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EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

CASE STUDY #5

Project Title	**European network for 3D printing of biomimetic mechatronic systems** **21-COP-0019**
Output	**IO4 - EMERALD e-case studies for project based learning method used in developing, testing and manufacturing of new biomimetic mechatronic systems by 3D printing technologies**
Module	**Case study #5 – Studies on 3D printed biomechatronic robotic gripper**
Date of Delivery	**September 2023**
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Contents

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1. Introduction

This document presents a description of a case study realized in the EMERALD project, as part of the IO4 work package. The case was selected on the basis of experience, possibilities, available solutions by the combined teams of University of Agder, Technical University of Cluj-Napoca, National University of Bucharest and Poznan University of Technology. Discussions conducted during various EMERALD project meetings were also taken into consideration and feedback of all partners was gathered and implemented.

The case study #5 focuses on a biomechatronic 3D printable robotic arm that can be used as a haptic device. The robotic arm was constructed as a project realized by University of Agder lecturers and students, as an educational example on how to construct and program simple robotic grippers. It has been used during the EMERALD project summer school in year 2022, in form of a toolkit available on GitHub platform [1], by students of all universities involved in the project consortium. Then, in the later phase of the project, the EMERALD consortium members realized material studies on the gripper, realizing 3D prints, tests and analyzes using various techniques and materials. This study is presented in this document.

Contents of this case study are also contents of a scientific paper, entitled “Use of high-performance polymeric materials in customized low-cost robotic grippers for biomechatronic applications: experimental and analytical research” by the same team of authors, submitted to journal Frontiers in Materials. At the moment of finishing the work in EMERALD project, the paper was not published yet, as such it is not cited in this study. It is noteworthy that the mentioned paper contains extensive material studies over PEKK material, which are not presented here (as the case study focuses on a specific device – robotic gripper). Reader is therefore encouraged to check on the paper to find more about material characterization.

2. Literature review and premises for the study

2.1. 3D printed robotic arms

Robotic arms have been an integral part of industrial automation, healthcare, and various other domains. The convergence of 3D printing technology with robotics has given rise to programmable robotic arms that offer enhanced versatility, cost-efficiency, and customization.

Various parts of robotic arms can be 3D printed, including joints, grippers, and even end-effectors. The ability to customize these parts to suit specific tasks is a notable advantage of 3D printing in robotics [2], with example of simple 3D printed parts shown in Figure 2.1.

Figure 2.1. Robotic arm parts 3D printed using low-cost FDM technology [2]

3D-printable robotics is characterized by its adaptability and customization. Robotic arms can be designed and printed to suit a range of applications, from educational platforms to industrial automation [3]. 3D-printed robotic arms have found a niche in education, enabling students and researchers to experiment with robotics and gain hands-on experience – which was also a point of this toolkit. The availability of DIY kits and open-source designs has democratized access to 3D-printable robotic arms, fostering innovation and experimentation in the robotics community [4].

3D-printed programmable robotic arms have made inroads into manufacturing, streamlining processes and increasing efficiency. They are used for tasks such as pick-and-place operations and quality control. In the medical field, these robotic arms can assist in

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surgeries, offering precision and minimally invasive procedures. Rehabilitation and physical therapy applications are also emerging [3].

Current technology allows to use various 3D printing technologies in construction of low-cost robotic arms. As shown in previous chapters, many designs can be used as DIY projects, to create home-made or school-made robotics. Students and researchers interested in this topic may easily find many suitable projects, along with customization possibilities. Fused Filament Fabrication (FFF) is a versatile additive manufacturing method used to create 3D-printed robotic arm components, including grippers and whole arms. Several papers and research studies showcase the application of FFF for building functional robotic components.

A comprehensive review of robotic arm grippers is presented in the paper "Current Designs of Robotic Arm Grippers." This review discusses various designs of grippers, many of which can be created using Fused Filament Fabrication. It identifies benefits and drawbacks of different gripper designs, providing insights into the use of FFF for gripper fabrication [5].

In the paper titled "Design and 3D Printing of a Robotic Arm," the authors introduce the design concepts and the 3D printing procedure for a robotic arm created using 3D printing technology. While this paper primarily focuses on design concepts, it highlights the significance of 3D printing in the fabrication of robotic arms [6].

A paper titled "FDM Based Custom 3D Printer Development in Robotic" discusses the development of a custom 3D printer that can be utilized for robotic arm component fabrication. This research showcases the potential of 3D printers for creating robotic arm mechanical components with precision and low tolerances [7]. In "Current Designs of Robotic Arm Grippers," an underactuated adaptive 3D printed robotic gripper is presented. This gripper is designed for interactions with unpredictable environments and demonstrates the potential of 3D printing in creating adaptable robotic components, including grippers [8].

These papers and research studies underscore the use of Fused Filament Fabrication (FFF) as a viable method for creating robotic arm components such as grippers and whole arms. Researchers and robotics enthusiasts can explore these references to gain insights into the capabilities and applications of 3D printing in the realm of robotics.

2.2. Materials used in biomechatronic devices

A wide range of materials is nowadays available on the market, each offering particular advantages and disadvantages in the realization of biomechatronic devices [9,10]. High-performance FFF (Fused Filament Fabrication) materials, including but not limited to PEKK, has garnered significant attention for their outstanding mechanical properties [11-13]. These polymers possess exceptional strength, stiffness, and resistance to heat and chemicals, making them ideal candidates for applications demanding robustness and durability [14]. High-performance FFF materials outshine their standard Fused Filament Fabrication counterparts, such as PET-G, in terms of mechanical resistance, allowing for the creation of biomechatronic components which are capable of withstanding considerable stress and wear in these conditions [15,16]. However, the use of these materials is not without challenges. Precise temperature control is essential during the printing process, and issues like warping can pose difficulties, especially for intricate and large-scale designs [17,18]. Balancing the advantages with the complexities of handling these materials remains a key consideration in the case of biomechatronic applications [19]. The integration of carbon fiber composites into Fused Filament Fabrication (FFF) materials has expanded the scope of possibilities further on in several domains, including biomechatronics. Composites combine the versatility of FFF printing with enhanced mechanical properties, introducing newfound strength and stiffness [20-22]. Yet, this enhancement comes at a cost, both in terms of material expenses and the demands placed on the 3D printing equipment [23]. Finding the right balance between performance and affordability remains an ongoing pursuit for researchers and engineers in the field of biomechatronics [24]. On the other end of the spectrum, PolyJet technology represents one reliable alternative, employing UV resins to produce highly detailed, intricate structures with remarkable precision and smooth surface finishes [25,26]. This technology excels in creating visually appealing and intricately designed components, a quality particularly important in applications like customized prosthetics [27]. However, the mechanical characteristics of PolyJet materials may not always meet the rigorous demands of biomechatronic devices, where strength and durability are highly important [28]. Moreover, the initial and ongoing costs associated with PolyJet technology can be one disadvantage for those seeking cost-effective solutions [29,30].

Biomechatronic devices, including robotic arms place a unique set of demands on the materials used in their construction [31]. Mechanical characteristics such as flexural strength, tensile properties, compressive and wear resistance are highly important in determining the performance and durability of these applications [32-34]. Robotic arms, for instance, rely heavily on bending and flexing to function effectively, directly influencing their lifting capacity and precision [35]. Consequently, the choice of materials for these devices must be made with thorough consideration of these mechanical characteristics [36]. To assess the justifiability of employing high-performance materials like PEKK in the development of customized robotic grippers for biomechatronic applications, the study was aimed to provide one comprehensive analytical and experimental approach. Analytical studies, including finite element analysis (FEA) have been utilized to simulate and optimize the mechanical behaviors of the components. Empirical research has been conducted to validate these analytical findings and to assess the performances of the robotic grippers that were taken into consideration in this research.

The study was aimed to provide an analytical and experimental research to provide one comparative analysis realized in the case of using high-performance materials like PEKK against conventional alternatives like PET-G and MED 857 (DraftWhite) materials, so one may comprise and understand both the advantages and challenges in utilizing these materials in the development of low-cost robotic grippers for biomechatronic applications by 3D printing technologies.

3. Materials and methods

3.1. Research concept and plan

The main concept of the presented case study was to answer the question if the use of the so-called high-performance 3D printing materials in production of customized robotic arms is justifiable by results of manufacturing processes and material tests. To answer that question, one high-performance material – PEKK – was selected and compared with two other popular materials (PET-G and MED 857 (DraftWhite) and technologies (FFF and Polyjet) by means of both analytical and empirical studies, based on previous knowledge and achievements of the authors.

In the initial phase of the research presented in this article, some materials and technologies were selected for the purpose of biomechatronic robotic devices. Then, by using a designed variant of an existing robotic gripper that was developed by part of the team of authors from the University of Agder (Norway) in previous studies [37-38] (Figure 3.1), parts of it were manufactured using various materials and have been subjected to strength tests emulating loading of a robotic arm. Simultaneously, the tests were performed using Finite Element Analysis, to check and compare analytical and empirical results. Various indicators were assumed to be used in order to compare selected materials and to answer the basic research questions. In this context has been considered the opportunity of considering, testing the mechanical behavior and using of new polymeric materials (like polyetherketoneketone - PEKK) for realizing of customized low-cost robotic grippers for biomechatronic applications. Regarding control algorithms for the proposed manipulator design, more details can be found in the following previously reported work and results [39-40].

The selected materials and technologies were: Fused Deposition Modelling, with PEKK (Polyetherketoneketone) as the test material and PET-G (Polyethylene Terephthalate Glycol) as control material, along with PolyJet technology, with DraftWhite (MED 857) UV resin material. Figure 3.2 shows the course of the research including the most important stages. Particular parts of the research are described in the next chapters of the article.

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Figure 3.1. The robotic gripper 3D design [41]

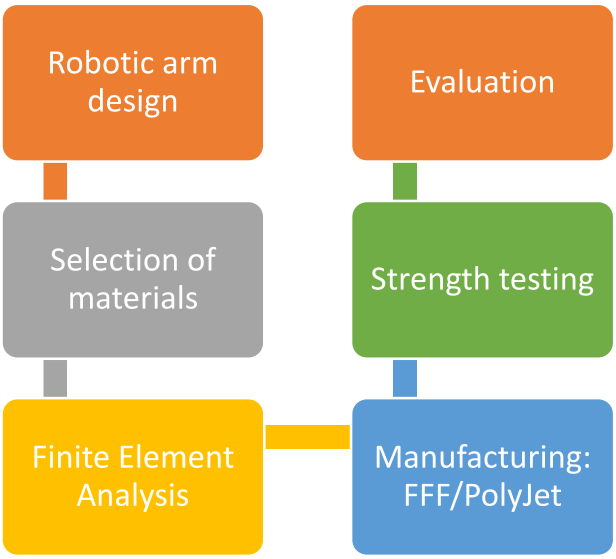

Figure 3.2. Course of the research described in the study

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3.2. Robotic gripper project description

The primary goal of the project presented in this toolkit was to design an easy-to-build and assemble haptic installation that can function as a haptic device. This is achieved through the utilization of a joint with integrated springs. By employing this innovative approach, it becomes feasible to achieve greater motor displacement for a relatively smaller amount of force when compared to a rigid robotic arm. This design allows for enhanced tactile feedback and improved user experience in haptic interactions.

Contents of this chapter are mostly taken from the GitHub solution, available under [1].

The robotic gripper was designed in 3D CAD with typical assumptions for simple, one-axis robotic arms. The basic construction is presented in Figure 3.1 and the 3D models for 3D printing are available in the GitHub repository at [1]. Also, a full disassembly instruction, containing animations of all steps with names of standardized parts was prepared. It is available online, under link [42]. Examples of operations presented in the online instruction are presented in Figure 3.3.

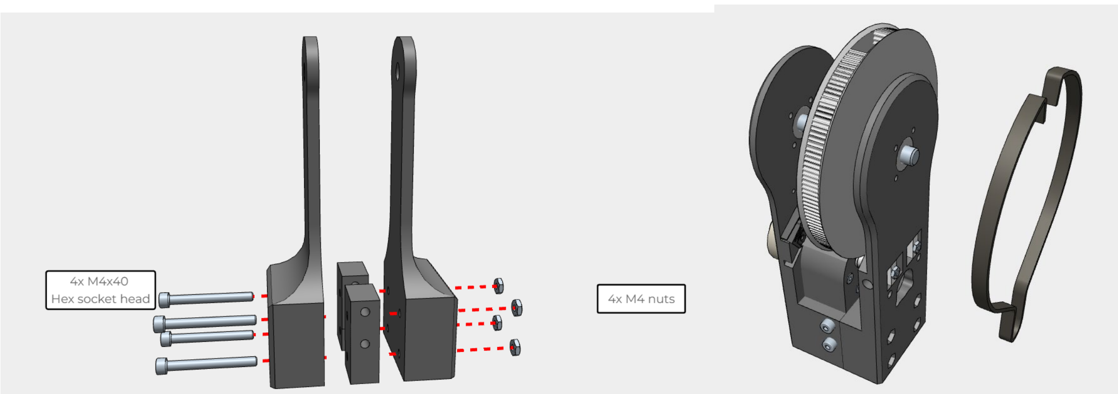

Figure 3.3. Disassembly instruction of the robotic arm, available at [42]

In robotic grippers used as haptic devices there are two main ways for control. Impedance control aim to steer the position by reading the motor force. Admittance control aim to control the force of the device by adjusting the position. This two are integrated as methods and can be used directly, By the use of the low level libaries these control codes may also be created by the user. A descriptive block diagram of the two control loops is presented in Figure 3.4.

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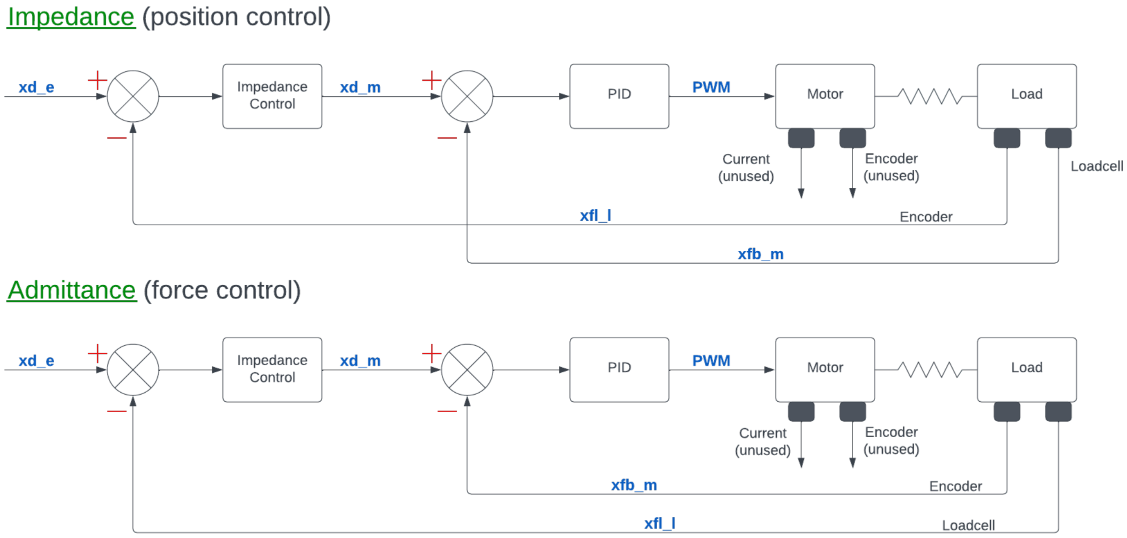

Figure 3.4. Control structure of the robotic haptic arm [1]

The software was built to be as modular as possible, aiming to ensure the easy operation of the robotic arm for users with varying programming backgrounds. The course is designed to cater to students with minimal to no prior experience in programming and control theory while also providing the opportunity for experienced personnel to conduct advanced control theory testing. For less experienced users, the steering library can be used, requiring adjustments only to control factor values. More experienced users have the option to build the control part themselves for implementing alternative steering methods. The basic libraries for data collection can be adapted and modified by experienced users to achieve optimal control, higher precision, and further system development.

The software comprises five classes. The AS5600 library, provided by Seed-Studio, facilitates the easy retrieval of data from the absolute magnetic encoder. Additionally, three low-level classes—PID, pwmMotor, and HapticSensor—are dedicated to data retrieval and the hard-coded control of the haptic arm. The final library, HapticArm, offers a variety of control methods based on control theory, utilizing the aforementioned classes for arm control. More details are available in [1].

The parts of the robot arm were 3D printed using the Fused Filament Fabrication technology, of PLA material. Using standard nuts and bolts, springs and other elements, mechanical part and actuators were assembled. Using Arduino, sensors and other electronic components, the electronic part was assembled. The result is presented in Figure 3.5. Total of 4 arms were manufactured and successfully launched.

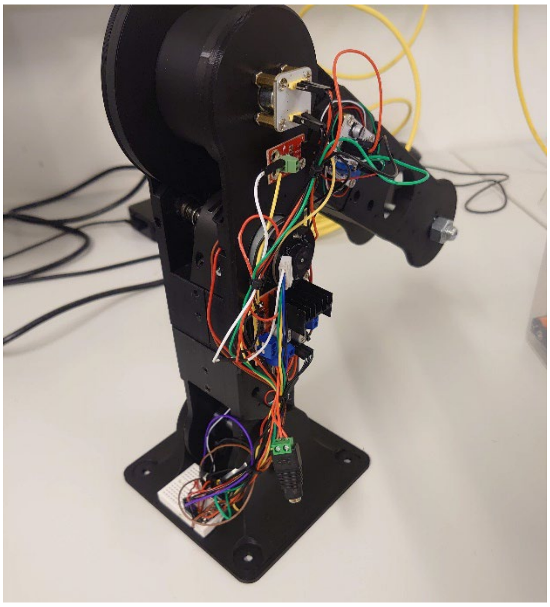

Figure 3.5. Assembled robotic arm made of 3D printed components [1]

Testing of the arm was also realized, checking correctness of movement and functioning as a haptic device. Some of its results can be found in a film, available under link [42] (Figure 3.6).

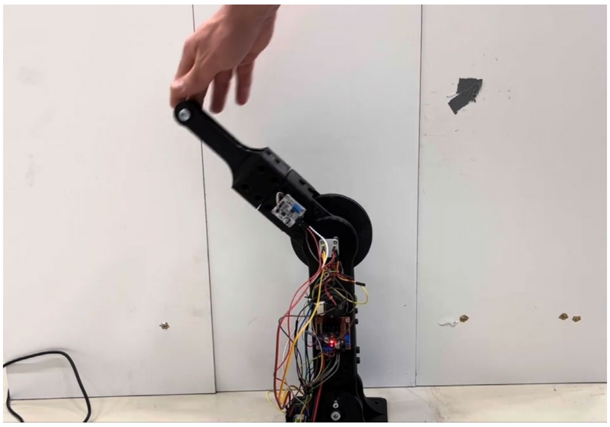

Figure 3.6. Haptic arm tests [42]

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4. Summary

In this case study, it was presented how the high-performance materials and 3D printing technologies like Fused Filament Fabrication (FFF) or Polyjet technology can be used to produce an exemplary biomechatronic device – part of a robotic gripper.

In terms of CAE analysis, the results obtained from finite element simulations, showed that each of the analyzed materials (PET-G, PEKK and MED 857 (DraftWhite) exhibited a consistent, incremental rise in stress, reflecting their escalating response to enhanced loading. This information has been considered crucial as it signifies the distinct mechanical resilience and capabilities of PET-G, PEKK-A, and MED 857 (DraftWhite) materials, thereby aiding in the informed selection of materials for specific load-bearing applications in robotic tooltips. The observed trends underscore the heightened stress tolerance of PEKK-A and MED 857 (DraftWhite) materials as compared to PET-G, influencing their preference in high-performance applications.

Based on results that were reached through mechanical testing experiments which were in close correlation with the ones reached through CAE analyses that were realized, it was possible to determine that PEKK, despite its superior performance compared to PET-G, exhibited brittle fracture characteristics, snapping suddenly under load, contrary to the more plastic deformation that has been observed in case of other tested materials like PET-G. The resilience of MED 857 (DraftWhite) markedly overshadowed others, supporting loads over 50% higher than PEKK and showcasing the least susceptibility to fracturing, attributing to its monolithic infill and stronger inter-layer connections from a distinct layer deposition method.

An interesting divergence between experimental and declared mechanical strengths was noted, particularly in the case of PET-G and MED 857 (DraftWhite) materials. While PEKK's experimental and declared values aligned closely, PET-G's experimental strength was half the declared value, and MED 857 (DraftWhite) exceeded its declared strength by almost 30%, signaling possible simplifications in stress calculations or the need for further diversified geometrical testing to ascertain the material's mechanical characteristics comprehensively.

In terms of 3D printing processes, crucial insights into the practicalities and challenges of each method have been provided. FFF manufacturing with PET-G and PEKK materials went seamlessly; producing parts with acceptable accuracy and no major errors, with a noted staircase effect and surface roughness in case of PET-G material. PEKK, while offering quality outputs was notably time-intensive and costly, making it a less feasible choice for regular production. The process demands prolonged layer deposition and material preparation time, leading to significant production delays in the manufacturing process. In contrast, the PolyJet process offers enhanced efficiency, yielding smooth and highly accurate parts, demonstrating its superiority in achieving detailed geometrical representation and fine layer thickness. This precision, however, comes at a steep cost. Despite its shorter manufacturing time, the high purchase and operational costs of the PolyJet machine make it the most expensive among the tested processes, presenting a barrier for its adoption in regular production of robotic parts. Furthermore, the PolyJet process results in substantial material consumption and wasting materials during the print. This, coupled with the creation of monolithic, heavier parts, underscores the limitations of this technology, despite its evident advantages in precision and finish.

In a cost and time-effective analysis, while all processes deliver satisfactory results in terms of stability and accuracy, the financial and time investment required for PEKK and PolyJet processes does not align with their output benefits for regular production of robotic arm parts. The utilization of these high-performance processes would only be judicious if specific, advanced material properties are imperative for the application, emphasizing the need for a balanced consideration of cost, time, and material performance in selecting the suitable manufacturing processIn the further studies, it would be worth performing other tests on high-performance materials, such as fatigue tests, tests of chemical and temperature resistance, dimensional accuracy studies and others. Also, a second direction of studies should include producing actual biomechatronic devices (such as orthoses or prostheses) and testing their use with real patients, to provide more answers about practical possibilities of using the current generation of 3D printing technologies in current trend with the new types of materials that are expanding and occurring on the market.

Important note: Case study has been submitted for publishing of a joint article in Frontiers in Materials journal. There are sections related to Finite Element Analyses, Scanning Electron Microscopy / FTIR analyses / mechanical testing which will be added as soon as the submitted article to Frontiers in Materials journal will be published (the article is expected to be published in December 2023)

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