A Biofueled Renewable Minimally-Critical Biodegradable Easy-to-Disassemble Robotic Manipulator: Initial Design

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***Abstract*—Making green and digital technologies such as robots rely on critical raw materials (CRMs), which are finite resources. As a consequence, the competition between nations to secure the access to CRMs is expected to increase in the next decades, which potentially could lead to conflicts. Simultaneously, the amount of waste electrical and electronic equipment (WEEE) is expected to increase making its management more challenging. To mitigate the international competition, the dependence on finite resources, and the complexity of WEEE management, this paper reports on the initial design of a robotic manipulator that: first, requires a minimal use of CRMs; second, has motors and links made of hard biodegradable bioplastic, and hence, its main structure is both renewable and unharmful at the end of its life-cycle; third, is easy to disassemble to facilitate repair and re-manufacturing, which reduce the raw material demand and waste generation by extending the robot life-cycle; and fourth, can be powered by biofuels.**

***Index Terms*—Circular robotics, sustainable robotics.**

I. Introduction

The paradigm of a circular economy (CE) is gaining interest as an alternative to the unsustainable linear economy based on take-make-dispose. The primary aim of CE is to keep at the minimum both the dependence on finite natural resources and the generation of waste and pollution [1]. In particular, the current geopolitical situation highlights the competition between countries to secure the access to critical raw materials (CRMs) [2] necessary to make green and digital technologies as pointed-out by Baranowski *et al.* [3]. The war in Ukraine also has generated disruptions in the international trade of rare-Earth minerals, which are CRMs [2], including the closure of supply routes to Europe via Poland and Germany [4]. Nygaard [5] analyzed that, as of 2022, at least 70% of cobalt, graphite, and rare-Earth element resources were in corrupt or unstable states.

The transition to CE can be achieved by applying the so-called "Rs", i.e., practices that are implementable at various stages of the product life-cycle. Examples of these practices are reduce, reuse, repair, recycle, remanufacture, replace [6]. The design stage of a product plays a crucial role in the transition from linearity to circularity because it defines the type and amount of materials needed to make the product. The design stage also affects the length of the material life-cycle depending whether product repair, re-manufacturing, disassembly, material degradability and recycling are taken into account or not [7].

The high operational costs and the contamination risks resulting from handling waste are among the main barriers to the implementation of the "Rs" [8]. Both these barriers can be mitigated using robots on a large scale for performing circularity operations such as disassembly and waste sorting. While the literature on robotic disassembly [9]–[12] and waste sorting [13]–[16] is expanding in support of circularity, to the best of the authors knowledge there is no work that performs the design a whole robotic manipulator (i.e., mechanical structure, actuators, and sensors) based on the circularity principles. Yet, this is important because, as it will be discussed in Section II, manipulators and grippers are typically made of several CRMs such as copper for the windings and the main body [17], rare-Earth minerals for the permanent magnets in servomotors [18] and soft parts [19], aluminium for the main body [20], and gallium for advanced soft actuation [21]. Hence, the benefits mentioned above of using robots to accelerate the transition to CE rely on the availability of CRMs necessary to make them, which further increases the demand and dependence on CRMs. This motivated us to rethink the design of a robotic manipulator ("rethink" is one of the circularity principles [22]) and raise the question: "Can a robotic manipulator perform well if it is designed by avoiding the use of CRMs, by increasing the fraction of renewable biodegradable materials, and by adopting an easy-to-disassemble structure to facilitate future repair?". This work is a first step to answer this question.

Paper contribution: We report on the design of a robotic manipulator based on circularity principles. These principles affect the choice of the materials (preferably renewable and biodegradable), the type of motors and actuation system (pneumatic to avoid CRMs), the primary source of energy (preferably a biofuel), and the mechanical assembly of the parts (easy-to-disassemble to facilitate repair).

This work led to the following definition of "circular robotics": *Circular robotics is an emerging field of study at the intersection of circular economy and robotics. It consists* *of the design, control, and deployment of robots implementing the circularity principles [6].*

The novelty of this paper lies in the design of a robotic manipulator that explicitly implements circularity principles at the design stage. In contrast, applications such as robotic waste sorting, disassembly, repair, and remanufacturing illustrate the deployment of robots as enabling technologies for circular-economy processes [10], [13].

II. Related Work

The ideal mechanical structure of a robotic manipulator is resistant to high loads, is lightweight, and is compact to achieve low energy consumption and portability. To achieve these properties, different materials have been proposed in the literature. For example, Yin *et al.* [20] used a combination of *carbon fiber reinforced plastic* (CFRP) and an *aluminium* alloy (AA) to make a robotic arm. With respect to an AA structure, they achieved a weight reduction of 24.3%. Hagenah *et al.* [23] combined cellular *titanium*, nanocrystalline aluminium, and *ceramic*. The final weight of their prototype is 4.9 kg. Since CFRP and aluminium tubes are among the preferred materials for lightweight industrial robots, Honarpardaz *et al.* [24] provided a benchmarking study between them in terms of flexural and torsional stiffness. A key factor affecting the stiffness of CFRP parts is the angle of the fibre. The lower density of CFRP makes them the preferred choice when low mass is the primary design objective, but they are relatively costly. Aluminium generally provides a stiffer structure, and hence, is the preferred material when flexural, tension, and compression loads together must be supported by the arm.

Softness is added to modern robotic manipulators to enhance both dexterity and safety in human-robot collaboration tasks [25]. Hence, soft parts of different materials have been proposed. For example, Chang *et al.* [26] developed a soft actuator as a sandwich of *copper* nanowires with two types of flexible substrates, namely, polyethylene-terephthalate (*PET*) and low-density polyethylene (*LDPE*). Wang *et al.* [21] reviewed liquid-metal (LM) based soft actuators and sensors proposed in the literature; a promising type of LMs are made of alloys of *gallium* such as gallium-*indium* and gallium-indium-*tin*. Davis [19] pointed-out that *neodymium* and *praseodymium* are hard magnetic materials used in soft robots, while Coey [27] states that it is very likely that rare-Earth magnets will play a role of increasing importance in robotics. Sreekumar *et al.* [17] built a parallel manipulator using *beryllium* and copper for the structure, and *nickel* and titanium for the shape memory alloy (SMA) actuators. Softness was obtained in a robotic hand by Deimel and Brock [28] by using *silicone* rubber.

To improve the sustainability of robotic manipulators, Khan *et al.* [29] developed a soft composite made of recycled neodymium-*iron-boron* powder recovered from end-of-life industrial rotor pumps, while Achilli *et al.* [30] developed a gripper made of polylactic acid (*PLA*) and polycaprolactone (*PCL*) for the rigid and flexible parts, respectively. The former is a renewable material as it results from biomass processing, while the latter is synthetic (i.e., non-renewable) and biodegradable. The sustainability of the mechanical structure of manipulators was addressed in [31]–[33] using *wood* and by Csiszar *et al.* [34] considering the use of *bamboo*. In particular, Csiszar *et al.* [34] pointed-out that replacing aluminium with more sustainable, but less stiff and more fragile materials derived from plants results in a reduction in the accuracy of the geometrical tolerances. Robust control techniques such as those based on advanced machine learning algorithms could solve this accuracy issue [34]. The use of soft grippers could further reduce the impact of large tolerances thanks to their ability to adapt to the object shapes, and hence, they require less accuracy in the kinematic chain of the robot to perform grasping. In contrast with [31]–[34], we use 3D printed biodegradable bioplastic, which is simpler to use than wood because it is printable and may yield more repeatable results (two bamboo rods could differ significantly). Furthermore, in contrast with [31]–[34], we put circularity constraints also in the materials used for the motors, and hence, we choose a pneumatic actuation over the electrical one to avoid the use of CRMs. Finally, in contrast with [31]–[34], we adopt an easy-to-disassemble structure to facilitate future repair, which yields a reduction of the rate of generation of waste. Because of these differences from the literature, this is the first manipulator whose design is highly based on circularity principles [6], [7].

III. Manipulator Structure and Actuation

A. Structure

The 3D-CAD model of the robotic manipulator is shown in Fig. 1 and was created using Autodesk Fusion. The motors are coloured with gray, the links are red, the motor clips are blue, the threaded bars are yellow, the axial bearing is green, and the base is black. The manipulator has 3 revolute joints and 3 links. Specifically, the rotor of the motor located inside the base, i.e., Motor 1, rotates around the vertical axis (first joint), whereas the other two motors rotate around horizontal and coplanar axes (second and third joints). All the links, namely, Link 1, Link 2, and Link 3, are made of hard biodegradable bioplastic material, *i.e.* the Green-TEC PRO (Extrudr, Austria) [35]. When the base is assembled with Motor 1 as in Fig. 1, it covers an area of about 29.3 cm $\times$ 23.0 cm. These dimensions are such that the robot does not overturn even in the worst case scenario of a cantilevered configuration. For reasons of safety during testing, the robot payload is currently limited to 500 g and the torques exerted by the motors are relatively small. Furthermore, the robot reach is about 29 cm so that the engineer can safely test the robot without working more than 1 m away from it. From the safety point of view, a key variable is going to be the pressure supplied to the motors via the air actuation system because it determines the motor torques and speeds. The axial bearing (in green) supports the weight of the structure above and the payload applied to Link 3, whereas the rotation of Motor 1 is transferred to Link 1 via a shaft key. The axial bearing has an internal diameter of 70 mm and a basic static load coefficient of 120 kN [36]. The whole assembly comprises 8 M4 threaded bars made of steel to block the stators of the 3 motors. Each motor has

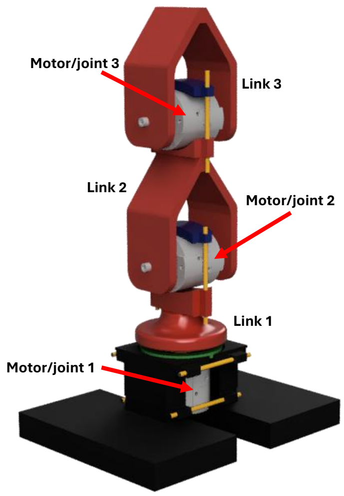

Fig. 1. CAD model of the robotic manipulator whose structural design and actuation system are based on circular-economy principles [6], [7].

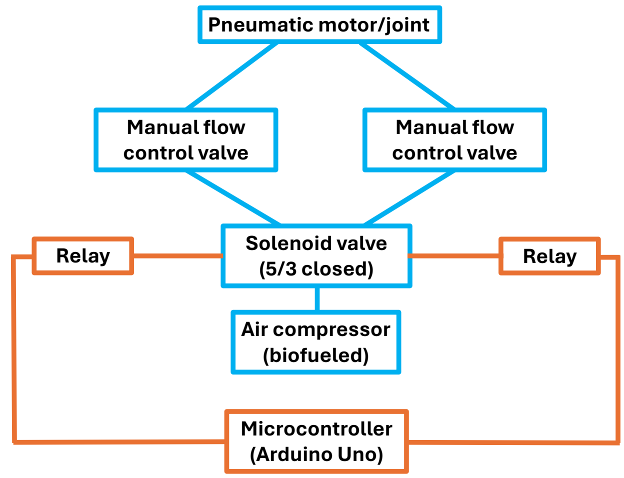

Fig. 2. Diagram of the actuation system for each motor. In blue and in orange the pneumatic circuit and the electronic circuit, respectively.

two holes for the input and the output of the air. These pairs are located on the same side for all the three motors, thus, that side must be kept free when actuating the joints to avoid interferences with the air lines. The pneumatic motors in Fig. 1 are the FESTO model DRVS-25-270-P [37], which can rotate in both directions for a maximum angle of 270° and have a theoretical torque at 6 bar of 5 Nm. The shaft is made of steel and nickel-plated, whereas the stator is made of aluminium. Since the latter is a CRM [38], we will revise the design of the motors by replacing aluminum with hard biodegradable bioplastic, e.g., [35] or PLA [39], [40], whereas the shafts will still be made of steel for high structural strength (steel is not a CRM [41]). In addition, the distance of the air holes on each stator from the motor mid-plane will be increased in the re-designed version to avoid interferences between the air lines and the threaded bars.

B. Actuation

Each pneumatic motor/joint will be moved by the system shown in Fig. 2. The pneumatic components are indicated with blue, whereas the electrical and electronic ones are indicated with orange. Specifically, the two flow control valves regulate the air flow to the motor, and hence, its angular velocity. As of now, the valves are manual with no feedback loop. Since there is not even an encoder measuring the motor position, currently the actuation system is completely open loop. Position and velocity control loops will be added at a later stage. The solenoid valve 5/3 is controlled by two solenoids connected to relays and the Arduino Uno microcontroller. The valve can either allow the air flow for clockwise rotations, allow the air flow for counterclockwise rotations, or seal the stator of the motor. The latter is necessary to hold the motor at a given position. The air is supplied by an air compressor. We use an electrical air compressor since those moved by internal combustion engines cannot be used in our laboratory due to the exhaust gases. However, the preferred set-up for this robot is the actuation via an internal combustion air compressor burning biofuels such as those produced by Atlas Copco [42], which are compatible with hydrotreated vegetable oil (HVO) biodiesel. The reason why an electrical compressor is not the preferred source of compressed air is because its manufacturing requires copper or aluminium for the windings, which are both critical materials [38], [43]. This motivates the choice of internal combustion engines that, if compatible with HVO, can burn a renewable fuel; furthermore, it is aligned with the net-zero target [44], [45] since the carbon dioxide emitted by the compressor combustion is approximately compensated by the carbon captured by the photosynthesis of the plants cultivated to produce HVO, i.e., burning HVO is approximately carbon-neutral. The relays between the valve and the Arduino Uno microcontroller operate to step-up the voltage and generate the current necessary to activate the valve solenoids. The digital output of Arduino Uno is 3 V, which is not sufficient to move the solenoid valve unless a relay is placed between them.

Remark: In general, the use of pneumatic rotative motors to actuate the joints of a robot has advantages and disadvantages compared to the electrical counterpart. The main advantage is that they are not made of the following CRMs, which in contrast are required to make and operate servo motors: rare-Earth elements are needed to make the permanent magnets [18], copper or aluminium is needed to make the windings [38], [43], and lithium is needed to make the batteries [46]. This advantage motivates their use in the design of this manipulator. Disadvantages of a pneumatic system with respect to an electrical actuation are: (a) lower accuracy; and (b) extra weight of the tank required to store compressed air in mobile robots, e.g., drones, compared to the weight of a battery required with electrical actuation. However, as robotic manipulators for industrial operations are stationary robots, the disadvantage (b), i.e., the extra weight, is not relevant for our stationary manipulator. In addition, the disadvantage (a), i.e., the reduced accuracy, can be mitigated by the use of soft grippers, which require less accuracy from the robot control system than rigid grippers thanks to their ability to adapt to the shapes of the objects to grasp [47], [48]. For these reasons, pneumatic rotative motors can be a valid option for the actuation of stationary robots such as the one introduced in this paper.

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