6-DOF 3D Printed Robotic Arm Prototype

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***Abstract*— A 6-DOF [1] robotic arm prototype with its links made entirely out of robust 3D printed material, developed for research purposes is presented in this paper. There are three main objectives that have been accomplished with the prototype. One has been to improve the strength-to-weight ratio of the *CrustCrawler* Pro-series robotic arm [2] links. The other to reduce the number of parts to assemble and the third has been cost reduction. This has been accomplished almost entirely by 3D printing. The structural integrity of the newly designed links have been tested by applying both a perpendicular and a torsional force on the links. The result concluded that the 3D printed links were far stiffer than their 6061 T6 brushed aluminium counterparts at a lower weight.**

I. INTRODUCTION

The need for rapid prototyping has become a main factor in accelerating technology. Reduction of both time and cost work in pair when talking about rapid prototyping. Prototypes are crucial when developing a product and being able to test different ideas in practice without resorting to mass production in order to get a good price from manufacturers is a challenge. Being able to manufacture your own prototype at home or at the office, straight from the CAD (Computer-aided design) model is the key to both accelerate the development of a product by receiving and at the same time reduce cost considerably [3]. This is where 3D printers come into the picture. 3D printers have existed since the 1980's, where the first-ever successful 3D printer patent was made public in 1986. Since then, 3D printers have continuously evolved, becoming more efficient and more accurate while prices have fallen considerably. This opens up for many possibilities where everyone can express their creativity much easier.

Companies, schools, universities and start-ups, among others, benefit a lot from 3D printing technology in that they can materialize and test out their ideas or prototypes in a much faster and affordable way.

An interesting area being explored in this paper is the use of 3D printing technology to design, manufacture and build a robotic arm prototype based on a composite material which could in theory produce the required structural links between joints lighter in weight and similar in strength to aluminium. One such material is Onyx [4], developed by Markforged. Onyx is a chopped carbon fiber thermoplastic which provides stiffness, strength, hardness and a nice surface finish. It can be reinforced with continuous carbon fiber, kevlar or fiberglass and achieve a strength a couple of times higher than without.

In robotics there is always a search for compact and high torque motors at a low weight and stiff and strong links that the motors are connected to, also at as low weight as possible. But cost is probably the most important factor when talking about who can be able to get access to a robotic system. Robotic arms are becoming more and more available to everyone due to their continuous reduction in price. Faster and cheaper manufacturing methods that have been developed during the years have helped in reducing price for robot components. Nowadays anyone can manufacture their own products at home using 3D printers and CNC (Computer Numerical Control) machines. But 3D printers are easier to use, make a lot less noise and are easier to clean and maintain than CNC machines, making them highly versatile. Being able to design your own links for a robotic arm and 3D print them from your own desk is a much faster and cheaper process than having to resort to a manufacturer that requires more time spent in communicating the desired product to the manufacturer, waiting for the product to be machined and then waiting for it to be delivered while the cost is much higher. Both the longer time needed to order a custom made robotic link together with the higher cost, results in an even higher cost because time is money.

There are many advantages in reducing weight, assembling time and cost of a robot's structural components, but the main one is reduction in torque requirements. This means that cheaper and lighter motors with lower torque values could be used instead, which results in a further reduction in cost and weight. In order for a robotic arm to move its end-effector from one point in space to another with precision, it needs its links to be as stiff and strong as possible. Any bending or pendulum effect will be a cause for error in achieving its desired position. There are many types or robotic manipulators that can be designed and 3D printed like both cartesian [5] and articulated [6] manipulators.

In this paper, a 6-DOF 3D printed robotic manipulator design will be presented. The manipulator links are 3D printed in onyx material, reinforced with carbon fiber. The robot's stiffness, strength and weight will be compared to a similar design with links made entirely out of 6061 T6 brushed aluminium.

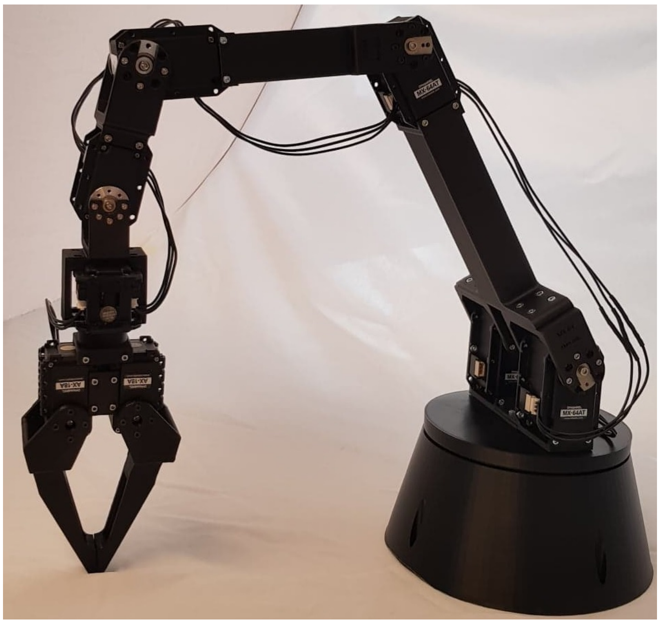

Fig. 1: 6-DOF Robot prototype.

II. BACKGROUND AND RELATED WORK

There are many types of 3D printing methods/processes. They can be grouped in categories like: Vat Photopolymerization, Material Jetting, Binder Jetting, Powder Bed Fusion, Material Extrusion, Direct Energy Deposition [7]. The most widely used method is **Material Extrusion**, also known as Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM) [8]. The reason for this is its wide adaptability, ease of use and low cost. The 3D printers using FFF have simple mechanics and low cost. The filaments used are also low cost, that is why this type of printing is so accessible to everyone. Another 3D printing method growing in popularity because of its fast printing time is the one by deposition of powdered material in layers. An extensive description of how this type of 3D printing works can be found in [3], where they present how they printed a ceramic part from 50 layers of 0.005 inch in thickness.

Among the many types of materials used in 3D printing the most used are Polylactic Acid, known as PLA and Acrylonitrile Butadiene Styrene, known as ABS. PLA is probably the most used material due to its low cost and versatility while ABS comes in second. Although PLA is a good candidate in robot construction in that it satisfies the requirements of being stiff and of high strength, it losses these properties almost completely when exposed to temperatures above 50 degrees Celsius. Another disadvantage of PLA is low durability, making it suitable in the end only for testing out ideas or for hobby applications. ABS on the other hand is not as strong or rigid as PLA but is tougher, lighter and more durable, with a impact resistance of up to four times higher than PLA. It also has the advantage of being more durable and heat resistant than PLA but that also makes it more difficult to print, requiring a higher temperature in order to be extruded through the 3D printer nozzle.

In [9], they reverse engineered the *CrustCrawler* robot arm and tried to reduce its total weight by replacing the aluminium parts constituting the links with 3D printed parts in ABS material. They managed to reduce the weight of the aluminium parts by around 70% on average and the manufacturing cost by around 350% . The performance of the robot's kinematics was improved by 17% for the X-axis and 37% for the Z-axis. They used both CAD and CAE software to develop the parts.

Although ABS seems adequate for building robotic arms, carbon fiber filled nylon is a much better candidate for building strong, stiff, highly durable and both heat and chemical resistant parts. This is the material we have been referring to as **Onyx**. Probably the most important property of this material is that when it is reinforced with carbon fiber threads it has a strength-to-weight ratio higher than 6061 T6 aluminium, which the manufacturer claims. They also claim it is up to 27 times stiffer and up to 24 times stronger than ABS. Details about the testing standards and material properties are listed in [10]. Haddington Dynamics has tested this material on their 3D printed 7-axis robotic arm which they supply to NASA, GoogleX and Toshiba, where they managed to reduce production time, number of parts and obtain a cost-effective and stiff robot with a high precision in movement [11]. While it is nowadays difficult to reduce the cost of motors when talking about higher torque needs when building a robotic system, it is worth starting with reducing the weight of the connecting links between the motors. Reducing the weight of the links translates to reducing torque requirement for the motors.

III. SYSTEM DESIGN

The design for the links has been developed in Fusion 360 by building/extruding material around the servo motors. The 3D models of the motors are made public by the manufacturer and those models were used in the design of the robot. Being able to attach the links to the motors is the first step. Motors used in the robot arm are Dynamixel AX-18A, MX-28 and MX-64 developed by ROBOTIS. They offer very powerful and compact motor solutions for robot applications. The list of their AX and MX series can be seen in Figure 2.

Fig. 2: An overview of the ROBOTIS AX and MX series servo motors.

The next step was to define the length and the shape of the links. The starting point was the links of the *CrustCrawler* robot. The most important factor was that the walls of the links had a closed shape, like a rectangular prism or cylinder and not an open structure like in the *CrustCrawler* robot links, making them susceptible to bending or torsional flexing.

The design of the prototype features easy assemble because of the reduced number of screws compared to the *CrustCrawler* links. The number of screws have been reduced from 172 to 138, while 14 of the 138 screws can be optional, making the final reduction of 48 screws.

The 3D printed links had a lot of material removed on the inside along their height to lower the weight. The links could be further modified in order to reduce the weight even more but because of the way the carbon fiber is inserted, the optimal solution was to cut on the inside and leave the outside in continuous connection between the link end-points. If holes were to be inserted along the width of the links it would prevent the insertion of fiber along the entire height, thus lowering the structural integrity of the links. An internal view of the prototype's link 3 showing the carbon fiber layers is shown in Figure 3.

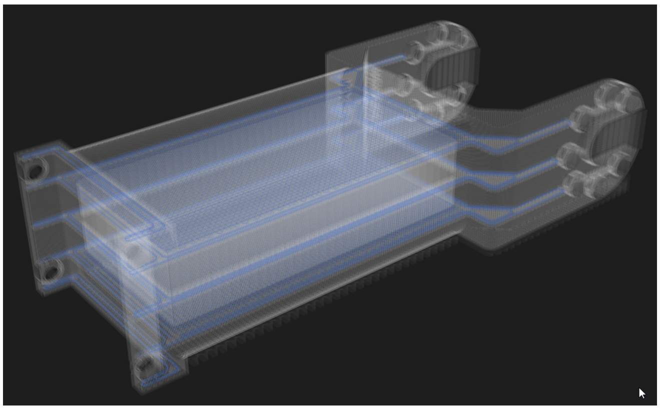

Fig. 3: Part view of the inner layers of a 3D printed Onyx link reinforced with carbon fiber. The blue layers indicate the carbon fiber layers.

The robot base was designed to sustain both radial and axial loads by using an industrial grade taper roller bearing, as shown in Figure 4.

The complete 3D model of the prototype can be seen in Figure 5 and the real robot can be seen in Figure 1.

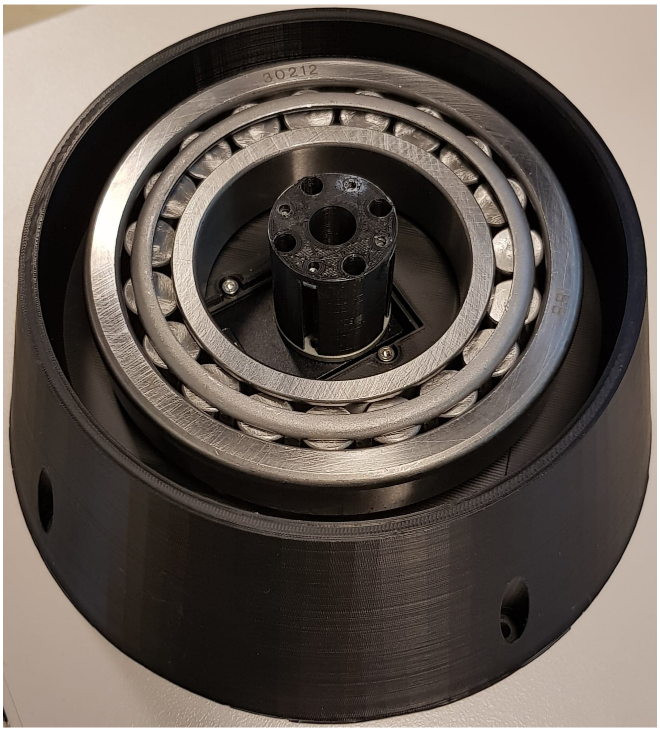

Fig. 4: Robot base construction including a taper roller bearing, a spacer and one MX-64 servo motor.

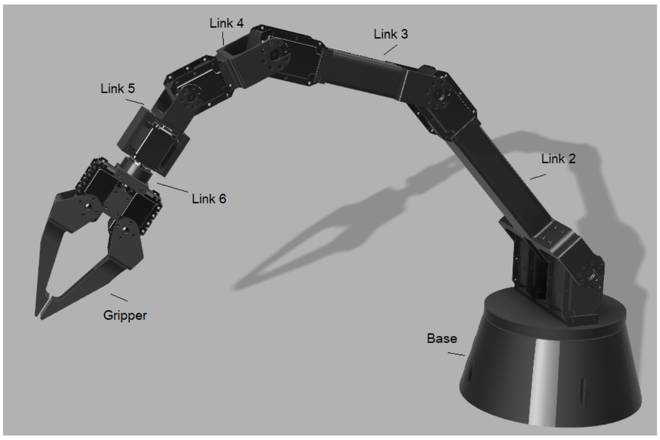

Fig. 5: 3D model of the 6-DOF robot prototype.

IV. EXPERIMENTS AND RESULTS

Because of the lack of Onyx material in the CAD program it was not possible to simulate forces applied on the links. The stiffness was tested by grabbing the end-points of each link and try to manually apply a torsional and perpendicular force from one of the end-points. The test showed an outstanding stiffness were the weakest links"were actually in the servo motor couplings. The construction of the rotating base of the robot prototype was also a success and provided a silent movement compared to the construction of the *CrustCrawler* base together with a more solid support able to withstand a much higher load.

A comparison between the cost and weight of the links for both the robot arm prototype and the *CrustCrawler* robotic arm are presented in tables I and II respectively. The base weight is not factored in the total calculations because it does not affect either the kinematics or dynamics or torque requirements of the robots as long as they do not move linearly or tip over. An improvement of 33% in weight reduction and of 336% in price reduction have been observed in the 3D printed links compared to the aluminium links of the *CrustCrawler* robot. It is important to mention that the kinematic model of both robots are the same, with the exception of the base. The prototype's rotating base is taller and wider than the *CrustCrawler* robot base.

V. CONCLUSIONS AND FUTURE WORK

The purpose of this paper was to demonstrate that a 3D printed robotic arm using carbon fiber reinforced onyx

Part Name	Weight	Price
Gripper	63.5g	$36.7
Link 6	9.8g	$3.9
Link 5	24.8g	$11.8
Link 4	21.2g	$6.2
Link 3	56.1g	$23
Link 2	65g	$23.3
Base	1.3kg	$140.5
Total	**240.4g** (w/o base)	**$245.4** (w/ base)

TABLE I: Weight and price for the 3D printed structural components of the robot prototype in Onyx material w/ carbon fiber reinforcement (Servos not included in the calculations).

Part Name	Weight	Price
Dual Gripper kit	72g	$99
Wrist to Dual Gripper Adapter	8g	$23
WristRotate28	49.5g	$69.99
MX28SA	17.3g	$54
MX64SA	24g	$64
2.5Girder	23g	$28
3xSingleaxismount	18g	$57
MX64SA	24g	$64
5girder	38g	$34
MX64DA	48g (w/o bottom mounts)	$184
Base	333g	$179
Total	**321g** (w/o base)	**$855.99** (w/ base)

TABLE II: Weight and price for *CrustCrawler* structural components (Servos not included in the calculations). Prices taken from *www.CrustCrawler.com*.

material can be faster to manufacture, faster to assemble, cost less in material expenses, have a better weight-to-strength ratio and provide the necessary high stiffness for good performance in any task a robotic arm might be used. There are still many ways to improve the design of the prototype, where the area with the most room for improvement that can be further explored is in weight reduction. There is still much material that can be removed from each link in order to lower the weight by quite a high percentage without affecting the strength and stiffness of the links.

Orienting the parts on the printer bed is also a factor worth thinking about in more detail when considering parts strength since this 3D printing method is based upon stacking of layers which makes a 3D printed part stronger in one direction but weaker in the other. In addition, the stacking of the layers of carbon fiber reinforcements are also dependent on how the parts are oriented on the print bed. Depending on how the configuration of the robot is designed, the way the links are to be printed and thus oriented on the print bed would have to be thought through.

Overall the design was a success.

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