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ENHANCING THE DURABILITY OF ROBOTIC ARM USING COMPOSITE MATERIALS AND ADDITIVE MANUFACTURING IN HARSH ENVIRONMENTAL CONDITIONS

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Abstract. *Despite the harsh environmental conditions, such as strong winds, radiation exposure and frequent forest fires, pose serious challenges for the reliable operation of robotic systems. Despite growing interest in robotics for disaster relief and hazardous operations, the durability of additively manufactured components under such stresses remains insufficiently explored. This study investigates the use of composite materials and additive manufacturing techniques to improve the performance of robotic manipulators in harsh conditions. A modular rover equipped with a robotic arm made entirely of composite elements was developed and tested. The research focused on evaluating the structural reliability of PETG plastic and carbon fiber in terms of thermal exposure, static load, and radiation resistance. The study also presented a gesture-controlled interface for remote control and produced a functional prototype. The results of the study provide new insights into material selection and design strategies for sustainable robotic systems, contributing to the development of sustainable robotics in harsh environmental conditions.*

Keywords: Computer-Aided Design, Printed Circuit Board, Computer-Aided Manufacturing, Computer-Aided Engineering, Telecommunications Relay Service, Fused Deposition Modeling.

1. Introduction

Robotic systems are increasingly being used in hazardous and extreme conditions, including disaster zones, forest fire areas and regions with elevated radiation levels. Applications range from nuclear waste cleanup to firefighting support and contaminated site investigation. However, one of the main challenges is ensuring the durability of robotic components manufactured using additive manufacturing technologies. Polymers commonly used in 3D printing, such as PLA or ABS, have limitations when exposed to high temperatures or ionizing radiation [1-3]. Consequently, the search for suitable materials and design solutions for robust robotic manipulators remains an open question for research.

Kazakhstan is a unique testing ground for such technologies. The eastern regions of the country, which were severely affected by more than 460 nuclear tests during the Soviet era, are still exposed to high levels of radiation. In addition, large-scale forest fires in 2023, more than 116,000 hectares of forest were destroyed, highlight the urgent need for robotic systems capable of operating in extreme natural conditions. These challenges make the development of robust, affordable and adaptable robotic solutions particularly relevant at both the regional and global levels.

This study investigates the possibility of integrating composite materials and additive manufacturing to increase the strength of robotic manipulators designed to operate in conditions of radiation exposure and high temperatures. PETG was chosen as the polymer due to its superior resistance to gamma radiation compared to PLA, ABS and carbon composites were chosen for their high thermal stability and mechanical strength [4-6].

The novelty of this work lies in the combination of mechanical and thermal modeling with prototype development, which bridges the gap between material characteristics and functional robot design. Specific objectives:

- To evaluate the resistance of selected materials printed on a 3D printer of static and thermal loads;
- To design and assemble a modular robotic manipulator integrated with a gesture control interface;
- To manufacture and test a functional prototype suitable for use in hazardous environments

By addressing these challenges, this research contributes to the growing body of knowledge on sustainable robotic systems and provides practical insights for the use of composite based robotic manipulators in extreme operating conditions.

2. Methods

2.1 CAD and Simulation Framework

Autodesk Fusion was used as the primary platform for design and simulation to evaluate the strength of potential materials under mechanical and thermal loads. This software combined CAD, CAM and CAE tools, enabling iterative development from geometry design to mechanical validation.

The analysis focused on the servo motor mount, gripper and structural joints of the robotic arm, as these areas are subject to the highest static and thermal loads during operation. CAD models were created with parametric constraints, allowing for rapid changes to geometry and material properties during optimization.

Static Structural Analysis. Static structural analysis was performed to evaluate the ability of key components of the robotic arm, specifically the servo motor mount and gripper claws, to withstand operational loads under stationary conditions. In Fusion 360, the material properties (modulus of elasticity, yield strength and safety factor) were determined for PLA, ABS, ASA and PETG, which are among the most common polymers used in fused deposition modeling (FDM). As shown in Figure 1, boundary conditions were assigned to the locations of bolts and screws of the main platform of robotic arm, and forces up to 1000N were applied to simulate gripping and torque transmission loads. Fusion 360 generated a finite element mesh and calculated stress and displacement fields to identify the area's most susceptible to failure.

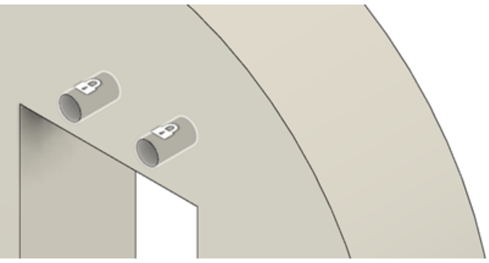
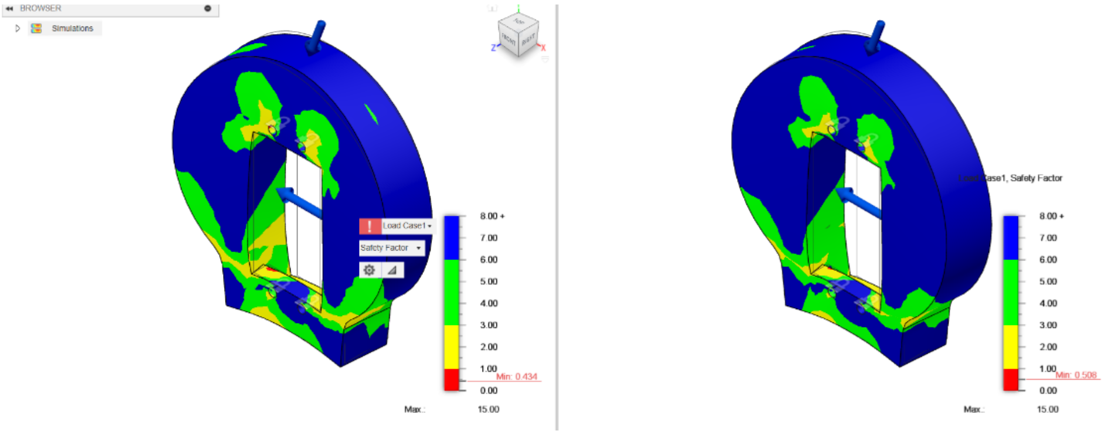


Fig.1. Boundary conditions

As can be seen in Figure 2, PLA plastic (a) demonstrated the highest safety factor under static loading of 1000 Newtons (the minimum result is about 0.5) than PET plastic (b), which has a result of about 0.44. Although PLA appeared to be more robust under static conditions, this did not account for thermal or radiation effects, which are critical for the intended application of the robotic arm. Therefore, additional analyses were required.

Thermal Stress Analysis. Thermal simulations were performed taking into account the effects of elevated ambient temperatures, which can exceed 200°C in forest fire conditions. The main focus was again on the servomotor mountings and structural connections, as these components are subjected to both thermal and mechanical stresses during operation.

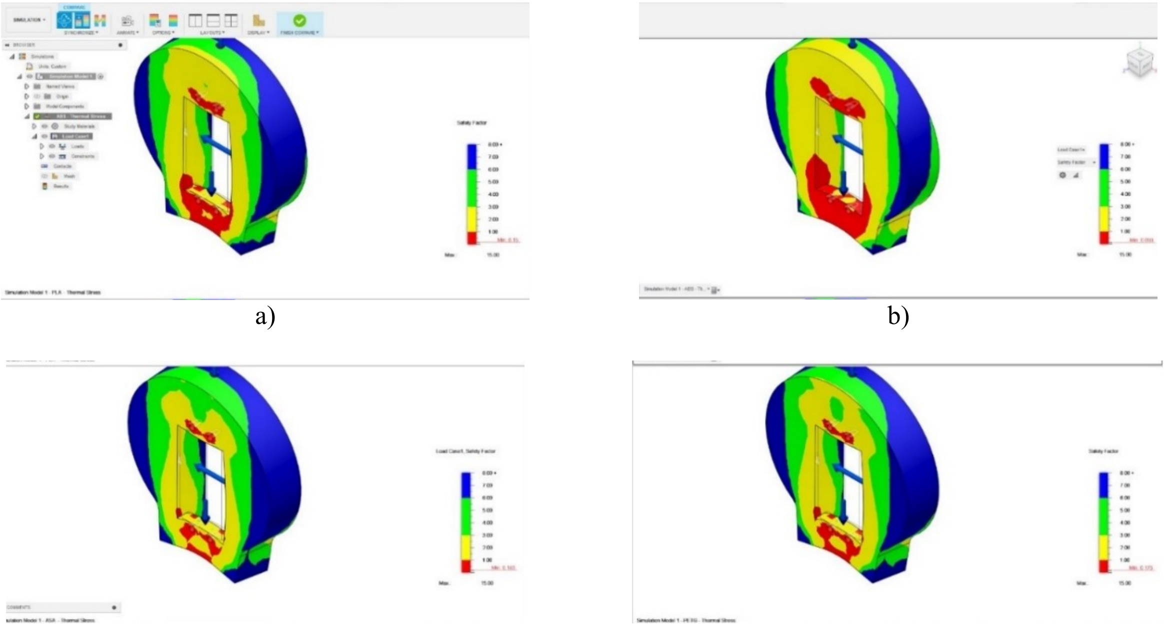
Material parameters such as thermal conductivity, thermal expansion coefficient and heat capacity were included in the model. Boundary conditions simulated heat transfer from the motor housing and convection from the surrounding air.



a) PLA b) PET

Fig.2. Difference of PLA and PET plastics

Combining Static and Thermal Analysis. In many cases, robotic components experience both mechanical and thermal loads simultaneously. Coupled thermal and structural analysis to evaluate the combined effects of these loads were performed. This analysis provides a more realistic assessment of component performance and helps identify potential failure modes. As shown in Figure 3, after a load of 100 newtons on the servo torque sides, and an ambient temperature of 200°C, ASA plastic (c) achieved the best result with a minimum safety factor of 0.183 with minimal critical zones, while PETG plastic (d) reached a comparable level 0.175 at significantly lower material cost. PLA shower only moderate resistance 0.15, with a larger vulnerable region, and ABS performed worst 0.099, failing in most of the tested areas.



a) b) c) d)

Fig.3. a) PLA, b) ABS, c) ASA and d) PETG under thermal stress conditions

These results confirmed that PETG represents a practical compromise, although not the strongest material in static testing, it provides sufficient load-bearing capacity and acceptable thermal resistance, while also being cost-effective and well suited for additive manufacturing.

3. Iteration and Optimization

The simulation results served as the basis for iterative improvements to the robotic arm design. Based on an analysis of static and thermal loads, the CAD geometry was adjusted to reinforce vulnerable areas such as servo mounts and grippers. Wall thickness, rib placement, and fill density were modified to maintain a safety factor above 0.15 under combined mechanical and thermal loads while minimizing material consumption and overall weight. Fusion 360 generative design tools were used to explore alternative configurations, providing geometry suggestions that balanced stiffness and mass efficiency. Several iterations demonstrated that even minor changes in rib geometry and layer orientation could reduce peak stress concentrations by more than 10% while remaining printable within standard fused deposition modeling parameters.

Thus, the iterative process not only improved the reliability of individual components, but also confirmed the choice of PETG as the primary polymer for the prototype. Although PLA demonstrated excellent static strength, its reduced heat resistance and brittleness under cyclic temperature changes limited its practical applicability. PETG, reinforced with optimized geometric shapes, provided the best compromise between strength, manufacturability and cost-effectiveness.

4. Academic Context

The suitability of components printed on a 3D printer for use in harsh conditions is determined both by internal properties of the materials used and by the external factors to which they are exposed. Previous studies show that polymers commonly used in FDM technology exhibit significant differences in their response to extreme conditions. For example, ABS is often preferred over PLA because of its comparatively higher resistance to radiation. However, PETG has been shown to outperform both ABS and PLA, retaining greater mechanical strength and plasticity after exposure to high-intensity gamma radiation [7-8]. These results indicate that PETG is a promising candidate for use in robotics in radiation-exposed environments.

In addition to radiation resistance, thermal stability is a critical factor for robotic systems designed to operate at elevated temperatures, such as those encountered in forest fires. Carbon composite materials have been extensively studied for their mechanical and thermal properties. Their high strength-to-weight ratio makes them attractive for use in lightweight structures, and their fire resistance is due to the formation of a protective carbon layer that reduces the heat release rate to a constant value of approximately 60 kW/m2 [9-10]. As a result, carbon fiber-reinforced composited can withstand temperatures exceeding 2000°C, ensuring structural integrity even under extreme thermal conditions [11].

Along with material characteristics, the choice of control strategy plays a decisive role in the effectiveness of robotic systems operating in complex environments. Traditional joystick interfaces are still widely used due to their reliability and simplicity, but they often lack flexibility and intuitiveness. Therefore, gesture-based control methods are attracting increasing interest. Such systems use cameras or sensor gloves to capture hand movements and translate them into corresponding robot actions [12]. A particularly promising approach is the use of strain-resistant sensors (TSR), which function by detecting changes in electrical resistance when bent [13]. These sensors provide continuous feedback corresponding to finger movements and are therefore well suited for intuitive human-robot interaction. For example, as shown in Figure 4 and Table 1, the resistance of a flexible sensor increases from approximately 30k Ohms in the straight position to approximately 70-80 Ohms when bent at 120° [14].

Overall, the analyzed studies show that PETG has superior radiation resistance, carbon composites provide exceptional thermal stability, and gesture-based TRS interfaces improve operator interaction with robotic systems. These considerations form the scientific basis for the present study, in which elastic materials and advanced control strategies are integrated into the design of a robotic manipulator intended for operation in extreme conditions.

5. Assemble

3D parts. The assembly of the manipulator began with the design of the end effector, which is a critical component for interacting with the environment. Various gripper concepts were evaluated, including angular jaw grippers, finger-based grippers, and parallel jaw grippers. Although angular and finger grippers have advantages when working with non-standard or fragile objects, their complexity and reduced gripping force did not meet the project's goal of developing on affordable and reliable prototype.

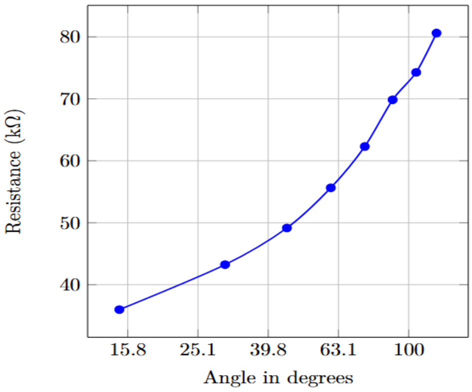


Fig.4. Dependence of the volt-ampere characteristics of a resistor on the degree of its bending.

Table 1: Angle versus Resistance

Angle [degrees]	Resistance [kΩ]
0	31.23
15	35.98
30	43.24
45	49.16
60	55.64
75	62.31
90	69.85
105	74.28
120	80.62

For this reason, a parallel gripper with toothed jaws was selected as the most suitable configuration, combining simplicity, versatility and reliability. The jaws were designed with a double gear transmission connected to a servomotor, which ensured synchronized movement in opposite directions. This design ensured constant gripping force and improved contact with objects, as shown in figure 5. The manipulator design was based on a three-coordinate system to provide sufficient freedom for practical tasks while maintaining the compactness of the overall design. Servo motors were used as drives because of their low cost, ease of control and compatibility with the proposed gesture-based interface. The base of the manipulator was designed as a large bearing with an internal cavity for electronic components, driven by a stepper motor to provide rotation. The design philosophy emphasized the balance between functionality and manufacturability, enabling the manipulator to be manufactured using additive technologies and assembled from readily available components.

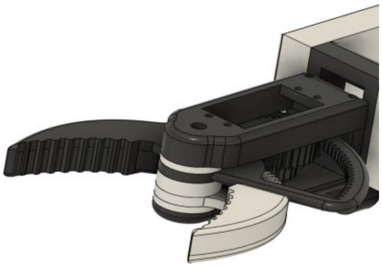
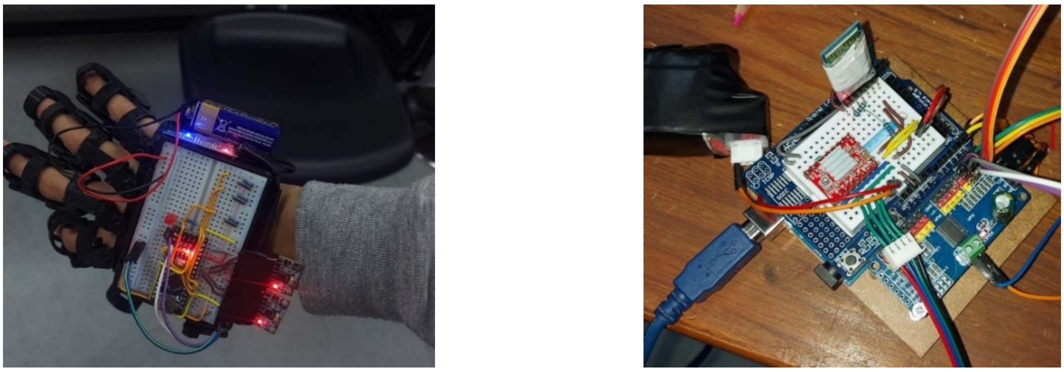


Fig.5. Crab type robotic arm

6. Electronics

The electronic subsystem was developed to ensure smooth interaction between the gesture-controlled glove and the robotic manipulator. As shown in Figure 6 (a), the glove is equipped with several sensors and microcontrollers that record the user’s actions and transmit control commands via wireless communication.



a) b)

Fig.6. a) Prototype of robotic glove and b) mainboard made on a breadboard

The glove's central processors are an Arduino Nano Rev3, which collects and processes raw data from the sensors and then transmits control signals via an HC-05 Bluetooth module. This wireless connection provides a reliable link between the glove and the manipulator, ensuring real-time responsiveness. Two MPU6050 inertial measurement units (IMUs) were built into the glove to collect acceleration and angular velocity data, allowing for accurate tracking of hand orientation. In parallel, three flexible sensors were installed along the fingers to measure bending angles, providing information about grip strength and finger position. Together, these sensors enabled intuitive control of the manipulator's joints and gripper using gestures. Initially, a breadboard was used for prototyping and rapid component integration, as shown in Figure 6 (b).

The sequence of operations included collecting signals from the sensors, analog-to-digital conversion using Arduino, filtering and processing the data, and then transmitting it to the manipulator control board, schematic view of the robotic glove is presented in Fig.7.

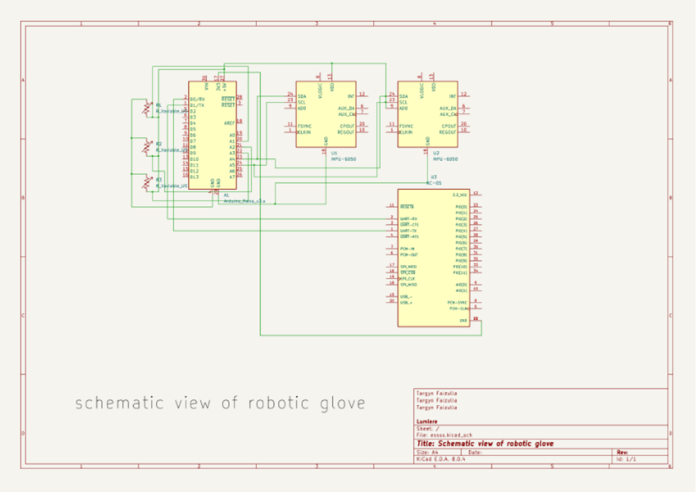


Fig.7. Schematic view of robotic glove

This represents a prototype of the electronics designed to control the manipulator. The board integrates key components that facilitate interaction between the controlling device (the glove mentioned earlier) and the mechanical parts of the manipulator, as shown in Figure 8.

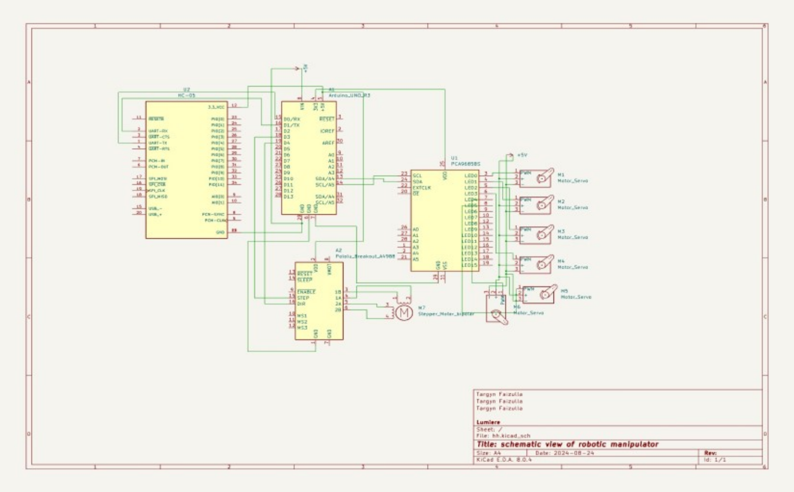


Fig.8. Schematic view of robotic manipulator

Key components and their functions include the Arduino Uno, which acts as the "brain" of the system, processing data from other components and sending commands to the manipulator's actuators:

– the Bluetooth module, which provides wireless communication between the controlling device (glove) and the manipulator, allowing commands from the glove to be transmitted to the Arduino Uno;

– the A4988 driver, designed to control stepper motors, likely used for controlling the manipulator's servos to ensure precise positioning;

– the PCA9685, a 16-channel 12-bit servo/PWM driver, used to control servos, providing smooth movement of the manipulator's joints; six servos, which are the actuators of the manipulator, driven by the PCA9685 driver to move the joints and grasp objects; and the breadboard, which is used for temporarily connecting components and facilitating the assembly and testing of the prototype.

The operation principle involves receiving commands through the Bluetooth module, which sends commands from the controlling device (glove) to the Arduino Uno. The Arduino Uno processes these commands to determine the necessary actions for the manipulator. It then sends signals to the PCA9685 driver, which controls the servos. The servos move the manipulator's joints, performing the required actions. The system is designed to control a manipulator with multiple degrees of freedom, allowing commands from the glove to control the position of each joint and the gripping force, enabling the manipulator to perform various tasks such as grasping and moving objects.

The integration of these components enabled the manipulator to respond to user gestures with several degrees of the freedom, converting natural hand movements into robot actions. This architecture not only demonstrated the possibility of gesture control in inexpensive robotic systems, but also laid the foundation for further adaptation of the system to harsh operating conditions, which is in line with the overall research goal of developing fault-tolerant robotic technologies.

7. Testing

The testing phase focused on verifying the power requirements and operational stability of the manipulator under various load conditions. Since the manipulator uses multiple servo motors for drive, ensuring sufficient power supply was identified as a critical step in system integration. Insufficient current supply can lead to voltage drops, uneven torque distribution or servo malfunction, which can affect the reliability of the robotic arm in practical applications.

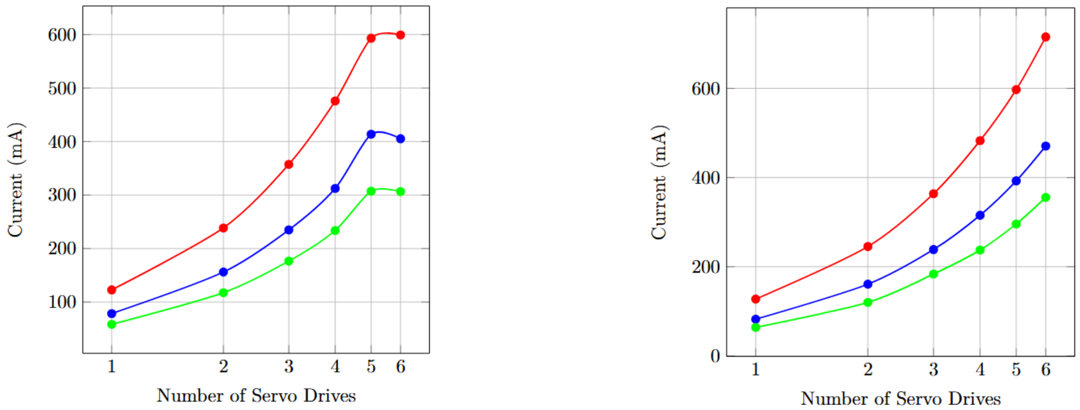
Initial experiments involved powering the system form nickel batteries with a total output of 5V. Current consumption was measured for different numbers of active servomotors, as shown in Figure 9 (a) and summarized in Table 2. The results showed that as the number of connected servos increased, the batteries could not provide sufficient current, resulting in significant voltage drops. These drops were particularly noticeable in the first servo drives in the chain, which consumed disproportionately high currents. To overcome this limitation, the system was reconfigured using a regulated power supply and, alternatively, lithium-ion batteries with higher output power. Under these conditions, the current supply was significantly improved, and no voltage drops were observed on the servo drives. The stabilized results are shown in Figure 9 (b) and Table 3, which demonstrate a stable current distribution.

Table 2: Current Measurements for Different Numbers of Servo Drives without power supply.

Number of Servo Drives	Average Current [mA]	Maximum Current [mA]	Minimum Current [mA]
1	78.53	122.77	58.34
2	156.12	238.56	117.63
3	234.87	357.43	176.54
4	312.45	475.89	233.78
5	413.76	593.12	307.25
6	405.34	599.29	306.45

Table 3. Current Measurements for Different Numbers of Servo Drives with power supply.

Number of Servo Drives	Average Current [mA]	Maximum Current [mA]	Minimum Current [mA]
1	82.23	127.45	63.97
2	160.87	245.31	120.15
3	238.54	363.78	183.66
4	315.46	482.89	237.43
5	392.57	597.22	295.88
6	470.68	715.33	355.49



a)   b)

Fig.9. a) Current vs Number of Servo Drives without power supply and b) Current vs Number of Servo Drives with power supply, where —●— is Average Current, —●— Maximum Current, —●— Minimum Current.

After ensuring a stable power supply, the manipulator successfully processed input signals from the gesture-controlled glove and converted them into coordinated servo movements. The prototype robotic arm in working condition is shown in Figure 10. These results confirmed the feasibility of the proposed electronic and mechanical integration and reinforced the importance of reliable power management for ensuring reliable operation.

Fig.10. Robotic arm

This testing phase laid the foundation for future developments in which the manipulator will be integrated with a mobile rover platform designed to operate in extreme conditions. This improvement will expand the capabilities of the system, allowing it to be used in hazardous situations such as search and rescue operations or disaster relief.

8. Conclusion

This study examined the problem of developing robotic manipulators capable of operating in extreme environmental conditions, such as those found in Kazakhstan, where high radiation exposure and frequent fires create significant obstacles for traditional robotic systems. The aim of the study was to evaluate the characteristics of materials under radiation, thermal and static loads, as well as to use the data obtained in the design and manufacture of a functional manipulator prototype.

The results of modeling and analysis of materials revealed the advantages of both PETG plastic and carbon composite materials. PETG demonstrated good plasticity and strength retention under simulated radiation exposure, making it a promising material for the manufacture of radiation-resistant components. Similarly, carbon composites demonstrated high thermal stability, forming a protective char layer when exposed to elevated temperatures, confirming their suitability for use in fire-hazardous environments. Simulation of static and thermal loads confirmed the mechanical acceptability of these materials, assembly and testing of the prototype confirmed the possibility of integrating gesture control electronics and mechanical design.

Although experimental testing of radiation and fire resistance was not conducted as part of the current project, the combination of simulation and prototyping results has created a solid foundation for future experimental research. The results obtained underscore the need to continue this work through controlled tests for exposure to radiation and high temperatures, as well as long-term assessment of strength under operating conditions.

In terms of practical results, the successful manufacture and testing of a gesture-controlled robotic arm demonstrated the potential for integrating composite materials, additive manufacturing, and intuitive control systems. This serves as proof of concept for the broader goal of developing mobile robotic platforms capable of performing tasks in hazardous environments, such as disaster relief and contaminated site investigation.

The present work is limited to simulation and protype-level validation. Direct experimental validation under radiation and fire exposure is essential and will form the next stage of this research.

In conclusion, this study contributes to the field of sustainable robotics by demonstrating how material selection, CAD simulation and low-cost electronic integration can collectively contribute to improving the design of robotic manipulators for harsh operating conditions. Despite limitations in experimentally verifying environmental resistance, the results provide practical insights and open avenues for further research. Future work should focus on experimental testing of materials under radiation and fire conditions, optimization of control systems, and development of a rover platform to extend the applicability of the manipulator in real-world extreme scenarios.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Askaruly R.: Conceptualization, Methodology, Validation, Investigation, Writing - Review & Editing; **Faizulla.T.:** Methodology, Resources, Investigation, Software, Writing – Original Draft; **Abylkanov M.:** Data Curation, Software; **Syzdykov A.B.:** Writing Review & Editing, Supervision, Funding acquisition; **Sakhanov K.:** Writing Review & Editing, Funding acquisition.The final manuscript was read and approved by all authors.

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