Digital Repair Chains in the Automotive Sector: Rapid Repair with 3D Technology

Rapid Repair with 3D Technology

Flexible Solutions for Spare Parts Sourcing and Component Repair

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This paper presents the prototypical development and demonstration of a Rapid Repair Workflow designed to address challenges faced by manufacturing industries, particularly medium-sized automotive suppliers, in sourcing and replacing obsolete or unavailable machine components. The workflow integrates 3D scanning, digital repair, and additive manufacturing (3D printing) technologies to rapidly recreate damaged parts, reducing lead times, storage costs, and downtime. We outline the process stages – initial assessment, scanning, digital file preparation, additive manufacturing, and quality assurance – highlighting the tools and techniques employed. The prototype was successfully showcased at a trade fair, receiving positive feedback for its precision, ease of use, and potential for industrial application. Key challenges such as intellectual property issues, technical limitations of scanning and CAD tools, and quality assurance requirements are discussed. Future work will focus on automation, AI-driven damage analysis, expanded VR functionalities, and broader adoption of additive manufacturing methods. Overall, the Rapid Repair Workflow demonstrates significant potential to enhance maintenance practices and operational efficiency across industries.

Keywords and Phrases: Rapid Repair Workflow, 3D Scanning, Additive Manufacturing, Spare Parts Reproduction, Digital Repair, Manufacturing Digitalization, Industrial Prototyping

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1 INTRODUCTION

In this paper, we present the prototypical use of a 'Rapid Repair Workflow'. Despite the considerable potential of I4.0 solutions in this area, their application remains in its early stages, with a notable lack of research at this intersection [9]. I4.0 technologies promise to enhance agility, operational efficiency, product and service quality, customer satisfaction, and sustainability in Spare Part Management (SPM).

Industrial enterprises – particularly small and medium-sized automotive suppliers – face recurring challenges in the management of spare parts. On the one hand, components in ageing machinery are subject to wear, with direct replacements often no longer available from original equipment manufacturers (OEMs). On the other hand, inventory costs for spare parts are high due to considerable heterogeneity, and long lead times in the event of a failure result in significant costs and downtime. Traditional procurement and repair approaches are often insufficient to effectively address these dynamic challenges.

In response to these critical demands, this paper presents the prototypical development and demonstration of a "Rapid Repair Workflow". This workflow represents a transformative solution aimed at fundamentally improving the procurement and repair of obsolete or damaged machine components.

In contrast to conventional repair strategies, which often depend on lengthy supply chains and reliance on OEMs, our approach enables the rapid on-site reproduction of defective parts [8]. This is achieved through the integration of 3D scanning, digital repair, and additive manufacturing (AM). The workflow offers advantages such as reduced lead times and decreased dependency on OEMs, which can lead to substantial cost savings. While the higher unit costs and potentially lower reliability of additively manufactured parts compared to conventionally produced ones are frequently cited as challenges, the Rapid Repair Workflow mitigates these drawbacks by flexibly leveraging AM as a dual-sourcing option. This approach enables significant cost savings, even where AM parts are initially more expensive or less reliable [2]. The concept of dual sourcing – combining conventional and additive manufacturing – is therefore essential for capitalising on the benefits of AM while minimising its limitations. Evidence also suggests that pure "on-demand printing" is often impractical for failure-critical components, and that maintaining physical stock remains essential to ensure high system availability [2].

Our workflow (Fig. 1) is embedded within the broader evolution towards Procurement 4.0 (P4.0), which is revolutionising supply chains through technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI), thereby enabling dynamic and rapid collaboration across organisational boundaries. The automation and digitalisation of procurement processes through such I4.0 technologies contribute to increased efficiency, cost reduction, and enhanced transparency [9].

The workflow process encompasses several phases: initial damage assessment; 3D scanning to create an accurate digital model; digital preparation and repair of the file (reverse engineering); the actual additive manufacturing of the replacement part; and final quality assurance. Tools utilised in this process are either already available within industrial settings or can be accessed with relative ease. Challenges such as intellectual property concerns, technical limitations of 3D scanning and CAD tools, and the need for rigorous quality assurance are also addressed.

In sum, the Rapid Repair Workflow demonstrates substantial potential to improve maintenance practices and operational efficiency across various industries. Its adaptability to different materials and complex geometries positions it as a pivotal tool for organisations aiming to optimise their operations while upholding high standards of quality and performance. Our contribution lies especially in the low entry barrier to this workflow, as well as the combination with a virtual reality (VR) pre-flight check.

2 RAPID REPAIR WORKFLOW OVERVIEW

The Rapid Repair Workflow process (Fig. 1) comprises four integrated stages to restore damaged components using advanced technologies, including 3D scanning, computer-aided modelling, and additive manufacturing.

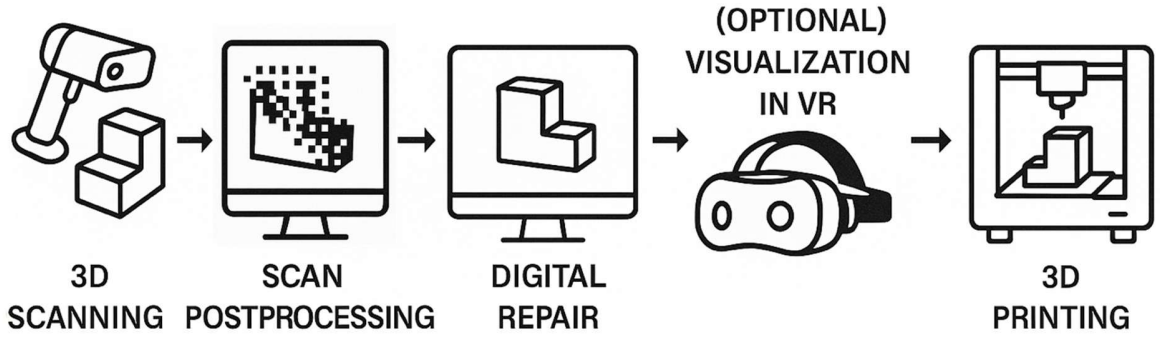

Fig.1 Rapid Repair Workflow.

2.1 Initial Assessment and Scanning

The initial step involves assessing the condition of the damaged component. Technicians often utilize troubleshooting guidelines to determine whether the issue originates from cabling, software, or the component itself. Once identified, the next step is to create a digital representation of the part using 3D scanning technology. Once the fault has been identified, the subsequent step is to generate a digital representation of the part using 3D scanning technology. This process produces an accurate digital model that captures the geometry and key features of the damaged component, forming the basis for its reconstruction.

2.2 Reverse Engineering and STL File Preparation

Following the scanning process, the resulting data is typically converted into a file format suitable for editing and/or subsequent additive manufacturing, such as STL or M3F. In addition to any necessary reparations or modifications, particular attention must be paid to the integrity of the file, as imperfections can result in failures during the printing process. Consequently, various software tools are employed to detect and rectify errors within the file, ensuring that issues such as non-manifold edges or surface holes are resolved prior to printing.

2.3 Additive Manufacturing

With a corrected file available, the subsequent phase involves additive manufacturing. Using technologies such as Fused Deposition Modelling (FDM), or more advanced methods including Directed Energy Deposition and Laser Cladding, new components can be produced rapidly. These techniques facilitate the reconstruction of parts while minimising material waste and enhancing the overall efficiency of the repair process.

The selection of materials for 3D printing is of critical importance, as properties such as strength, durability, and compatibility with the original component must be carefully considered to ensure that performance requirements are met effectively.

2.4 Quality Assurance and Testing

Upon completion of the new part, quality assurance procedures are undertaken to ensure that the repaired component meets the requisite standards. This involves functional testing and validation aligned with the intended application of the part. Regulatory considerations, as outlined in relevant guidelines for additively manufactured devices, help ensure compliance with quality system requirements, encompassing both design and testing processes.

3 TECHNOLOGIES USED

3.1 Overview of 3D Scanning

3D scanning is employed to capture the physical dimensions of objects and environments in digital form, facilitating the creation of detailed three-dimensional models. This process utilises various techniques – such as laser scanning, structured light, and photogrammetry – to accurately represent real-world assets. [1]

3.1.1 Types of 3D Scanners

Various types of 3D scanners exist; each suited for different applications:

- **Structured Light Scanners**: Use a projector to project patterns of light onto the object and a camera to capture the reflected patterns, ideal for small objects with fine detail. [13]
- **Laser Scanners:** Use lasers to measure distance and are effective for detecting larger objects, even outdoors. [17]
- **Photogrammetry Scanners:** Use multiple cameras to capture images from different angles, which are then processed to reconstruct complex shapes. [14]

Choosing the right scanner depends on the size and shape of the objects to be scanned, as well as the budget available for the technology. In this project, a portable lightweight 3D laser T-SCAN hawk 2 from ZEISS was used to capture the 3D data of the scanned object. This device achieves a volumetric accuracy of 0.02 mm + 0.015 mm/m, enabling detailed, high-speed scanning of both small and large parts. Following this procedure, the data set was merged in the GOM inspect software to obtain a realistic image via 3D point clouds. Cloud information enables further procedures, such as reverse engineering or reproduction (e.g. 3D printing).

3.1.2 How 3D Scanning Works

At its core, 3D scanning involves projecting a laser or light pattern onto the surface of an object. The scanner measures distortions in the reflected pattern, collecting data about the object's geometry and surface characteristics. This information is processed by specialised software to create a digital 3D model that can be manipulated and visualised in a virtual environment.

3.1.3 Key Phases of the Scanning Process

The scanning process (Fig. 2) generally consists of four key phases:

1. The scanner emits a scanning element (such as a laser stripe) towards the object.
2. The scanner's sensor detects the reflected data, capturing size, shape, and potentially color information.
3. The software processes these scans to create a full three-dimensional digital mesh, which approximates the object's surfaces.
4. Mesh post-processing finalizes the model for applications such as 3D printing or visualization.

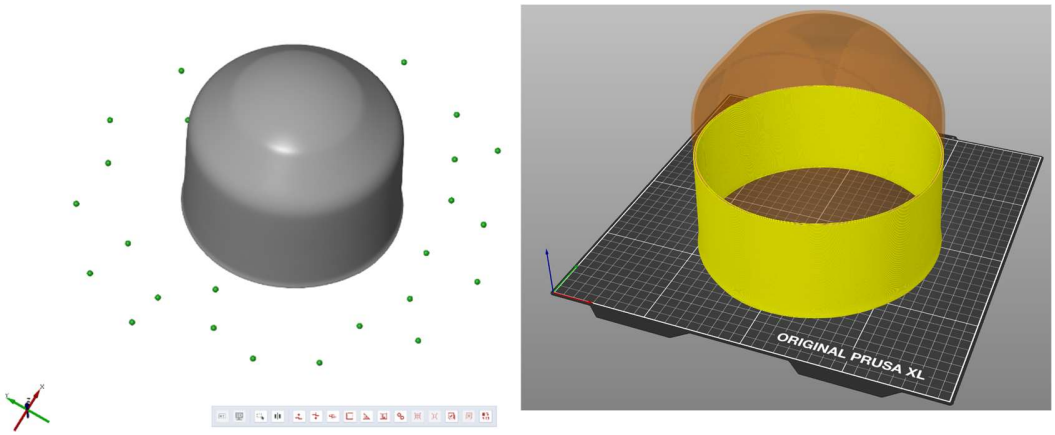

Fig.2 3D digital mesh (left) and mesh post-processing on a 3D printer (right).

Despite its advantages, 3D scanning has limitations, particularly when it comes to capturing fine detail due to resolution and sensor capabilities. Techniques such as photogrammetry can help mitigate these challenges by enabling detailed capture of complex geometries.

3.2 AR/VR Technologies

Augmented Reality (AR) and Virtual Reality (VR) are immersive technologies that alter or replace a user's perception of their environment. While VR creates fully digital environments for users to interact with, AR overlays digital elements onto the real world through devices like smartphones, tablets, or AR glasses. In our case a HTC Vive Focus 3 was used. For visualization the app Gravity Sketch VR was used. It also allowed us to alter and annotate the 3D object.

3.3 3D Printing Technologies

3D printing technologies 3D printing, also known as additive manufacturing, encompasses a range of methods and technologies that enable the creation of three-dimensional objects from digital models. The core principle is to build objects layer by layer, using different materials and processes to achieve desired shapes and functionalities.

3.3.1 Methodologies

There are several prominent 3D printing methodologies currently in use:

- **Fused Deposition Modeling (FDM):** FDM works by extruding thermoplastic filament through a heated nozzle, which is then deposited layer by layer. It is one of the most commonly used technologies due to its accessibility and affordability. [6]
- **Stereolithography (SLA):** This method employs ultraviolet light to cure liquid resin into hardened plastic. It is used for producing high-resolution parts with fine details. [7]

- **Selective Laser Sintering (SLS):** SLS utilizes a laser to fuse powdered material, typically plastic or metal, into solid structures. This method is particularly well suited for the production of complex geometries and functional parts without the need for supporting structures. [16]
- **Multi-Jet Modeling (MJM):** This technique involves depositing droplets of material layer by layer, which are then cured by ultra violet light. It allows for a wide range of materials and colors, facilitating the creation of intricate designs. [3]

3.3.2 Materials Used

The choice of materials is crucial in 3D printing and impacts the properties and applications of the final product.

- **Plastics**: Such as PLA and ABS, which are popular for their ease of use and versatility. [10]
- **Ceramics**: Used for applications requiring higher temperature resistance and specific aesthetic qualities. [15]
- **Metals and Metal Alloys**: These much more expensive materials are utilized in industries where a lot of durability is required, such as aerospace and automotive. [5,12]
- **Biological Substances:** Research is underway in the use of other biological materials, potentially paving the way for a more eco-friendly approach that can substitute plastics. [4]

4 PROOF OF CONCEPT

4.1 Retrofitting at a Manufacturing Business

In the context of implementing a rapid repair workflow for industrial machinery, a specific retrofitting scenario was carried out involving a decades-old screw production machine. The machine in question, still in daily use, is fully mechanical and lacks any digital control interface or connectivity. As a matter of fact, neither construction drawings nor maintenance documentation were available – an issue commonly encountered with legacy equipment in traditional manufacturing environments.

The central objective was to capture and digitally reconstruct a worn shaft that is critical for the machine's operation. Due to the absence of any digital blueprint and the special geometry of the part, the shaft could not be replaced or reproduced using conventional CAD-based manufacturing methods. To overcome this, the component was disassembled and digitised using our 3D scanning workflow:

Following the scan, the raw point cloud data underwent post-processing, including noise reduction and alignment, before surface reconstruction techniques were applied. This process, known as reverse engineering or surface modelling, allowed for the generation of a watertight, parametric CAD model that accurately represented the original shaft geometry. The resulting model can now be used not only for reproduction via CNC machining or additive manufacturing, but also as a reference object for further digital retrofitting of the entire system. As the geometry of the shaft is a direct result of all the parameters that control the machine, the manufacturer is now in a position to create many different shaft variations and finetune all parameters for an optimal workflow.

4.2 Automotive Supplier Exhibition

After first steps in the real world, the refined "Rapid Repair Workflow" was presented at a trade fair for automotive suppliers using a demonstrator. The workflow combines 3D scanning, digital repair and additive manufacturing (3D printing) to quickly reconstruct damaged or no longer available components.

Firstly, the trade fair participants were shown how the handheld 3D scanner works (Fig. 3). The scanner captured the damaged component using laser technology and photogrammetric technology to create a precise digital representation. The scan data was then corrected (errors such as non-manifold edges or holes were corrected using the "GOM" software) and the files were prepared in STL format for 3D printing.

Visitors to the trade fair were able to view, manipulate and virtually test the scanned components in a virtual reality environment (Fig. 4). The process from digitisation to virtual representation was fully demonstrated and explained by experts. At the same time, examples of processes and materials that could be used for subsequent 3D printing, such as FDM and SLS, were presented.

Fig 3. Demonstration of the scanning process. The hand scanner is moved around the object.

4.3 Feedback

The retrofitting case study involving the digitisation of a decades-old screw production machine provided valuable insights into the challenges and opportunities inherent in bridging legacy mechanical systems with modern digital workflows. The project, while successful in achieving its core technical objective – the digital reconstruction of a critical shaft component – also revealed key considerations relevant for future retrofitting efforts.

The use of 3D scanning and reverse engineering methods proved to be both feasible and effective for dealing with irregular, undocumented geometries. The resultant parametric CAD model did not only enable reproduction of the shaft but also opened new avenues for design iteration and optimisation of machine parameters.

Despite these benefits, the process was not without its limitations. The quality and completeness of the 3D scan data proved heavily dependent on the surface condition and complexity of the part. Manual alignment and noise filtering were necessary to ensure reliable surface reconstruction, demanding a level of expertise and tooling that may not be readily available in all industrial settings. (It is important to recall that one of the primary objectives was to enable low-barrier access to this technology through the use of off-the-shelf components.) Additionally, the disassembly of the component, though successful in this case, is not always feasible or risk-free in other contexts, particularly with more delicate or integrated assemblies.

Regarding the exhibition, after the demonstration was over, the participants were asked for feedback on the implementation, the quality of the scans and the usefulness for their company. The feedback was positive, many mentioning problem areas overlapping with the literature. Particularly emphasised were

- the high precision of the 3D scans
- the fast and intuitive processing of the digital models
- the immersive and vivid visualisation of the components in the VR environment.

In addition, the practical implementation of the entire workflow – from damage diagnosis to digitalisation and virtual inspection - was rated as realistic and application-oriented. The participants saw great benefits in the rapid reproducibility of spare parts, particularly for medium-sized companies in the automotive and manufacturing industries. Critical comments mainly related to known challenges such as the need for careful quality controls and compliance with legal framework conditions when using additive manufacturing technologies.

Fig 4. Demonstration of digital downstream refinement of digitized object.

5 CHALLENGES AND LIMITATIONS

5.1 Intellectual Property Issues

Intellectual property law plays a significant role in the domain of 3D printing, affecting hobbyists, small businesses, and large corporations alike. While the law aims to foster innovation and creativity, it often leads to complex legal challenges. Individuals and organizations may face potential legal actions, particularly from larger companies, which tend to benefit from rulings that may be unfavorable to smaller entities or open-source initiatives. [11]

5.2 Technical Limitations of CAD and Scanning

The technical limitations inherent in CAD software and 3D scanning technologies pose additional challenges. High-performance workstations equipped with powerful processors and graphics cards are crucial for managing complex models and simulations. These requirements can be a financial burden for smaller organizations and individual users, restricting access to advanced 3D printing capabilities.

Furthermore, interoperability issues arise from file format incompatibilities among different CAD systems, complicating collaboration and risking data loss during transfers.

When utilizing 3D scanners, accuracy and precision are essential for good results. Calibration errors can lead to significant inaccuracies in scanned data, which in turn can result in flawed 3D models and subsequent printing failures

Employing advanced scanning techniques and post-processing software can mitigate these issues, but not all users have access to high-quality tools, which can exacerbate challenges in achieving precise scans.

6 CONCLUSION AND FUTURE WORK

As part of this work, a first prototype of a “rapid repair workflow” was developed and successfully presented at a trade fair. The workflow combines modern 3D scanning technologies, digital model preparation and additive manufacturing to reconstruct damaged or unavailable components quickly and efficiently.

The presentation of the demonstrator met with a very positive response from trade fair participants. The intuitive operation, the high quality of the digital models and the enormous potential for optimising repair and maintenance processes in industry were particularly emphasised. This feedback confirms the relevance and benefits of the developed concept and motivates further consolidation and development.

As this is still an initial prototype, there are numerous approaches for future work:

- Automation of the scanning and repair process: Currently, the post-processing of scan data and preparation for 3D printing is largely carried out manually. Future developments could aim to largely automate error correction and model preparation in order to further accelerate the process chain.
- Integration of AI-supported damage analysis: The integration of artificial intelligence could enable the automatic detection and classification of damage patterns directly based on scan data. This would enable even faster diagnosis and repair proposals.
- Expansion of VR interaction options: The virtual reality component could be expanded to allow users not only to view but also to carry out interactive repair or modification processes on the digital model, for example through intuitive gesture control or simulation-based load tests.
- Material and technology expansion in 3D printing: The workflow demonstrated so far has focussed on standard processes such as FDM. In future, other additive manufacturing technologies such as SLS or SLA could be integrated to a greater extent in order to cover more complex materials and higher component quality requirements.
- Development of a mobile rapid repair system: A portable version of the workflow - consisting of a mobile scanner, VR headset and compact 3D printer - could be developed to carry out repairs directly on site at the customer's premises or in production.
- Pilot projects in real industrial environments: Building on the positive trade fair experience, concrete application projects are to be initiated with industrial partners in further work. The aim is to validate the practicality of the system under real conditions and to obtain valuable feedback for the next stage of development.

Overall, the prototype developed impressively demonstrates how innovative technologies can be combined to address existing challenges in spare parts supply and maintenance. The consistently positive feedback and the future opportunities identified emphasise the potential of the 'Rapid Repair Workflow' to become a permanent fixture in the field of digital repair methods.

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