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Experimental Validation of a Physics-based Simulation Approach for Pneumatic Components for Production Systems in the Automotive Industry

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Abstract: Automated assembly systems in automotive industry require thorough digital validation procedures prior to commissioning and ramp-up processes. One essential validation procedure is Virtual Commissioning, a method to test and validate real PLC-programs based on a virtual 3D-model of the production system using a HIL-approach. In order to increase the level of maturity of Virtual Commissioning and enrich the quality of the virtual 3D-model of the production system an innovative simulation approach using physics-based simulation capabilities based on game engine technology has been adopted. In particular, a physics-based model of pneumatic components (cylinders, clamps, etc.) typically found in automated assembly systems has been developed. The physics-based pneumatic model (PPM) enables more realistic simulations in real-time and is expected to be used within the next generation of Virtual Commissioning. However, before being utilized in industrial application PPM has to be validated. Kinematic and dynamic accuracy as well as compressed air consumption - a key performance indicator for energy consumption of the entire production system - of the PPM model are analytically and experimentally validated. In detail, validation was carried out considering different internal and external model parameters, such as pressure level, throttle valve settings, etc. and analyzing their impact on the PPM’s informative value. Overall, PPM’s validation shows promising results throughout all three different aspects (kinematics, dynamics, and compressed air consumption) and has thus a high potential for application in Virtual Commissioning.

Keywords: Physics-based Simulation, Pneumatic Components, Validation, Virtual Commissioning, Kinematics, Dynamics, Compressed Air Consumption

1. Introduction and Motivation

Nowadays Original Equipment Manufacturers (OEMs) face manifold challenges while designing and manufacturing innovative products in order to place them on highly competitive global market segments. With respect to the field of automotive production systems some major challenges essentially conflict: high productivity, reliability, and output quality must be guaranteed while featuring high degree of system flexibility and adaptability alike. In particular, increasing number of product variants, high product complexity, new product features (e.g. CFK, electrical/hybrid engines, driver assistance systems), new production technologies, modular packaging strategies, and high degree of product customization cause high requirements for production systems. OEM’s production planning departments are additionally forced to shorten planning periods and cut planning cost while increase quality of planning without usage of expensive real product prototypes. In order to cope with these challenges OEM’s production planning departments apply innovative methods and tools of the Digital Factory to validate production processes and to ensure production system quality. For Plant Manufacturers (PMs) being assigned as engineering procurement construction contractor, offering their services of designing and providing production systems as turn-key projects to the OEM’s shop floor, fierce competition arises likewise. Production system complexity and strict standards in terms of system design (engineering, software, documentation, etc.) and project management procedures (milestones, approvals, etc.) specified by the OEM
entail increasing development efforts while dealing with lower development budgets and managing dependencies to many specialized subcontractors.

For streamlining the development process encompassing all individual design and validation stages across different corporations, methods and tools of the Digital Factory become continuously more widespread among practitioners and are increasingly used in industrial application. One virtual validation method based on the Digital Factory is Virtual Commissioning which is well established within the development process of automated production systems for the automotive industry (cf. Fig. 1). One promising approach to improve Virtual Commissioning is to utilize physics-based simulation capabilities based on game engine technology [2]. Physics-based simulation capabilities enable dynamic multi-body simulation with respect to real-time restrictions by approximating physical phenomena of rigid body dynamics.

In this paper the results of the experimental based validation of the physics-based simulation of pneumatic components for Virtual Commissioning of body-shop and assembly systems are presented. Particularly, aspects of simulation accuracy with respect to three important aspects kinematic behavior, dynamic behavior, and compressed air consumption are considered in detail. In the second chapter fundamentals of automated production systems and Virtual Commissioning are introduced. The third chapter encompasses the modelling of pneumatic components adopting the physics-based simulation approach. A detailed description of the validation procedure and corresponding results are presented in chapter four. Ultimately, conclusions and potential for future research are denoted in chapter five.

2. Virtual Validation of Automated Production Systems

Within this chapter fundamentals about the structure and components of automated assembly systems for the automotive industry are described and the two phases of virtual validation are introduced from an OEM’s and PM’s perspective.

2.1. Automated Assembly Systems in the Automotive Industry

Production systems for automated assembly in the automotive industry are considered as special purpose machines [3]. Due to the high variety of different products at this late stage of the automotive manufacturing process less standardization in terms of system design, layout, and implemented subassemblies and components can be found in comparison to body-shop systems. A simplified overview of the typical structure of an automated assembly system is presented in Fig. 2.
Hierarchically an automated assembly system can be divided into different levels representing the lower layers of the conventional automation pyramid. Centralized factory process control at factory building level supervises multiple inputs including several PLCs (Programmable Logic Controllers) which control individual assembly cells. An assembly cell consists of several assemblies and subassemblies, e.g. turntables, robots or assembly-tools. Component level is built by all different components exchanging signals with the PLC in order to execute the desired manufacturing process, e.g. sensors and actuators. Although these components are highly standardized their arrangement and their distinct operating mode are mostly unique. Electrical and pneumatic components fulfill multiple production tasks, e.g. positioning, clamping or acting as drives. In the assembly process development the correct functionality of both types of components are validated based on virtual and digital models within the validation procedures Virtual Engineering and Virtual Commissioning.

2.2. Virtual Engineering and Virtual Commissioning

In parallel to the design tasks within the assembly systems creation the assembly system validation tasks Virtual Engineering and Virtual Commissioning are carried out (cf. Fig.1) [4]. In Virtual Engineering (VE), prior to Mechanical Design Approval, an extended 3D-geometric model of the assembly system is utilized for visualization and simulation-based validation of system processes, cycle-time and collision-avoidance considering different product variants [5]. Several tools of the Digital Factory such as DELMIA V5, Process Simulate, and Tecnomatix Plant Simulation are currently used [6]. Subsequently, Virtual Commissioning (VC) utilizes a mechatronic system model while incorporating the real PLC applying the Hardware-in-the-loop approach (HIL). Virtual Commissioning enables precious evaluation, optimization and validation of the entire production system, in particular the integration of new products, production system’s mechanical, electrical, and pneumatic components as well as control software.

In order to increase the quality of the extended 3D-geometric model and the mechatronic system model the approach of physics-based modelling of electrical and pneumatic actuators from the component level (cf. Fig. 2) can be used.

3. Physics-based Modelling of Pneumatic Components for Virtual Engineering and Virtual Commissioning

In this chapter the innovative simulation method physics-based modelling with respect to automated production systems gets introduced and the model for pneumatic drives is presented.

3.1. Physics-based simulation of production systems

Physics-based simulation capabilities based on game engine technology incorporate a physics engine to realistically reproduce the dynamic behavior of a multi-body system. This simulation approach takes additional physical aspects like forces and torques as well as environmental conditions (e.g. gravity) into account and thus shifts the quality of the simulation results to a higher level. To generate this benefit, additional input parameters like masses and moments of inertia of each dynamic object are required for the physics engine, a precompiled software library delivering the results of the equations of Newton’s laws of motion. In VE and VC for production systems in the automotive industry the physics-based simulation approach hasn’t been applied. For VC of CNC-machines or hauling systems of bulky goods physics-based simulation was applied successfully [7], [8].

Based on the structural analysis of automated assembly systems in the automotive industry a model for pneumatic actuators was developed and implemented.

3.2. Physics-based Model of Pneumatic Components

Pneumatic components in automated assembly systems are predominantly used for rotary and linear movements (e.g. linear cylinder) or fixing and positioning semi-finished goods e.g. clamer). These components have a similar schematic structure with a piston sectioning a cylinder in two separated chambers with alterable volume (cf. Fig. 3 (b)). Both chambers are individually connected to a compressed air reservoir via pneumatic tubes and non-return valves with throttles. The manually adjustable throttle’s width determines the air outflow from the chamber and thus piston’s velocity.

![Fig. 3. (a) Algorithm representing the behaviour of a linear pneumatic cylinder (PPM); (b) Simplified schematic diagram of a pneumatic cylinder](image-url)
the pneumatic cylinder with respect to the mechanical load. While physical object deformation is out of scope, static and dynamic friction forces are regarded with an approximated state-based implementation.

The simulation of the realistic dynamic behavior of pneumatic components is a significant improvement for the extended 3D-geometric model in VE and the mechatronic model in VC. In state-of-the-art tools for VE and VC there is no feature for reproducing the dynamic behavior of the production system components. In order to utilize PPM in the next generation of VE and VC the kinematic and dynamic accuracy and the compressed air consumption were analytically and experimentally validated.

4. Validation Procedures of the PPM

In this chapter the procedures and the results of the validation of kinematic accuracy, dynamic accuracy, and accuracy of compressed air consumption of the PPM are presented and discussed. All examinations are conducted using the pneumatic cylinder ADVU-50-250-A-P-A by FESTO.

4.1. Validation of Kinematics

The validation of kinematics was performed by experimentally measuring the piston’s movement during expansion. The measurement was conducted using a laser position sensor (CP35MHT80 by WENGLOR) that returns the position value with accuracy of 50 μm every 0.01 seconds. The sensor was mounted on the cylinder’s shaft, measuring the distance to an additionally installed plate, reflecting the laser beam to the sensor (cf. Fig. 4).

In terms of a high quality of the kinematics validation, the actual measurements were made at different pressure levels (3, 5 and 7 bar) and throttle widths (10 … 100%). For each specific parameter setting the piston’s movement was measured five times. The physics-based simulation was conducted with the same parameter setting and the simulation step of 0.0001 s. In order to compare PPM’s and experimentally measured position values the simulated values were reduced by a factor of 10. The experimentally measured position values and the reduced PPM’s position values are exemplarily plotted for the parameter settings of 7 bar and throttle width 40% (cf. Fig. 5).

The comparison of both position values shows that the simulated motion of the piston has a minimal deviation to experimentally measured motion. In this example, the average error of the simulation is \( \omega = 12.3 \% \). The absolute error based on the average simulation error was determined to \( \triangle w_{abs} = 11.4 \% \), respectively, resulting in a simulation accuracy of 88.6 \%.

4.2. Validation of Dynamics

The validation of PPM’s dynamic accuracy was examined analytically based on a mechanical model, focusing the accurate calculation of forces and torques. Here, a basic model of a rotating (0°…90°) and expandable (0…180 mm) bracket was designed in the physics-based simulation environment (cf. Fig. 6 (a)). From this basic model of the bracket the dynamic accuracy of PPM can be concluded due to the use of the same physics-based simulation environment and the same physics engine, respectively.
To compare the results of the computed forces and torques provided by the physics engine an analytical schematic model of the bracket was developed (cf. Fig. 6 (b)). The resulting forces and torques were analytically calculated using Newton’s laws. For the validation the values of the force $F_{R1}$ and the torque $M_{R1}$ were calculated and compared to the results of the physics-based simulation. The rotation of the hinge joint $R1$ was altered from $0^\circ$ to $90^\circ$ in steps of $1^\circ$.

The curve of the simulated force $F_{R1}$ almost identically superposes the analytically calculated force $F_{R1}$ (cf. Fig. 7). Only minimal deviations in a limited number of data points can be identified. As a consequence, the dynamic accuracy of the physics-based simulation model with respect to resulting forces can be constituted as confessed as very high. Moreover, the curve of the simulated torque $M_{R1}$ compared to the analytically calculated torque $M_{R1}$ displays comprehensive overlay with some significant deviations in the beginning of the rotation resulting from characteristics of the physics-based simulation approach (cf. Fig. 8).

Based on the calculation of the average error of simulation $\omega_{avg}$ and the absolute error of simulation $\Delta W_{abs}$ the simulation accuracy can be quantified to 99%.

### 4.3. Validation of Compressed Air Consumption

PPM was analytically and experimentally validated regarding the accuracy of the amount of compressed air consumed. The consumption of compressed air is an indicator for energy efficiency of a production system considering the entire process chain of creation, conditioning, distribution, and usage of compressed air [10]. In the first three stages of the process chain electrical energy is required in order to provide compressed air with adequate quality to the shop floor. Hence, less consumption on a component level (cf. Fig. 2) can lead to lower electrical energy consumption in the previous stages of the process chain.

With respect to the PPM algorithm (cf. Fig. 3 (a)) the amount of compressed air consumed is calculated for every single simulation time step based on the inbound mass by means of the equation of an ideal gas. Here the volume of the compressed air in standard conditions (unit: Normliter [Nl] or Normcubicmeter [Nm$^3$]) was computed using ISO 6358 [11]. Experimentally the validation was carried out on a real assembly system containing the examined cylinder type using the sensor SFAB-600U-Q10-28A-M12 by FESTO mounted right in front of the chamber’s inlets. The cylinder was once extended and retracted while compressed air consumption was tracked in the simulation and on the real production system alike. The test setting was repeated ten times for each considered throttle width (20/40/60/80/100%). Additionally, analytical calculations for the total amount of compressed air consumed have been carried out based on the equation of an ideal gas. In the table below the results of the sensor measurements on the real production system, the analytical calculations and the simulation results of the PPM are exemplified considering throttle width 40%.

| [bar] | 3   | 5   | 7   |
|-------|-----|-----|-----|
| Sensor measurements | 3.67580 | 5.70278 | 7.23872 |
| Analytical calculations | 3.72592 | 5.58889 | 7.45185 |
| PPM | 3.81649 | 5.74010 | 7.78157 |

Within this setting, but also for settings not presented in this paper, the deviation between PPM’s volumes with respect to the analytical and experimental volumes constitutes less than 10%. PPM’s throughout higher volumes for all different pressure levels could be caused by PPM’s shortfalls, e.g. deficient modelling of piston plate.

Despite absolute volume of compressed air consumption the consumption over time was examined as well examining a single expansion and a single retraction (cf. Fig. 9). Here solely experimental validation was carried out by means of comparing sensor measurements with PPM’s simulation results.

The chronological sequence of the PPM’s curve coarsely echoes the characteristic shape of the sensor’s curve. The significant deviations between the plateaus during the stable mass inbound phase ($t = 1…5s$ and $t = 12…15s$) could be caused by imprecise manually set throttle width in the simulation model as well as on the real production system.
entailing different simulation settings. With respect to the parameters (pressure level and throttle width) were varied M’s input amount of compressed air consumption. PP in terms of kinematic behavior, dynamic behavior, and the Three aspects were examined in detail: the accuracy of PPM automated assembly systems in the automotive industry. pneumatic components for utilization in VE and VC of validation of a physics based simulation approach for automated production systems.

5.1. Summary and Results

In order to cope with today’s challenges in the development process of highly complex automated assembly systems OEMs and PMs have collaboratively established virtual validation procedures utilizing methods and tools of the Digital Factory. As fundamental background a simplified structure of automated assembly systems and virtual validation procedures currently applied in the automotive industry were introduced in this paper, motivating the physics based modelling of pneumatic components. The PPM was outlined with respect to the physics-based simulation approach for automated production systems.

This paper further presents the analytical and experimental validation of a physics based simulation approach for pneumatic components for utilization in VE and VC of automated assembly systems in the automotive industry. Three aspects were examined in detail: the accuracy of PPM in terms of kinematic behavior, dynamic behavior, and the amount of compressed air consumption. PPM’s input parameters (pressure level and throttle width) were varied entailing different simulation settings. With respect to the experimental comparison with the behavior of the real pneumatic cylinder under test and with analytical calculations PPM shows good results at reproducing the pneumatic behavior within a physics-based simulation environment and can thus be recommended for the utilization within VE and VC.

5.2. Outlook

In order to improve VC and VE of automated assembly systems in the automotive industry additional components are modelled (electrical engines, robots, etc.) using physics based simulation approach in order to enrich the quality of the simulation utilized within these validation procedures. The physics-based models of two types of electrical engines are already developed and are presently validated with respect to energy consumption. A simple physics-based robot model is developed as well and will be further detailed. With respect to the modelling of pneumatic components PPM is currently under refinement essentially to simulate compressed air consumption more precisely (leakages, dead volume, etc.). All research efforts are directed to create an energy signature of an automated assembly system encompassing all individual components based on a virtual physics-based simulation model in order to predict the system’s energy consumption.

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