ABSTRACT

Brushless Direct Current (BLDC) actuators are recognized for their combined torque capabilities, precision control, and operational versatility, especially in regards to their smaller size. Actuators of this caliber are commonly implemented in high-performance industrial robotic arms, development in exoskeletal technologies, and quadrupedal robotic platforms. Professionally-developed brushless actuators available in the commercial sector deliver in their performance, however at a significant monetary expense. Our aim is to produce cost-efficient robotic actuators which are capable of replicating the design specifications and performance of commercial models. Our research focuses on the understanding and validation of fundamental principles of how brushless motors operate, and how the manipulation of respected variables can be combined to produce an optimized, robotic actuator design. The design and manufacturing process for each actuator prototype for this research revolves around a modular approach, where specific components can be repaired or replaced without compromising the structural integrity or robustness of the system. Each prototype utilizes a unique rotor and embedded planetary gearbox design as a mechanical means for increasing the potential torque output. We believe that the results from our project can make cost-effective actuators available to the robotics community for advancing legged-locomotion robotic research.

Keywords: Motor Design, BLDC Actuators, Robotics.

1. Introduction

Significant time and effort have contributed to the research and development of various robotic applications, which require a high degree of precision and performance efficiency. These include, but are not limited to, automated machining services [1], autonomous quadruped robots [2] able to navigate and perform tasks across different environments, exoskeletal systems and prosthesis for therapeutic and work-enhancing services [3], and robotic arms which operate over multiple degrees of freedom [4]. Across each of these respected applications, they each retain their precise operation from their implemented brushless actuators. Majority of these actuators are designed specifically for their intended applications; however, they all follow the same principles and take the same variables into consideration to maximize their performance.

With brushless actuators capable of this degree of precision, they are the perfect choice in developing other areas of robotics research. Precision and compliance allow machinery or robotic systems to interact with their environment and not only be able to make immediate corrections, but also provide the opportunity to perform calculations and make predictions on how they continue to navigate. The application of commercially available brushless actuators are determined by a few key variables, including but not limited to speed, weight, and torque density. These variables apply towards their rated performance as well as their peak performance. One field of research gaining significant prominence is the development of quadruped robot platforms. One design which provided significant inspiration for this research is the MIT MiniCheetah quadruped robot [5].

Another application for these actuators would be the continued development of industrial-grade robotic arms. Various models can be found amongst manufacturing industries, where they are revolutionizing the process of automating assembly line industries. These robotic arms are required not just to have a high degree of precision, but must also be capable of repeating that precision across hundreds, if not thousands, of command iterations. Additionally, this precision is reflected across different tasks or instructions these robotic arms are assigned to, whether they are performed sequentially or simultaneously. There are many designs of robotic arms tailored to specific and multiple applications. For instance, INNFOS developed its own GLUON modular desktop collaborative robotic arm [6].

Applications for robotic actuators have extended even further to improve the welfare of human health. The demand for precise, high-torque density actuators prevailed in the current development of exoskeletal harnesses for improving the motor functions of the wearer and improving endurance. These would aid workers and laborers required to lift and transport heavy equipment with-
out the need for large machinery. Furthermore, a significant impact of exoskeletal technology is in the medical field, where they provide helpful aid to those undergoing strenuous physical therapy or rehabilitation. They can even serve as a vessel for regaining means of transportation for those who suffer from physical disadvantages like muscular dystrophy or amputees [7]. This is a significant application for high performance robotic actuators, where the response time would need to keep up with the muscular reflexes of the wearer, output a high torque density for withstanding the weight of the wearer and any additional weight they may be carrying, and ultimately provide a mechanical advantage to any task performed.

This research encapsulates the physical science, variable considerations, and design process for a new cost-efficient robotic actuator, capable of replicating the design and performance specifications of similar actuators sold commercially (Fig. 1). Multiple prototypes were developed utilizing 3D printing for the structural and mechanical design, as well as purchased stock components for the electronics and electromechanical power conversion. These actuators have a modular assembly for ease of inspection and repair, can be modified to best suit their applications at little monetary cost, and can incorporate multiple combinations of variables to best fit the needs of the consumer. For the overall design, the prototype actuators feature a printed planetary gearbox reduction, hand-wound electromagnetic stator cores with various winding configurations, complementary configurations of permanent magnets within the rotor, and a compact assembly to maximize the power output to weight ratio.

2. Modeling and Prototyping

Multiple design iterations of the actuator prototype were printed and tested before the final testing prototype design was developed. Much of the background theory and physical understanding of how BLDC motors operated was conducted simultaneously with the design process. This impacted both the electrical and mechanical approach for this design, and why specific design qualities were implemented in particular fashions. Both the planetary and rotor sub-assemblies, and how they interacted with each other, proved to be higher in priority, since they were both constrained by the dimensions of the stator core, rotor yoke, and permanent magnets. Once the dimensions for these components were roughly estimated, it became easier to source the necessary bearings and external hardware for the assembly process.

A big design consideration for the planetary subassembly was the potential gear reductions which were able to fit within the inner diameter of the stator core. This constraint directly impacted the number of teeth within the sun gear the most, which then affected the possible planetary and sun gear configurations. The reduction was directly proportional to the ratio of the ring and sun gear teeth. Once the number of teeth for the ring gear was determined in regards to the stator core diameter (60 teeth maximum), the reduction could then be controlled by the number of teeth implemented to the sun gear, which would then determine the number of teeth for the planetary gears. Choosing 12 teeth for the sun gear appeared to be the best choice for multiple reasons. When comparing to commercial actuators with similar stator pole numbers, a 6:1 planetary reduction was the most common, and implementing this reduction to the prototype would make it more comparable during the testing procedures and defining the specifications. Furthermore, the diameter of the sun gear is proportional to the number of teeth it can accommodate, and inversely proportional to the potential diameter of the planetary gears and its number of teeth within the fixed-dimensioned ring gear. A design goal for the planetary subassembly was for it to be compact and robust, and to both limit and isolate any points of potential failure. With this goal, planetary subassembly, as well as the ring gear, are aimed to be printed as structurally durable as possible. For consistency, the pitch of the gear teeth was set to a 0.8 modulus for all gears used in the planetary subassembly. In terms of the height of the planetary subassembly, the only direct constraints were the overall height and weight of the actuator, which were chosen based on actuators commercially available. Additionally, having a taller planetary subassembly would impact the dimensions of the conjoined rotor subassembly, potentially impacting its moment of inertia and consequently making it more difficult to control. The initial concept for the planetary subassembly accommodated only one support bearing, that is the large planetary output bearing.

Aside from the lack of structural support, the next realization was the fact that all gears would be 3D printed, and any mechanism involving plastic-on-plastic moving components would need lubrication. This initial concept left the inside of the planetary subassembly exposed, where lubrication could seep out to other components and debris could enter in and affect performance. The dimensions of the carrier remained rather unchanged, however the mounting column that encompassed the ring gear was extruded upward. The inclusion of a second bearing, like the one located on the planetary output surface, on the opposite side of the carrier would
not only add to the structural stability, but aid in making the entire gearbox sealed. The second concept of the subassembly incorporates this second bearing. To maintain a compact assembly, the next biggest design consideration was how this secondary support bearing would also join the rotor. The inner diameter of the bearing was press fitted onto the carrier, which would leave the outer diameter free to be fitted onto the bottom surface of the rotor. This was also when design concepts were generated in order to securely bridge the electromechanical movement of the rotor to the planetary subassembly. Some of the component models and corresponding prototypes used in this study are depicted in Figs. 2-4.

3. Finite Element Analysis of Components

The initial actuator prototype was limited by the number of mounting positions. A large reason for this was the primary goal of reducing the overall weight of the actuator, and adding more mounting positions would require additional 3D printer filament and structural support for the printing process. The seven M4 x 0.7 tapped holes located on the front output face of the actuator proved sufficient for the testing process using a dynamic torsion sensor. However, the ease of 3D printing in comparison to machining allows the external structure to be modified in whatever way best fits its intended application, which would include the addition of more mounting points. Factoring in the Young’s Modulus of the PETG plastic, which was programmed into the SOLIDWORKS software at approximately 2.96 x 109 N/m², performing multiple loads on specific actuator components provided an excellent approximation of how well the prototype overall would perform in specific applications.

The first test was performed specifically on the external housing of the actuator, including the endcap and the stator core mount, which was fixed in place by the seven mounting holes and a normal force applied to the front face (Fig. 5). Given the elastic properties of plastic materials, especially when considering the addition of glycol to form the PETG copolymer, it was expected to see high displacement. Most of this displacement occurred in the support flanges that tie the gearbox housing and the outer support wall together. Following the axial loading, another potential area of concern was the applied torsion forces specifically on the ring gear of the stator mount. Since the outer portion of the ring gear was left unsuspended, it experienced the greatest concentration of deformation. This torsion analysis is depicted in Fig. 6. Factoring in the press-fitted stator core around the outer wall and the large bearings from the output face and rotor subassembly, these would improve the structural integrity of the ring gear.

![Figure 6. Torsion Analysis of the Actuator Ring Gear.](image)

Additionally, the stress analysis by applying a bending force to the rotor shaft was performed as well (Fig. 8). The deflection of the shaft can be observed with respect to the concentric reference axis. The maximum stress distribution is divided on the top and bottom of the shaft, with respect to the image orientation. The stresses distributed along the top are due to compression, while the stresses along the bottom are due to stretching. The neutral axis for determining these stresses runs through the center of the shaft, making these tensile and compressive stresses numerically similar in magnitude. While the opposite end of the rotor shaft would be supported by bearings when embedded into the planetary gearbox, the reason for performing this analysis was to highlight the stress concentrations that occur whenever the cross section of the shaft changes in shape. When the output of the actuator is subject to either continuous or cyclic loading, the result would be the non-uniform points of stress like those seen in Fig. 8. When performing under these heavy load conditions for extended periods of time, it will dramatically increase the chances of fracture at any one of the three cross section changes. Furthermore, these stress points, regardless of stretching or compression, will also affect the air gap when the teeth of the sun gear are meshed with the planetary gears. This will cause high concentrations of friction between the gears, impacting the quality and integrity of the teeth over time. Furthermore, the abrasiveness will cause gradual deterioration, increasing the presence of shrapnel within the gearbox and decreasing operational efficiency.

The bending stresses of the rotor shaft were confirmed when performing material tests on a failed prototype. By observing the pro-
Table 1. Unit Cost Per Brushless Actuator Manufactured

<table>
<thead>
<tr>
<th>Part</th>
<th>Cost Per Quantity</th>
<th>Quantity</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total 3D printed parts (supports included)</td>
<td>$21.99/kilogram</td>
<td>~171 grams</td>
<td>~$3.76</td>
</tr>
<tr>
<td>Small bearing</td>
<td>$9.49/10</td>
<td>7</td>
<td>~$6.65</td>
</tr>
<tr>
<td>Flange bearing</td>
<td>$10.49/10</td>
<td>1</td>
<td>~$1.05</td>
</tr>
<tr>
<td>Large bearing</td>
<td>$9.99/4</td>
<td>3</td>
<td>~$7.50</td>
</tr>
<tr>
<td>Copper wire</td>
<td>$15.50/0.5 lb</td>
<td>0.09 lbs</td>
<td>~$5.60</td>
</tr>
<tr>
<td>Stator core</td>
<td>$48.00 ea.</td>
<td>1</td>
<td>$48.00</td>
</tr>
<tr>
<td>Rotor yoke</td>
<td>$29.00 ea.</td>
<td>1</td>
<td>$29.00</td>
</tr>
<tr>
<td>Neodymium magnets</td>
<td>$20.99/100</td>
<td>84</td>
<td>~$17.64</td>
</tr>
<tr>
<td>Magnetic Encoder</td>
<td>$15.75 ea.</td>
<td>1</td>
<td>$15.75</td>
</tr>
<tr>
<td>External hardware</td>
<td>~$5.00</td>
<td>N/A</td>
<td>$5.00</td>
</tr>
</tbody>
</table>

Total Sum: ~$139.95

(T-MOTOR AK80-6) Total Sum: ~$569.90
(MiniCheetah Old Module) Total Sum: ~$115.00

Figure 8. Bending Stress Analysis of Rotor Shaft.

Figure 9. Fracture of Rotor Shaft Due to Bending.

Figure 10. Fracture Points of Planetary Carrier Due to Torsional Loading (Before and After).

totype shaft in Fig. 9, it can be concluded that the stress due to bending forces caused the shaft to fracture at the outermost cross section. This is likely due to the combination of being the smallest cross section in the entire shaft, the comparatively small thickness from the inner and outer radius of the cylinder, and is subject to the highest deflection with respect to its distance away from the fixed surface, that being the bracket mounted to the rotor. Additionally, one prototype of the planetary carrier had also fractured due to torsional loading, causing the three primary support columns to shear off completely from the base. This fracture can be seen in Fig. 10. The primary cause for this component’s failure was due to the length of the metric bolts not being threaded all the way through the support columns and into the base. This can easily be addressed by choosing longer hardware for threading through the columns. However, the planetary carrier, the planetary output, and the internal planetary reduction act as one floating subassembly, while a primary load is applied by the independent rotor shaft. This ultimately means that the fracture of these columns during application performance is unlikely, and longer bolts were not necessary.

With respect to the printed components which were subjected to the forces, the loads applied to the components proved difficult to conclude. The reasons for this would point to the fact that these are components which are printed through fused deposition modeling (FDM) at non-uniform densities, rather than being a solid plastic component. This significantly increases the probability of inconsistencies and imperfections within the print layers, which can augment the chances of failure when applied under various loads. Furthermore, the environment where components are printed, varied in terms of atmospheric temperature, moisture content, and the closed-loop feedback delay for maintaining a constant temperature needed for extruding the filament. For improved print quality, a higher-quality 3D printer operating in a better controlled environment would be required.

4. Cost Analysis

The stator core and the rotor subassembly components used for manufacturing the MiniCheetah actuator were purchased off-the-shelf rather than manufactured in this study. These components are identical in specifications compared to the U8 actuator, also developed by T-MOTOR. These components were priced between $60 and $90, encompassing more than half of the cost of the actuator overall [5]. For the prototype actuator, the stator core had also been
purchased from a supplier, but at only $48. Additionally, rather than purchasing the fully machined and assembled rotor subassembly, the rotor yoke and permanent magnets were purchased separately, leaving the rotor and shaft to be manufactured using 3D printing. By taking this approach, a custom manufactured rotor subassembly for this research was implemented at under $50 each. Another significant cost efficiency was also choosing to print the planetary and ring gears, which helped avoid minimum purchasing quantities from other manufacturers and save on shipping costs. While the actuator could be designed to encompass pre-machined stock gears rather than custom machining, this would have still been at greater expense in comparison to 3D printing the gears. Details of unit Cost per actuator is given in Table 1.

5. Conclusions and Future Work

After the theoretical data had been calculated from the actuator prototypes developed, it was then possible to perform a cost analysis of the implemented components. Overall, the total sum of each actuator came very close to the MiniCheetah Module, and less than a fourth of the total cost of the AK80-6 actuator. This research does not encapsulate the speed and torque tests that were anticipated to occur. There will need to be further research in the dynamics of brushless motors and the necessary variables which govern them. After further investigation, other viable alternatives for 3D printing material would also be considered for strength, durability, and heat resistance testing. This would hopefully allow proper tests to be conducted using external stationary machinery for measuring the actuator specifications, as well as making accurate comparisons to the specifications of actuators available commercially.

Acknowledgments

This work was supported by the University of West Florida (UWF) Office of Undergraduate Research (OUR) Project Award (Award Number: P2122B-077G).

References