A SELF-OPTIMIZING HYDRAULIC SYSTEM APPROACH FOR AGILE METAL FORMING

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This research presents a novel concept of a smart hydraulic press system, enhanced with an expert system and a multi-objective optimization loop, aimed at flexible metal forming in agile manufacturing. Unlike traditional forming systems designed for mass production, the proposed solution enables adaptive, multi-phase control for producing a variety of products. By integrating AI-driven data analytics and real-time adaptive control, the system supports predictive decision-making, anomaly detection, and self-optimization of the forming process. The expert system utilizes historical datasets and machine learning models to minimize response error and adapt to process variations. Experimental validation demonstrates over 95% improvement in hydraulic system performance. The study also highlights the potential for further enhancement through an additional control loop focusing on product dimensional accuracy based on material properties and tool geometry. This approach aligns with Industry 4.0 and 5.0 goals for flexible, efficient, and sustainable manufacturing.

Keywords:
hydraulic press,
flexible manufacturing,
adaptive control,
self-optimizing,.
agile manufacturing

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1 Introduction

Manufacturing companies are undergoing a paradigm shift, transitioning from traditional production-centric operations toward service-oriented, intelligent manufacturing systems. In this context, hydraulic presses, widely used in metal forming, are evolving into smart systems that integrate expert knowledge, sensor data, and optimization algorithms to enhance flexibility and performance in agile manufacturing environments [1].

This paper focuses on the development and implementation of smart hydraulic press systems, specifically designed to support flexible metal forming processes such as incremental forming, deep drawing, and other advanced processes [2]. The integration of expert systems (ES) in such machines enables real-time process adaptation, fault diagnosis, and parameter tuning, while a multi-objective optimization loop supports decision-making to balance conflicting goals such as forming accuracy, energy efficiency, and cycle time.

The key research challenge is to establish a systematic design methodology for such smart systems, bridging the gap between market demands for flexibility (servtization) and technological enablers such as Cyber-Physical Systems (CPS) and data-driven control [3].

This contribution presents a modular framework composed of building optimization control loops for smart hydraulic press integration. These control loops serve two main purposes: (1) to reduce the hydraulic press instability by identifying real-time data patterns observed in real environment, and (2) to improve the final product quality.

2 Self-optimizing hydraulic system

Manufacturing processes typically follow the behaviour of Gaussian (normal) distributions, where it is common for the majority of process variation to fall within a 95 % probability range [4]. This level of repeatability is generally considered adequate for most production environments. However, in high-performance required environments, such as lean manufacturing, stricter requirements are imposed, often demanding process probability range above 98 %.

In this context, the proposed concept of a self-optimizing hydraulic system highlights the necessity of integrating various research domains, including simulation tools, machine learning techniques in order to designate the services for flexible manufacturing [5]. These are essential for the development of a purpose-built expert system capable of recognizing deviations, reconfiguring parameters, and adapting in real time i.e. when the hydraulic system operates outside the 95 % confidence range or when product specifications deviate from target requirements.

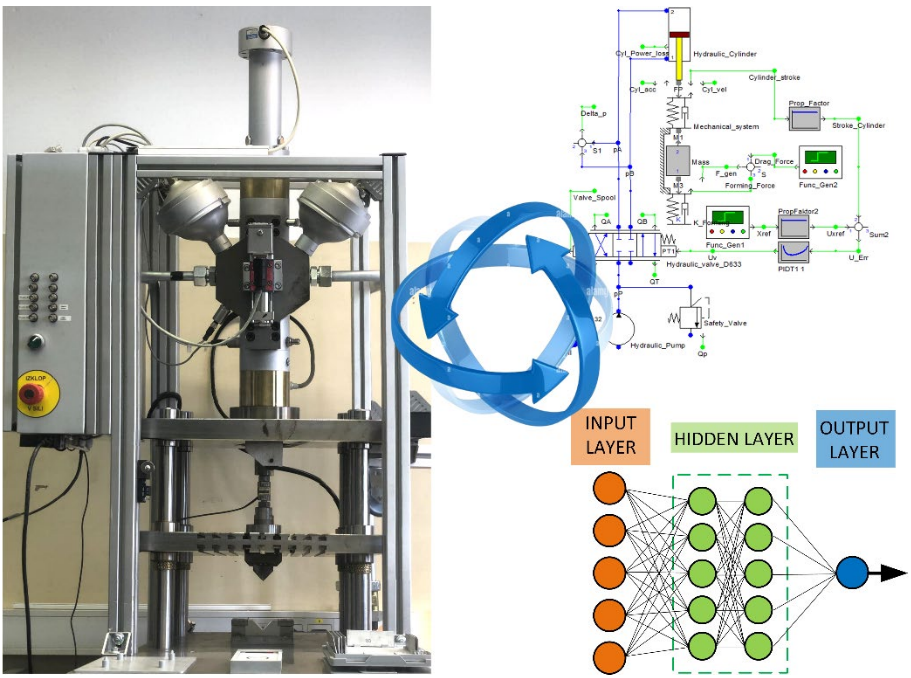

Figure 1: Hydraulic press analysis approach and data exchange.

The behaviour of any manufacturing system, including hydraulic systems, which play a key role in forming processes, can be predicted using well-established physical principles implemented in simulation models. The simulation tools replicate the system's physical behaviour within a virtual environment, enabling detailed analysis and optimization before real-world implementation [6].

In this context, the proposed concept emphasizes the importance of using multiple specialized tools designed to analyse the performance of distinct subsystems. This includes the simulation of hydraulic systems using tools such as DSHPlus, and the simulation of forming processes using advanced finite element software such as Abaqus. Moreover, data-driven models have gained significant popularity and are increasingly becoming a core element in integrating intelligent decision-making into the system. The results obtained from both domains are later integrated and interpreted in conjunction with expert knowledge to develop a comprehensive understanding of overall system behaviour and performance, as illustrated in the Figure 1.

The hydraulic press system is interpreted as a multi-node structure, consisting of key hydraulic components such as the hydraulic cylinder, PI controller, hydraulic power unit, hydraulic oil, pressure accumulators, hydraulic valves. Moreover, the studied hydraulic system is part of manufacturing process of sheet metal bending. Here, the forming process is described as subsystem. Each node must be accurately represented within the simulation model to ensure realistic results.

Specifically, the forming process can be modelled using Abaqus, a simulation environment purposely designed for analysing complex forming operations. This enables detailed insight into material deformation, stress distribution, and tool-workpiece interactions, which are critical for evaluating and optimizing the performance of the hydraulic press system.

Recent research shows that the accuracy of real-environment systems is best achieved using data-driven models [7]. A wide range of modelling techniques in the area of Machine Learning and Artificial Intelligence is available, including high-performance models such as Gaussian Process Regression (GPR) and Neural Networks (NN), as well as simpler models such as Polynomial Regression and Support Vector Regression (SVR).

In previous research, aiming at modelling the hydraulic press, a Polynomial Regression has proven to be sufficiently effective. It offers several advantages: it is computationally efficient, fast to train, and quick in prediction, while still providing high prediction accuracy in modelling the behaviour of the investigated system [8], [9].

Smart services are a combination of physical and digital services that are based on gathered data from a physical system. As a result, smart services are integrated product-service systems with a focus on digital, data-based service components. The challenge in our research is to combine theoretical considerations in the field of hydraulic systems operation, cyber-physical systems (technology push) and the predetermined requirements (hydraulic press stability, product quality). Our approach shows steps required to designate multi-objective optimisation loop for hydraulic presses, which can be used to plan new smart services based on an existing product and to implement them based on reference solutions.

3 Multi-objective optimization concept for hydraulic press

3.1 Hydraulic system optimisation loop

Hydraulic system optimization loop aims to align the actual movement of the hydraulic cylinder with its desired movement, which is pre-defined based on the hydraulic press cycle required for the forming operation. Expert systems are effective tools for supporting this process by autonomously identifying deviations, inefficiencies, and optimization potentials in the hydraulic press control logic as shown on Figure 2. These systems not only monitor and analyse the dynamic behaviour of the press but also assist in:

- reducing energy consumption,
- reducing cycle time,
- and increasing process stability.

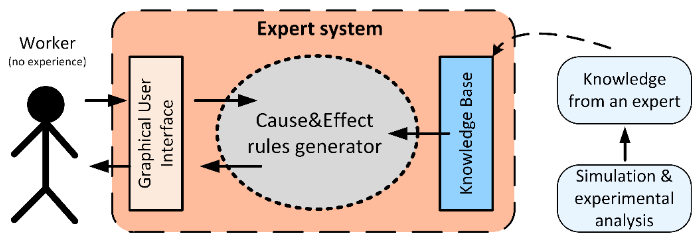

Figure 2: Expert system integration.

3.1.1 Knowledge integration into the expert system

By leveraging real-time and historical data, the designated expert system detects patterns in system responses, suggest parameter adjustments, and adapt control strategies accordingly. This data-driven optimization is particularly valuable in modern manufacturing, where sustainability and energy efficiency are key priorities beside product quality. The integration of expert systems into hydraulic press operations contributes to operational stability and indirectly to product quality requirements. Here the hearth of the expert system is cause & effect rules generator, which is set up by hydraulic system experts required to perform in depth simulation and experimental analysis.

The knowledge base describes the behaviour of the hydraulic press under various loading conditions, which are determined by different hydraulic cylinder velocities and the intensity of the forming process (different forming materials, products require different forming cycles). An observer i.e. worker accompanies the hydraulic press operation and monitors the response error reduction of hydraulic press to confirm the hydraulic system operational stability during the manufacturing process.

Furthermore, a detailed analysis was conducted in a simulation environment, achieving an average similarity of 80.3 % compared to the behaviour of the hydraulic press under various loading conditions in real environment, as illustrated in Figure 3. In contrast, learnt models using machine learning and artificial intelligence techniques, based on polynomial regression analysis demonstrated a significantly higher prediction accuracy of 98.3% compared to hydraulic press system behaviour.

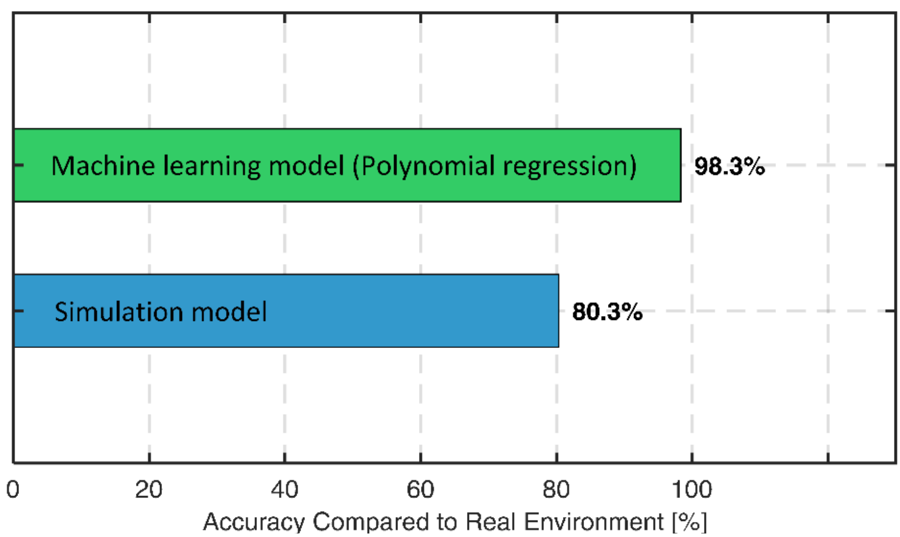

Figure 3: Comparison of system modelling accuracy between simulation environment and machine learning approach.

This notable improvement highlights the strong potential of data-driven approaches for capturing complex nonlinear system behaviour with high fidelity [7]. The achieved prediction accuracy of the ML model not only surpasses traditional simulation models but also confirms the scientific relevance and robustness of using AI techniques for predictive modelling in advanced manufacturing systems. Such results contribute meaningfully to the development of intelligent control architectures and position the methodology at the forefront of current research in smart forming technologies.

However, beyond sophisticated diagnostic capabilities, the practical and user-friendly software tools MATLAB are used to develop ML and AI tools which enable rapid implementation of expert knowledge into the control environment. The presented expert system simplicity shows fast development and deployment of expert logic, that emerged as essential enablers in this context. A standardized interface for rule-based reasoning, simplify integration into existing hydraulic press control systems and enables improvement in hydraulic press behaviour.

This paper presents a comparative evaluation of the proposed expert system with respect to its applicability in hydraulic press optimization, with a particular focus on forming processes. Based on the limitations identified in existing solutions, we introduce a novel expert system framework implemented within the TwinCAT environment. This implementation provides enhanced flexibility, transparency, and seamless integration into both research and industrial settings.

3.1.2 Improvement in operational stability of hydraulic press

Operational stability of a hydraulic press is determined by its ability to minimize the absolute mean error ΔX_C in the hydraulic cylinder displacement response. Figure 4 illustrates the improvement in the hydraulic press position accuracy, where the implementation of the proposed intelligent methodology resulted in a reduction of the absolute displacement error ΔX_C by up to 3.5 mm. This significant improvement validates the effectiveness of the developed approach in enhancing system control fidelity. By integrating machine learning models into the control processing unit, the system is able to dynamically adapt to changing operating conditions, reducing the error range across various phases of hydraulic press cycle.

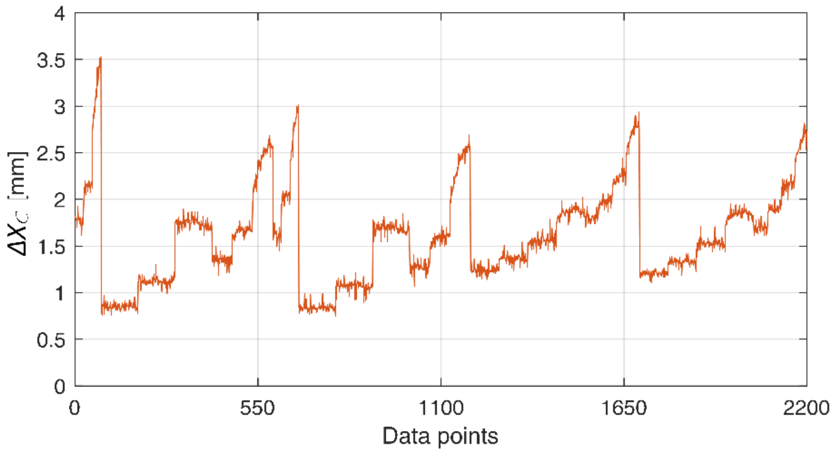

Figure 4: Hydraulic press response error reduction.

The operating conditions represent different load scenarios of the hydraulic press, where variations in specimen cross-sections directly affect the magnitude of force required by the hydraulic cylinder, as well as the cylinder's movement velocity. Larger cross-sections result in increased resistance of the material, requiring higher forces to be applied by the hydraulic cylinder. Additionally, at higher movement velocities, the hydraulic cylinder must overcome material resistance within a shorter time interval, which further stresses the system. Conversely, smaller specimen cross-sections and lower movement velocities reduce material resistance, resulting in lower force demands and more stable system response.

Regression models represent the core intelligence of the expert system, where the capability of predicting system states with sufficient accuracy based on the data used for training. However, improper learning strategies often lead to degraded model performance, particularly when exposed to previously unseen operational states. Despite this, the proposed expert system demonstrated robust generalization capability during validation in the context of various scenarios, where the hydraulic system operated under unfamiliar conditions.

Overall, the integration of AI-driven regression models into the hydraulic press control logic significantly improves system responsiveness and robustness, offering a scalable and scientifically grounded solution for next-generation forming technologies.

3.2 End user product optimisation loop

In the context of flexible manufacturing, where products vary in shape, size, and material properties, diverse operational requirements are addressed within the concept of the multi-objective optimisation loop, as illustrated in Figure 5.

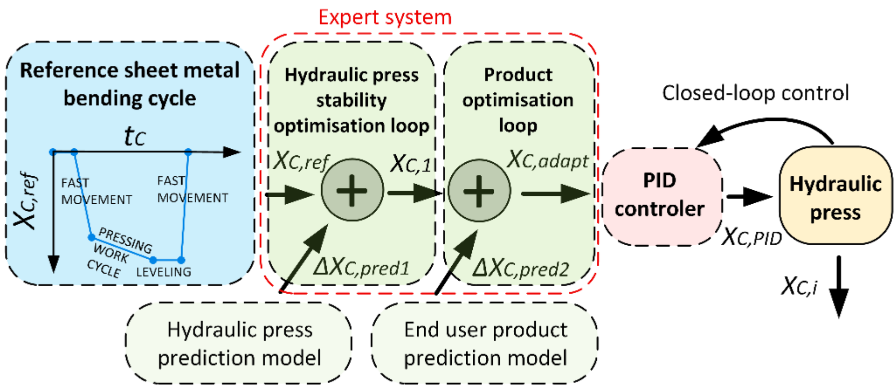

Figure 5: Multi-objective optimisation loop.

The operation of the hydraulic press is dynamically adapted to $X_{C,adapt}$ through a purpose-built optimisation framework tailored to the specific demands of each forming scenario given by the hydraulic press cycle (reference movement $X_{C,ref}$).

Within the proposed multi-objective optimisation loop integrated into the expert system, two primary objectives are considered:

1. In the first step hydraulic press stability optimisation loop focuses on the dynamic behaviour of the hydraulic system (hydraulic cylinder properties, internal and external leakages, hydraulic oil properties such as viscosity, temperature, pressure etc.) [10]. A dedicated optimisation model predicts the response error $\Delta X_{C,pred1}$ of the hydraulic press and actively corrects its behaviour (X_{C1}) to maintain operational stability under varying system dynamics.
2. In the second step the adapted signal from hydraulic press stability optimisation loop, the product optimisation loop targets the correction of hydraulic press response error $\Delta X_{C,pred2}$ resulting from variations in material properties, product geometry, dimensional tolerances, forming speed, temperature effects, lubrication conditions, and tool wear. This loop relies on a product prediction

model that estimates the expected deviation in forming outcomes and adjusts the control signal accordingly, after the hydraulic stability correction.

In the final step, a robust PID controller ensures precise execution of the optimised control signal $X_{C, PID}$. It compensates for any residual uncertainties and disturbances in the system, maintaining both process stability and product quality. The PID controller operates within a closed feedback loop, continuously aligning press performance with the desired forming results.

This layered approach enables real-time adaptability in agile production environment, where the interplay between system dynamics and product-specific requirements must be managed with high precision.

4 Discussion

The integration of expert systems and predictive models into hydraulic press control opens new possibilities for intelligent forming systems. The high accuracy achieved by the regression models demonstrates that data-driven approaches can effectively capture nonlinear system behaviour in real-world production environments.

The multi-objective optimization strategy enables a coordinated balance between internal system dynamics and product quality requirements. This is especially relevant in agile manufacturing contexts, where forming parameters must adapt in real time to disturbances. The combination of predictive logic and corrective control (via the PID layer) contributes to overall process robustness, yet its performance still depends on the quality and representativeness of the training data.

One of the advantages of the developed system is its modular design and compatibility with existing industrial platforms, allowing practical deployment without major retrofits. However, further research is needed to evaluate long-term system performance under varying production conditions, including tool wear, fluid degradation, and system fatigue.

In future developments, integrating additional sensory inputs (e.g., acoustic emission, vibration analysis) and exploring deep learning methods could further enhance the system’s adaptive capabilities.

5 Conclusions

In this study we developed a smart hydraulic press system for flexible sheet metal forming, designed for agile production environments.
The key achievements are:

- Implementation of an expert system with real-time and historical data integration,
- Predictive modelling using polynomial regression with accuracy up to 98.3 %,
- Development of a dual-loop control structure combining optimization and PID regulation,
- Modular system architecture, tested in MATLAB and TwinCAT environments,
- Demonstrated reduction in force fluctuation and improved press stability.

The system lays the foundation for adaptive, intelligent forming processes aligned with Industry 4.0 and 5.0 goals.

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