Development of a Composite-Based Long Reach Robotic Arm

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Abstract

This paper focuses on the design and development of an industrial-grade, long-reach robotic arm with a reach of 5 m and payload of 50 kg characterized by high stiffness-and-strength-to-weight ratios that would be capable of preserving high precision and speed under variable external excitations. A novel multi-segment link design is introduced. An appropriate polymeric composite material was selected and utilized. The implemented manufacturing procedure is presented in detail. A 35% size prototype was produced and tested. The results indicated high stiffness and minimal amounts of deflection. Construction of a full scale prototype is the next stage.

Keywords: Polymeric Composites, Robotic Arm, Payload-to-Weight Ratio, Development, Displacement

1 INTRODUCTION

Currently, robotic arms that are used for large-scale applications are featuring a poor payload-to-weight ratio. In order to provide the necessary stiffness required for their tasks to be performed accurately, such arms are commonly constructed of either steel or aluminum and are therefore relatively heavy. The ultimate goal of this research work is to address this deficiency through the design of a novel long-reach robotic arm with a high payload-to-weight ratio, i.e., to improve both the stiffness and load carrying capacity of the arm, while decreasing its weight while at the same time maintaining high accuracy and repeatability and without compromising its utility.

In this context, polymeric composites are a good choice for material for the links of the arm because they are about eight to ten times better than steel and aluminum in terms of specific stiffness (stiffness/density) and specific strength (strength/density) [1]. Polymer composites are generally around six times lighter than steel and half the weight of aluminum. Despite the dramatic reduction in weight, polymeric composites offer stiffness and strength that is better than aluminum and competitive with steel. Additionally, they offer improved vibration dampening which leads to improved accuracy and repeatability.

The use of polymeric composite materials in robotic systems has been investigated over the last 20 years. Many physical and computational tests have been performed on robotic systems that have links constructed of a polymeric composite material. The results presented in [2–8] indicate that the replacement of steel or aluminum with a polymeric composite material results in considerable improvement in the dynamic properties of the robotic arm as a result of an increase in both the natural frequency and the damping capacity. Static improvement of the robotic arm is also achieved with the use of polymeric composite materials. The high strength- and stiffness-to-weight ratios of polymer composite materials resulted in a reduction of the deflection experienced at the end of the robotic arm as discussed in [7–9]. Additionally, the use of light-weight polymer composite material results in a reduction in the weight of the link which leads to a reduction in the torques and forces that are required to move the manipulator. The study shown in [10] found that for a two degrees-of-freedom (DOF) robot the required torque and force was reduced by nearly 30% . In all cases, the tests on a robotic link constructed of a polymeric composite material show the potential for improvement in its operation in terms of both cost and time.

In 2007, a German company utilized the aforementioned benefits by redesigning their pick and place robot to have hollow carbon fiber reinforced plastic links with laminate inserts at the joints. It resulted in reduced cycle times due to a 25% reduction in weight [11]. In 2005, Kuka began selling the first commercial large-scale robotic arm that featured carbon-fiber composite. This enabled it to stack loads weighing up to 100 kg to heights of up to 3 m, at rates as high as 600 palletizing cycles per hour [12]. However, only the third link of the robot is made of carbon-fiber composite and it still weighs in excess of over 1,200 kg [13].

2 BACKGROUND

Arm Configuration. The newly developed robotic arm would be particularly useful for performing operations on large surfaces with complex curvature such as airplane fuselages and wings. Therefore, the configuration of the composite-based long-reach robotic arm is being conceived with 6-DOF such that it can perform operations on the intricate contours of the large surface. As depicted in Figure 1, the arm has a serial configuration beginning with a revolute joint perpendicular to a second revolute joint that is parallel to a third revolute joint that terminates with a spherical wrist. This layout helps to reduce the weight of the arm while increasing the stiffness and load carrying capacity by eliminating any unnecessary offsets and or link lengths, maximizing the spherical workspace, and permitting the use of a drive-train [14]. Additionally, since the two main links of the robotic arm work in the same plane, it minimizes the amount of torsion which helps to limit the total displacement experienced by the end-effector due to the deflection of the links [15].

Link Geometry Considerations. The links of the robotic arm are designed in accordance to the thin-walled beam criterion. Therefore the links are developed with the thickness being at least 10 times smaller than any characteristic dimension of the cross-section which can be no more than one tenth of the length [16]. Thus, the link design, as depicted in Figure 2, has a rectangular profile in which the greater of the two dimensions is in the same direction as the force applied due to the payload of the end-effector. Additionally, there is a straight support in the middle of the rectangle that is also in the same direction as the force. This internal support member is novel as all other composite robotic links consist of either a hollow or completely solid cross-section. The link has a negative half degree taper angle along the length of the link. These choices have been based on preliminary FEM tests that were performed on links with various profiles with equal perimeters and various simple internal support structures and taper angles ranging from 0 to 1 degree that are outlined in greater detail in [17].

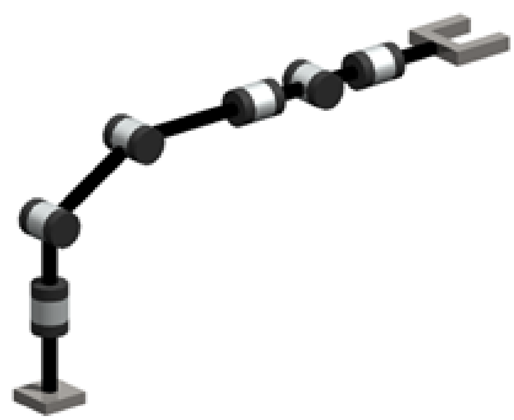

Figure 1: 6-DOF Serial Configuration of the Arm

3 PROTOTYPE COMPOSITE LINK

Prototype Composite Link Design

Modular Joints. For the purpose of the prototype, Power Cube motors by Schunk Amtec Robotics were selected because they are considerably powerful in comparison to how light and compact they are. The largest and most powerful Power Cube motor in the series, the PR 110, will be used to move link A relative to the base. It has a maximum allowable torque of 425 Nm. The prototype developed has a length of 1.75 m and a payload of 17.5 kg resulting in a torque that is

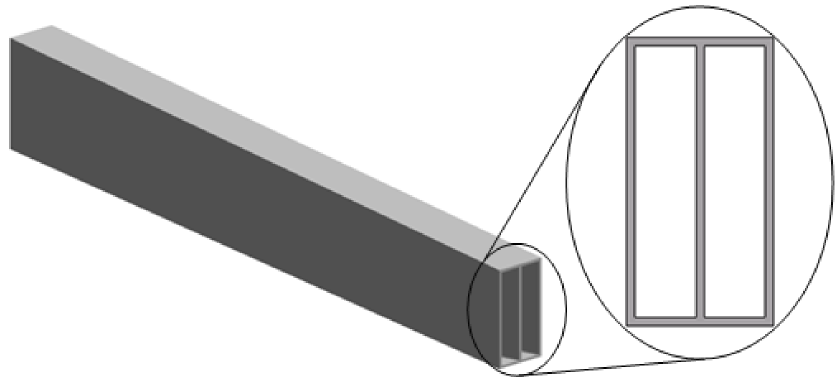

Figure 2: Design of Carbon Fiber-Epoxy Composite Link

90% of the maximum operable torque of the PR 110 motor. The less powerful PR 090 motor is connected to link B since a lower value of torque is applied on it. Therefore, based on the size of this motor, the width of the links was selected to be 60 mm such that it can be attached to the motor easily. The height at the end of link A and the beginning of link B was selected to be twice the width, i.e., 120 mm. Since the developed link has a negative taper angle of half a degree, the height at the beginning of the first link and at the end of the second link are around 135 mm and 105 mm, respectively.

Material Considerations. The reinforcement material selected for the links of the polymer composite robotic arm is a long-strand carbon fiber. Compared to glass and aramid fibers it has superior mechanical properties including but not limited to its elastic modulus. Consequently, carbon fibers can produce links with the highest stiffness. Furthermore, epoxy was selected as the matrix material. PR2032, an epoxy manufactured by Aeropoxy, was used for the production because of its structural properties. In addition to this, PH3660, a methyl ethyl ketone peroxide (MEKP) catalyst also manufactured by Aeropoxy, was used to improve the stiffness of the polymeric composite. Although it is envisioned that the industrial-grade robotic arm will be constructed using filament winding, the scaled-down prototype was planned to be developed using hand lay-up for reasons of economics. Therefore, with ease of production in mind, a carbon fiber twill manufactured by BGF Industries, Inc. was used. The carbon fiber twill selected was uni-directional because it permits control over the mechanical properties of the composite by having complete control over the fiber orientation.

Composite Link Lay-up Concept. Because the majority of the loading acting on the arm is bending, no less than 65% of the layers should have their fibers oriented parallel to the longitudinal axis (0˚ layers). Approximately 25% of the layers should be oriented at an angle of 45˚ to the longitudinal axis so as to promote strength against both torsional and shear loads. Finally, no more than 10% of 90˚ layers should be present to couple with the 0˚ layers and improve the axial strength. A total of 12 layers were used for the link because this was the lowest number of layers that were necessary to arrive at values close to the aforementioned percentages of each layer orientation. Therefore, 8 of the layers have a 0˚ fiber direction, 3 layers have a 45˚ fiber direction, and 1 layer has a 90˚ fiber direction. The order of fiber layers was chosen to be repetitive to provided an even distribution of the types of layers. The inner layer was 0˚, followed by 45˚, 0˚, 0˚, 45˚, 0˚, 0˚, 90˚, 0˚, 0˚, 45˚, and finally concluding with another 0˚ layer. The link produced with 12 layers resulted in a final part with a thickness of approximately 3.4 mm.

Prototype Composite Link Making

Step 1: Link Mold Assembly Design. A mold to produce a composite hollow link was designed as shown in Figure 3. It was conceived as a fully detachable mold to facilitate the removal of the hollow link relying on the compliance of its sides. The mold is therefore designed to be made of two aluminum halves that have an L-shaped profile that can be detached from one another. A wooden skeleton is placed inside the combination of the two halves so as to help keep the shape of the mold and prevent it from collapsing in on itself and altering the shape of the link being constructed. The side walls were made of aluminum because it is non-porous and thus does not allow the epoxy to permeate the mold creating a stronger bond that makes removal more difficult. Additionally, aluminum permits the flexibility necessary to pull the side walls off from the cured composite. The resulting mold, as presented in Figure 4, was used to create only half of the link for the robotic arm.

The novel technique that was used for production of the links is based on creating the hollow segments of the link individually and then wrapping around the combination of the segments in order to produce the internally supported link. This technique can be used for production of any simple internally supported hollow shape, not just the profile of the presently discussed link. This technique is favourable because it requires one simple mold that can be used to produce both halves of the link. This is considerably less expensive than a mold that would be necessary to create the composite link at one time. In addition to this, most epoxies have a pot life of around an hour which makes it difficult to lay-up all 12 layers of the link before it begins setting. Therefore, making separate segments of the link helps to ensure that it can be created before setting of the epoxy occurs. This technique of utilizing a simple mold to create a hollow component also allows for the possibility of creating the links using the filament winding process, which is the manufacturing procedure that will be used to create the full-scale industrial robotic arm.

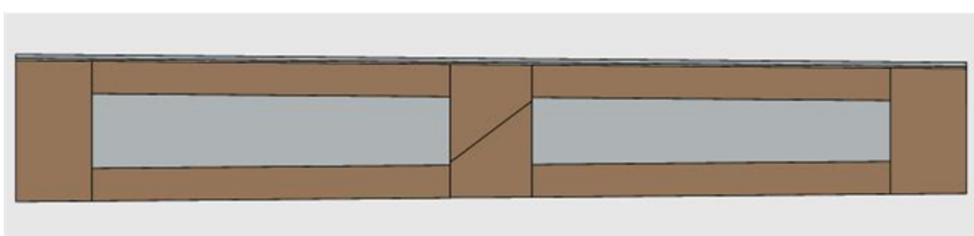

Figure 3: Design of Mold

Step 2: Link Making. The production of the polymer composite link was achieved by using vacuum bag molding. It was used in conjunction with hand lay-up because it helps to reduce the amount of epoxy over hand lay-up alone. The vacuum draws away the excess epoxy from the carbon fiber. This results in a final composite product that has a greater percentage of carbon fiber.

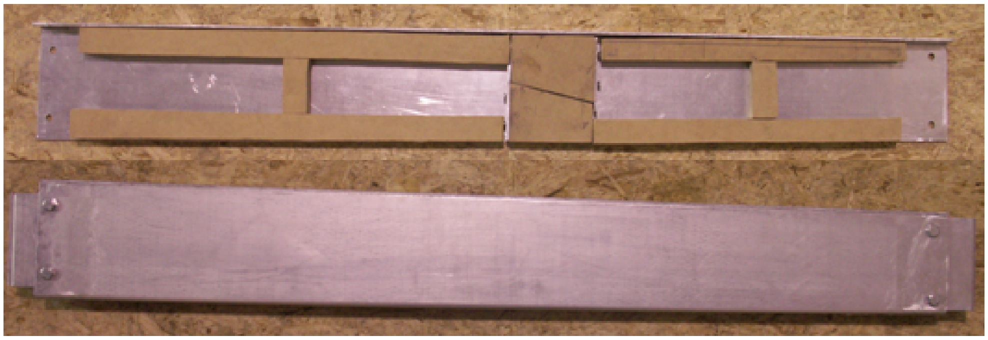

Figure 4: Fully Detachable Mold Used for Link Production

This is ideal because it is the carbon fiber that provides the reinforcing properties to the composite whereas the epoxy is just used to support and hold the carbon fiber in place.

Figure 5 shows the vacuum bagging apparatus implemented. The epoxy is first applied to the layers of carbon fiber twill. The carbon fiber twill is then placed directly onto the mold that is coated with a release wax or gel. Peel ply is then placed on the carbon fiber twill followed by release film and breather fabric. The peel ply aids in the removal of the release film and the breather fabric that helps to absorb the excess epoxy. The part is then surrounded by a vacuum bag that is fully sealed and connected to a vacuum pump. During the production of the link, the mold was coated with six layers of release wax to ensure the release of the mold. Application of the epoxy to the carbon fiber twill was achieved by using a firm roller to 'roll out' air bubbles and help ensure that the part produced does not have any voids in it.

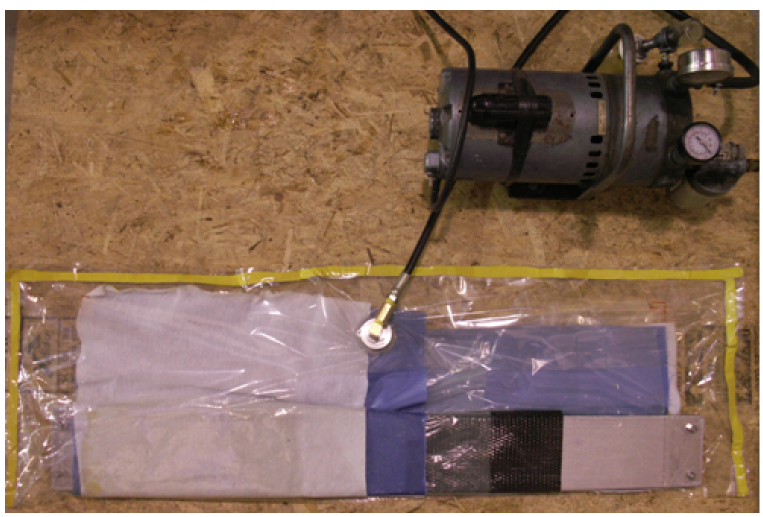

Figure 5: Vacuum Apparatus Used to Produce Composite Link

Step 3: Attachment Assembly Design and Making. Once the link was successfully produced, the bracket for attaching to the motor needed to be designed and manufactured. Figure 6 shows the design of the bracket. It consists of six plates that enclose the exterior and interior support walls of the link. It also includes a series of spacers that are placed between the plates in the hollow portion of the link. The two plates that attach to the exterior walls of the link are rigidly connected to a base plate that can be attached to the motor. The other four plates and spacers are then inserted into the link. Four bolts are then tightened to connect all the parts to the link and enable it to be securely fastened to the motor. For the purpose of testing the link, the attachment device is constructed of steel. Steel was chosen because its high modulus of elasticity helps to ensure that any deflection of the attachment device is minimal. The plates of the connection device were designed such that the diameters of the bolts that connect it to the link are smaller than the diameter of the holes, the same is applied for the holes that are drilled through the composite link. The end result is a connection that is free of stress concentrations from the link resting on the bolts. Consequently, the connection between the attachment device and the link is fully frictional. This is necessary to prevent any damage to the composite link from stress concentrations.

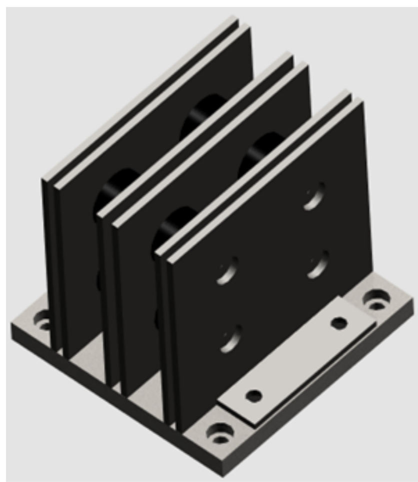

Figure 6: Design of the Bracket for Attaching Composite Link to the Joint Motor

4 EXPERIMENTAL SETUP

Prototype Composite Link Testing

Physical Testing Procedure. As presented in the schematic of the experimental setup depicted in Figure 7, the larger end of the composite link was rigidly attached to a cement wall. For this segment of investigation of the composite link, it was studied as a cantilever beam. By not mounting the link to the motor, it eliminated any displacements that are a result of the motor, including any inadvertent rotation of the motor during the loading of the composite link. This enabled the measurement of the displacement that occurs due to the deflection experienced by the composite link only.

Observation of figure 7 shows that the composite link was rigidly attached to a cement wall using the steel bracket. At the far end of the composite link a laser was mounted such that it was 30 cm below the bottom of the link and perpendicular to the ground. The laser was shone on the end of the link and measured the vertical distance between the laser and the link.

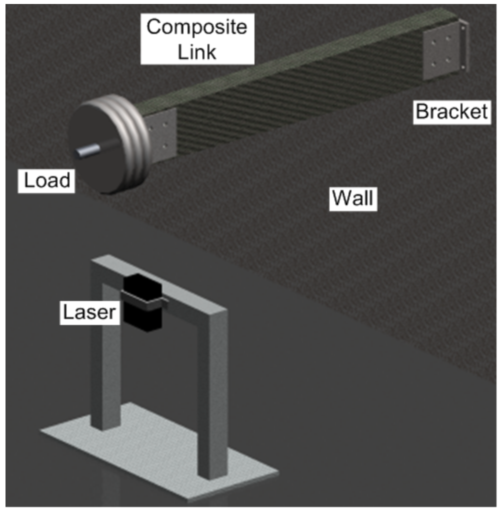

Figure 7: Schematic of Experimental Setup

Loading Procedure. Once the experimental setup was operational, the physical tests were performed. The displacement was measured at four intervals. First, the link was tested with just the weight attachment device mounted on the end of the link. It has a mass of approximately 3.86 kg (8.5 lbs). Measurements were then taken by incrementally adding 4.55 kg (10 lbs) to the link. The measurements were taken 10 minutes after the weight had been added to allow the link to settle.

5 Results and Discussion

The average values of the data collected from a series of 5 tests using the laser is shown in Table 1. It is a measurement of the vertical displacement. These results indicate a primarily linear displacement. The percentage error between the values obtained from the various tests using the same loading was less than 4% . This indicates that the testing procedure is fairly consistent. The difference between each subsequent measurement is close to the same value; in fact the maximum percentage difference is less than 5% . The overall vertical displacement measured by the laser was 0.354 mm. This indicates that under full loading, the first link by itself is capable of having a repeatability of approximately ± 0.35 mm.

Table 1: Vertical Displacement of Link as Measured Using Laser

Weight of Load (kgs)	3.86	8.41	12.95	17.5
Laser Measurement (mm)	300.000	299.885	299.766	299.646
Displacement (mm)		0.115	0.119	0.120

There are a few sources of error to note about the experiment that was performed. First, the composite link is undergoing bending and thus has components of displacement in both the vertical and horizontal direction. The measurements taken by the laser only indicate the vertical displacement. Consequently, any end-effector that would be attached to the end of the link would actually not be capable of a repeatability as low as 0.354 mm. Another source of error is the fact that the laser is not positioned at the very end of the link, only near it. The absolute end of the composite link would actually experience a displacement that is greater than that found using the laser. Another source of error is the settling of the link. The laser data continues to vary as the link continues to creep. In order to eliminate this from affecting the results, the measurements were taken at the same time intervals for all 5 series of tests. This however still presented an issue as upon taking the load off of the link, the link did not return back to exactly 30 cm above the laser.

6 CONCLUSIONS

A novel prototype composite link was built and tested. The results demonstrate that under static loading, for one link of the 35% size prototype a deflection of 0.354 mm is experienced at the end of the link while a load of 17.5 kg is applied at the end of the link. This reveals that at its full length, two links connected in series, the prototype would undergo a maximum deflection of under 1 mm. The results indicate that producing this novel design which includes a hollow carbon fiber epoxy composite prototype link with a simple vertical internal support structure for an industrial grade robotic arm is a suitable method to achieve high stiffness and strength-to-weight ratios as long as an appropriate joint between motors and links is used.

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