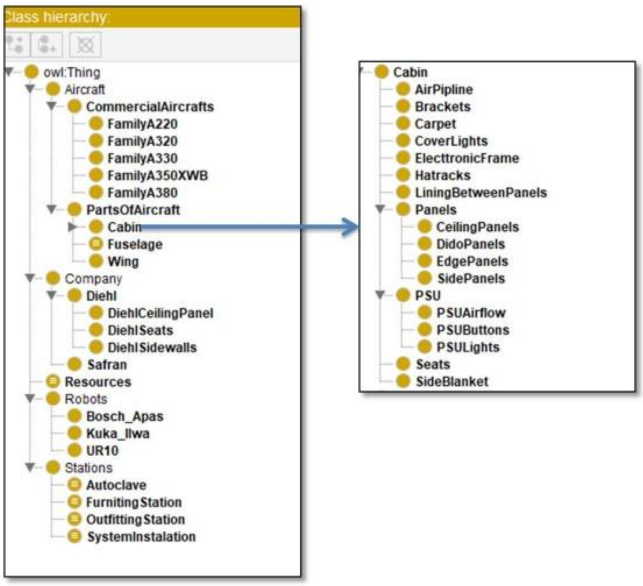


FIGURE 3: CLASS DIAGRAM OF THE AIRCRAFT AND CABIN

5.3 Hardware set-up of the use case

To study and validate the ideology on creating digital thread for automated cabin assembly process the following infrastructure is built. The assembly tasks are scheduled to be split between 1. Pre-assembly cell 2. Cabin assembly. In pre-assembly cell, the sub-assembly of cabin components is carried out and once the sub-assembly is complete the "in cabin assembly" takes place. With this in mind, there are three robots employed, Universal Robot UR10e, Bosch APAS[4] and KUKA KMR[5] iiwa[6]. UR10e and APAS are fitted on the Pre-assembly station where a Roboception Sensor (rc_visard 160) monitors the table and communicates with the robots. KUKA KMR iiwa fitted with another Roboception Sensor (rc_visard 65) transfers the pre-assembled components to the cabin infrastructure where autonomous or assisted assembly takes place. The interconnections between different modules on the pre-assembly cell are shown in FIGURE 4.

The robots UR10e and APAS can move on linear axis of the table, such that picking and placing the required components at different locations are possible. This is controlled by the PLC[7] module that communicates with robots and traverses them accordingly. Emergency circuit of PLC and robot controller are connected such that bi-directional communication is possible, which leads to automatic stop of one member when other stops due to some reasons.

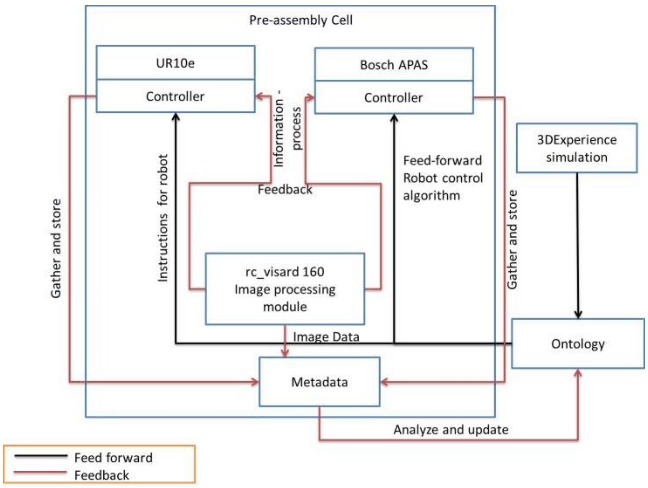


FIGURE 4: INFORMATION FLOW BETWEEN PLANNING AND EXECUTION IN THE PRE-ASSEMBLY CELL[8]

5.4 Robot control paradigm for cabin assembly

Modular control of robot is planned to be implemented such that any customizable ontology change would trigger the particular module to function. In this use-case of pre-assembly cell, the robots UR10e and APAS are considered for modular control. Modularity ensures that right function is executed based on latest ontology model. This is described in FIGURE 5, where the process-plan is reframed based on user request for customization and validating the same. On successful validation, the new process plan is conceived and the appropriate module to function is invoked. Here it is shown that Pick and place of sidewall panel is invoked and respective robot identified for the task would be fed with joint control information.

[4] Automatic Production Assistant
[5] KUKA Mobile Robot
[6] Intelligent industrial work assistant
[7] Programmable Logic Control
[8] Planned work flow

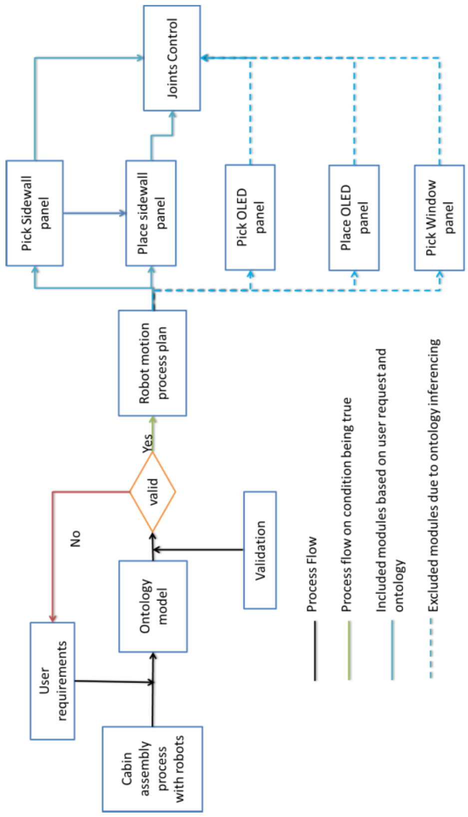


FIGURE 5: EXAMPLE ON PROCESS FLOW FOR MODULAR ROBOT TASKS BASED ON RECONFIGURABLE PROCESS PLAN

5.4.1 Associating relevant cabin assembly tasks for robot control

A part of digitalizing the cabin assembly process includes optimized usage of resources, such that process cycle time is minimum. To achieve process improvement and to minimize the cycle time, it is necessary to understand the information that is provided as feedback from the robot. Without understanding the stored information, it would be difficult to analyze and optimize the planned process. This is exemplified in FIGURE 6 and FIGURE 7 where joint angles for UR10e and APAS are shown for continuous time points. Without understanding the actual task the robot carried, it wouldn't be possible to understand an anomaly or a disturbance that caused any undesired motion.

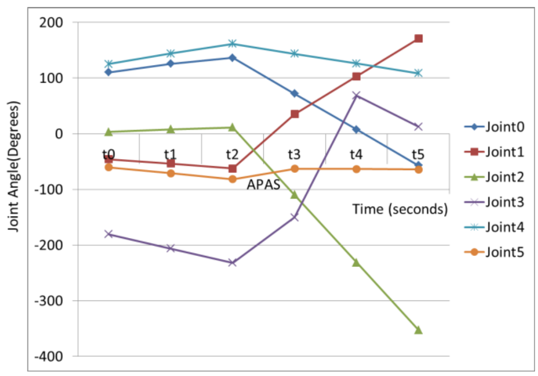


FIGURE 6: JOINT ANGLES FOR APAS ROBOT[9]

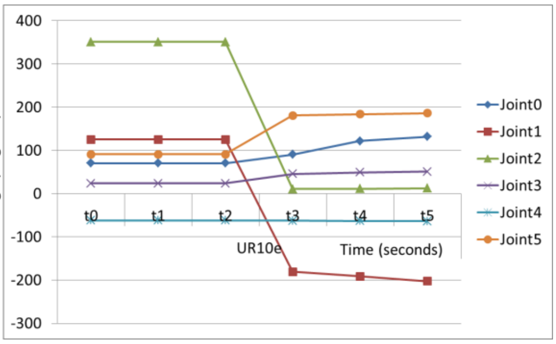


FIGURE 7: JOINT ANGLES FOR UR10E ROBOT[9]

So event based inferencing is envisioned such that the information about tasks is stored in the database for later use. Event-based inferencing would be interesting for an end-user who is more concentrated in knowing the nature of the occurred events and with the *descriptors*, events can be inferred. For example, the first three timestamps APAS might be picking a sidewall panel and UR10e at the same time might be idle (as Task2), and then robot1 continues to place the sidewall panel (as Task3) where UR10e could be screwing the fasteners. This is shown in FIGURE 8 and FIGURE9.

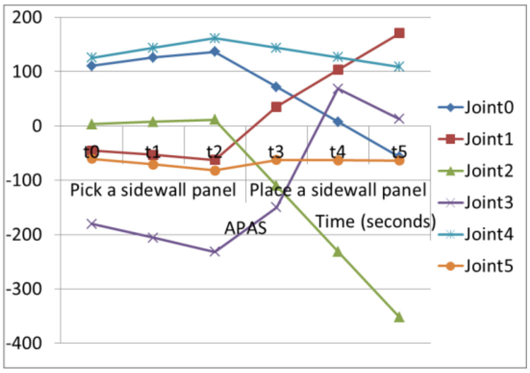


FIGURE 8: JOINT ANGLES AND ASSOCIATED TASKS FOR APAS[910]

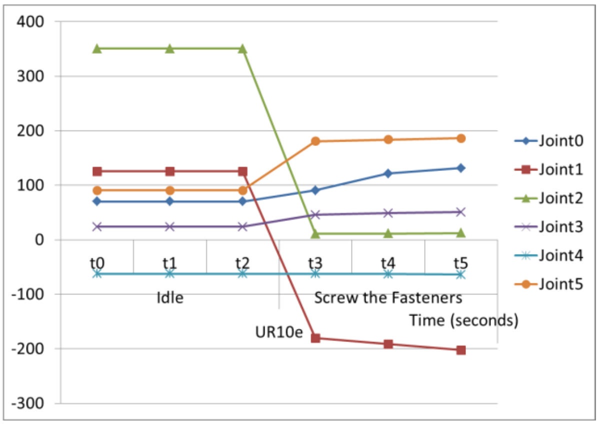


FIGURE 9: JOINT ANGLES AND ASSOCIATED TASKS FOR UR10E[1010]

5.5 STORING META DATA

The data from the robots are available so frequent that the resulting storage of information compounds to a huge database. For UR10e robot, it is possible to retrieve information at a speed of 125Hz (using RTDE[11]), such that for a complete robot execution over hours of time might result in unimaginable data size. To begin HDF5[12] format is employed for storing the information as it stores the data in binary format. HDF5 is designed for flexible and efficient I/O, high-volume, complex data and it supports different data types [2]. HDF5 is useful to store information in hierarchical manner, where it is possible to store information in groups and in tables. For our application, we have 3 groups (for each robot) and each group there are different number of tables (based on retrievable information from robot) containing timestamp as the "primary key" across tables belonging to same group as depicted in FIGURE 10.

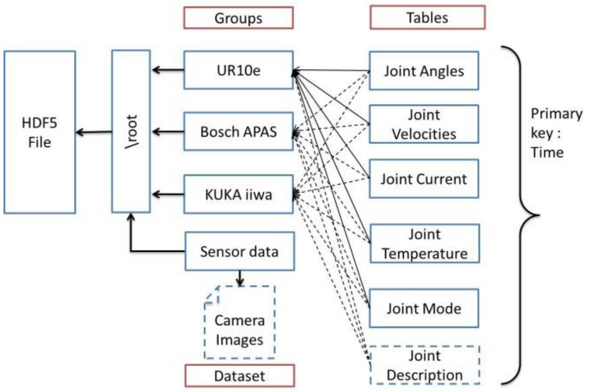
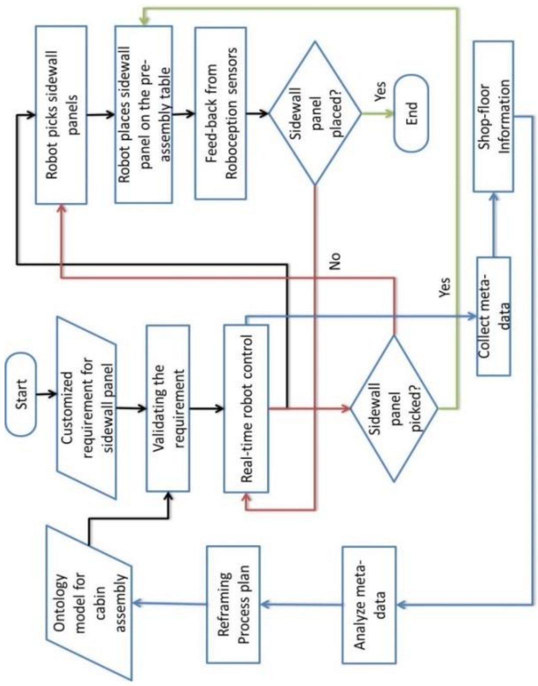


FIGURE 10: HDF5 FILE FORMAT FOR ROBOT DATA STORAGE[13]

5.6 Use cases for cabin assembly

Side wall panels, hat-racks are considered for the pre-assembly station, cabin linings and 3D-scanning of the cabin environment are scope of autonomous functions for the iiwa robot.



[9] Trivial
[10] Planned steps

[11] Real Time Data Exchange
[12] Hierarchical Data Format
[13] Black dotted lines denotes the uncertainty about particular data availability from APAS and KUKA iiwa. Blue dotted box is not yet implemented.

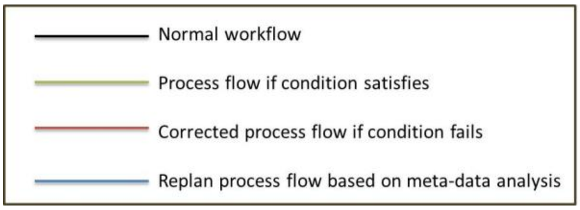


FIGURE 11: PROCESS PLAN FOR PICKING AND PLACING SIDEWALL PANEL IN PRE-ASSEMBLY CELL

FIGURE 12 and FIGURE 13 depict the components and steps to assemble side-wall panel along with hat-racks in real time. Based on the analysis of interpreting different metrics from the robots, the appropriate process-plan is conceived similar to the one shown in FIGURE 11.

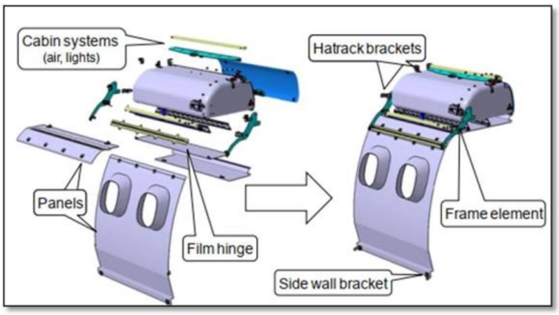


FIGURE 12: STEPS FOR PRE-ASSEMBLY OF SIDEWALL PANELS AND HAT-RACKS [1]

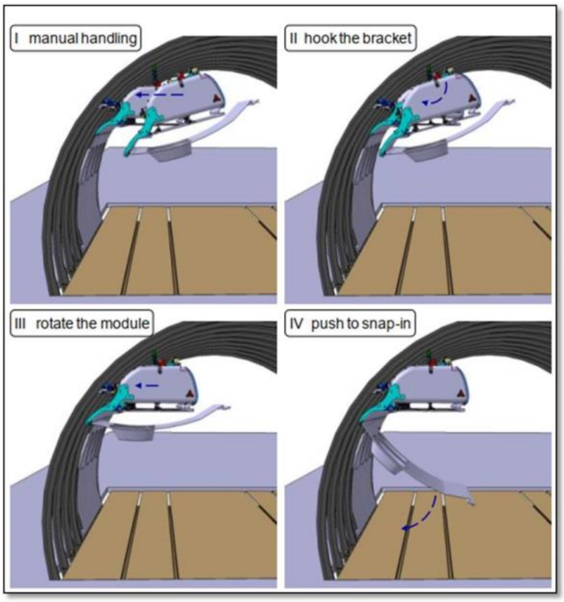


FIGURE 13: MANUAL HANDLING OF PRE-ASSEMBLED COMPONENTS [1]

6. VISUALIZING THE USE-CASE PROCESS DATA

With the stored information regarding the control of robot motion based on ontology information, it is often desired to visualize the results graphically. This is used to find the probable improvements to robot motion and imparting visualization by end user to see his/her desired changes in process plan virtually. Another type of visualization is to analyze the data in live stream. This is done so to identify and to evaluate the performance of the robots (for example joint current data),

6.1. Live data visualization

Data such as joint current and temperature are visualized live from computer such that the performance of the robot could be devised. The probable reasons for failure and their future occurrences could be pre-empted based on the analytics such that future mishaps are averted. For example, prolonged usage of robot on picking particular component might result in increased usage of current. There would be a break-away point at which the current might shoot to the maximum threshold. This poses a threat to the motors on the joints. So, to avoid occurrence of such overshoot, necessary measures could be pre-empted based on the observations and with live data stream, this could be evaded based on observed values.

6.2. Simulating stored information

Stored information such as joint angles and images are used for later visualization. Visualization is done in Blender, where the stored data across different time-points are utilized to infer the position and orientation of robot. Employing the stored description (from HDF5 data) for identifying the associated tasks is used for generating the Blender task-filter for different timestamps. One such representation is given in FIGURE 14.

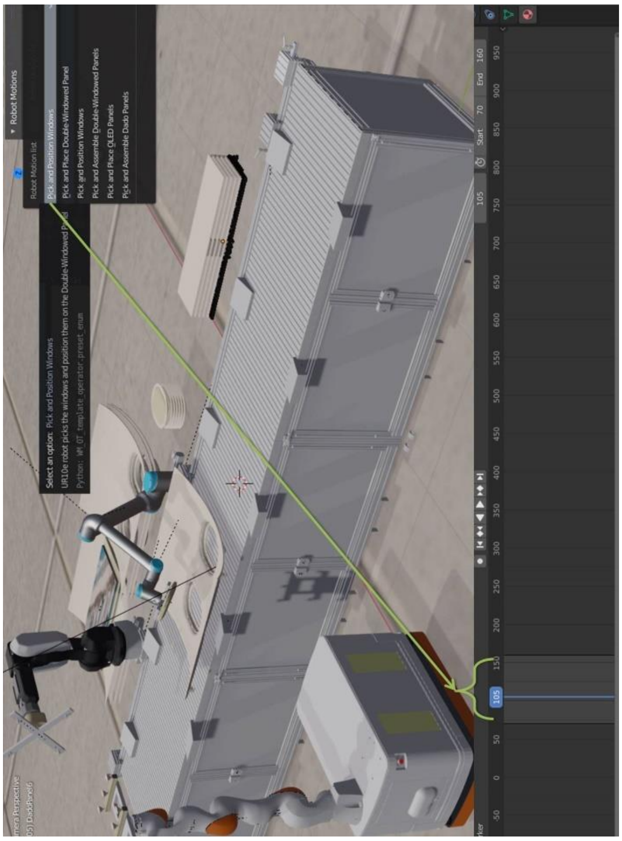


FIGURE 14: VISUALIZATION IN BLENDER- ASSOCIATING TIMESTAMPS TO TASKS[14]

7. CONCLUSION

To fulfill the vision of implementing Digital thread for the Cabin Manufacturing process starting from Design until Assembly, this work focuses on the research related to employing robots for the automated assembly process, where the information from multiple inputs, such as

[14] Planned

Ontology and image processing systems are analyzed and processed. Initial idea on the customizable process flow is elucidated with the help of Blender simulation, where robot kinematics and process flow is visualized. Industrial simulation is carried out with 3DExperience from Dassault Systems which proves to effectively program the robot with simulated program. Meta-data from UR10e robot is collected and stored in HDF5 format. For KUKA IIWA and Bosch APAS, similar methodology would be adopted and real time parameters would be stored. The live visualization of robot parameters such as robot current is realized in real time, such that learning from gathered experience is used to avert any future mishaps. Implementing the automated assembly process with robots and Ontology marks our contribution to the Digital thread for Cabin processes.

8. FUTURE WORK

Next steps in the work are associated in implementing the parts of digital thread that are described above. Meta-data from the real application would be collected and the data store would be analyzed to see if HDF5 format is efficient to store real time large volume of information. To analyze the efficiency of robot utilization, meta-data with different components and different grippers under different working conditions are collected. The stored data would be then visualized on events in Blender. Study on integrating the Blender animation in Virtual Reality would be carried, such that users feels the automated cabin assembly process with respect to their requested changes virtually. Analyzing the stored information (Joint data from robots) for validating the robots utilization for faster production with lesser cycle time would be carried. Real time feedback from other sensors, such as force-torque sensor would be collected and analyzed. Study on feasibility of minimizing the steps would be conducted such that the automated assembly with robots results in time-efficient and optimized usage of resources (such as information from camera or force torque sensor from robot).

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