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Exploring Welding Techniques for the Integration of Pneumatic Artificial Muscles into a Soft Everting Robot

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Abstract: In this paper, different welding techniques for manufacturing pneumatic artificial muscles (PAMs) for the use in soft everting robots for colonoscopy are presented. The focus is on developing reproducible prototyping methods for manufacturing robust and cost-efficient PAMs. Two welding techniques, including laser welding and contact welding, are analyzed for their effectiveness in creating durable and scalable PAMs. Preliminary results show that laser welding offers high precision but inconsistent airtightness, crucial for PAM functionality. In contrast, contact welding, though slower, provides more reliable airtight seals and better reproducibility. Optimized contact welding settings balance weld seam thickness and production time. Further refinements are needed to improve speed and seam quality, with potential for large-scale production. These findings offer valuable insights for scalable PAM manufacturing in soft robotics.

Keywords: robot-assisted colonoscopy, soft everting robot, pneumatic artificial muscle, contact welding, laser welding.

1 Introduction

Current generation endoscopic technologies possess some entrenched limitations, including patient discomfort, the endoscopists long learning curve and fatigue, limited field of view, and overlooking pathology behind colonic folds. An opportunity to overcome these limitations is seen in medical robotics. The use of novel robotic technologies has the potential to reduce pain and time and to increase safety and reliability of lower gastrointestinal tract endoscopy [1].

A promising solution are soft everting robots (SER) due to their unique locomotion characteristics, which greatly reduces friction with the environment. For expansion, the robot body is inflated with a gas. The volume inflow causes the tip of the robot body to evert, which is a characteristic movement of the thin, tubular robot body. Additional material is supplied from

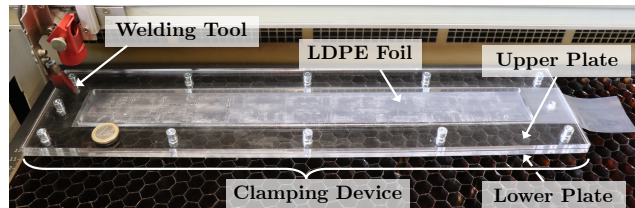


Fig. 1: Setup for laser welding with clamping device.

inside the robot. A key aspiration for SERs in colonoscopy is to create a system that can be maneuvered through the colon environment in a controlled manner [2].

An important aspect of achieving this goal is the steering of the robot. Steering can be performed passively or actively. Passive mechanisms include the interaction with obstacles or preformed body geometries [2, 3]. Active methods typically rely on sensors and actuators. These can be divided into distributed steering, which controls a significant length of the robot body, and localized steering, which is limited to a smaller area. An active, distributed method investigated for the use in SERs are so called pneumatic artificial muscles (PAMs). These are actuators, which contract whilst inflated with gas and transforming potential to mechanical energy during that process [4]. There are different types of PAMs used for steering SERs [4, 5]. The contraction of the PAMs induces local deformation in the robot body, which acts as their backbone, supporting and guiding their movement. This deformation leads to bending or directional changes. By selectively actuating different PAMs, the robot body can be guided along a desired path, offering new flexibility and enabling smooth movement. The controlled adaptability makes PAMs well-suited for use in medical devices, where precise motion and safety are crucial [6]. Therefore, PAMs are a good first approach as actuators for a precise direction control of a SER. A remaining challenge is the fast, cost-efficient and reproducible production of such PAMs in combination with the robot body of the SER.

Current state-of-the-art approaches for producing robust PAMs aim to reduce manual labor and accelerate production. Common materials for fabricating PAMs include low-density polyethylene (LDPE) and textiles with thermoplastic polymer layers, such as polypropylene (PP), polyethylene (PE), nylon, and thermoplastic polyurethane (TPU). The properties of these

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textiles — such as weave, stretch, and pattern — can be easily manipulated to affect the performance of the PAMs [6].

Non-contact welding techniques such as CO₂ laser welding, offer high precision and accuracy, making them ideal for rapid prototyping, intricate shapes, and reduced downtime [7, 8]. To improve welding outcomes, some studies have pre-pressed the layers with a heat sealer [8]. Additionally, laser-transparent and -absorbent materials, like infrared (IR)-absorbing intermediate layers or additives, have been used. These materials improve the absorption of the laser beam energy, thereby enhancing the welding result [9]. An alternative approach by SILDARRIAGA et al. uses a zinc selenide (ZnSe) heatsink to defocus the Gaussian laser beam. This eliminates the need of IR-absorbing pigments [7]. Furthermore REN et al. explored the use of IR-laser with TPU-coated sheets for improved fusion bonding [10].

In addition to non-contact methods, there are mechanical welding techniques relying on direct contact to achieve material bonding. For instance, heat seals are employed to create precise weld seams [11]. These techniques can be labor-intensive. Masking layers are used to define the geometry of PAMs by acting as protective barriers that prevent unwanted welding. However, their removal after welding can cause leaks. Ultrasonic (US)-welding offers a faster, more precise alternative that requires no additional material such as adhesives or masking layers. Though uneven pressure distribution can lead to weak spots [12, 13].

Computer numerical control (CNC)-based welding techniques, such as adding a heat sealing pencil [14], soldering irons [15] or 3D-printing extruder on a three-axis CNC-gantry [16], provide a precise, automated solution, although the system setup can be challenging. Unlike methods using masking layers and heat sealers to create all weld seams simultaneously, the CNC-based approach generates weld seams sequentially, which can increase processing time in comparison. Nevertheless, the advantage of using CNC gantries lies in their ability to achieve highly repeatable and precise movements along a specified path, ensuring consistent weld seams, particularly in complex geometries. In addition, this approach allows for quick design changes [6].

In this paper various welding processes with the aim of developing a reproducible technique for rapid prototyping to add PAMs to our SER system are presented. A detailed explanation of the SER system is given in a previous publication [17]. The goal is to identify a technique and define requirements that enable the fast and resource-efficient production of LDPE-PAMs while ensuring robustness, airtightness, and effective integration with the SER body.

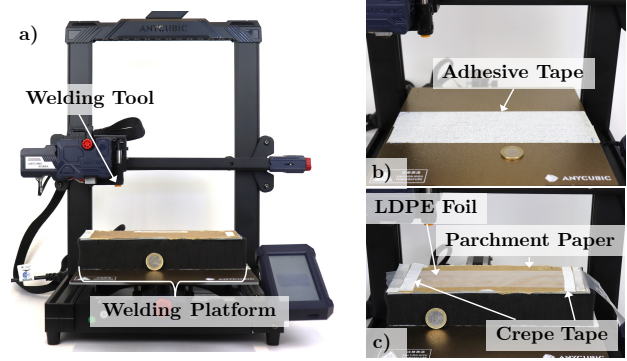


Fig. 2: Setup for contact welding (a), detailed view of the print bed without the modified set up (b) and detailed view of the print bed with the welding platform added (c).

2 Materials and Methods

The PAMs manufactured in this paper belong to the category of serial Pouch Motors, based on the concept presented by NIYAMA et al. and KÜBLER et al. [13, 18]. A Pouch Motor is a single PAM that takes on a cylinder-like shape when pressurized. The serial arrangement of multiple Pouch Motors results in PAM strings, which can be used for the directional control of a SER.

Preliminary tests have shown that the 50 μ m thick LDPE foil (Low-Density-Polyethylene, Fa.ars, Borken, DEU), used for both the PAMs and the robot body, could be welded manually via contact and that laser welding is feasible in general. Laser welding and contact welding were chosen due to their relevance in literature and their ease of use. In the following tests, PAMs are created by overlapping two LDPE foils (50 μ m thickness) and melting them together.

laser welding: The basic principle of laser welding involves the melting of the LDPE foils and bonding them locally. During the process, the weld seam is defined by a vectorized geometry, which the laser system traces precisely. This allows for complex welding patterns to be realized with high accuracy.

The test setup is shown in Fig. 1, where the LDPE foils are clamped between two acrylic glass sheets. A rectangular opening in the upper sheet allows the direct application of the laser beam to the foil. The clamping device is placed in the working area of the laser cutter (Trotec Speedy 300, Trotec Laser GmbH, Marchtrenk, AT).

To achieve robust weld seams, the following parameters are systematically adjusted: laser power, focal distance, weld speed and pulse per inch (PPI). The focal distance (using a 2.0 inch lens) is set to 80 mm with a PPI of 10000. They are kept constant, while the laser power is increased in 1.0 % steps from 13.0 % to 30.0 % of the maximum laser power of 60 W.

Correspondingly, the weld speed is systematically increased from 0.2 % to 1.0 % in 0.1 % steps, depending on the maximum speed of 2.8 m/s. Single Pouch Motors (30 mm x 30 mm) are manufactured. The seams are tested for robustness and airtightness by filling the PAMs with pressurized air in a water bath.

contact welding: Welding LDPE foil with a 3D printer uses the thermal energy of the extruder, to soften the foil locally through mechanical contact, bonding it together. Targeted extrusion along a specified G-code-based path creates customized welded seams for the PAM.

For this technique, the 3D printer (Anycubic Kobra, Anycubic Technology Co., Shenzhen, PRC) must be modified. The detailed setup is shown in Fig. 2. As welding tool, a standard conically shaped 3D printer nozzle with a 0.4 mm diameter is used. To maintain a relatively constant contact force between the welding object and the welding tool, a compliant support platform (welding platform), is placed on the print bed using adhesive tape. The platform's contact surface is covered with parchment paper to facilitate the removal of the PAM from platform after welding. The LDPE foils to be welded are secured with crepe tape and covered with another layer of parchment paper. The top layer of parchment paper prevents the melted LDPE foil from sticking to the hot welding tool. Due to the size of the platform and the need to attach the foil, the maximum welding area is 195.0 mm x 70.0 mm. The movement, more precisely the geometry of the PAM, the velocity and the temperature of the welding tool are controlled via G-Code.

Relevant parameters for contact welding include the contact force, the welding velocity, and the welding tool temperature. A system-centered analysis of these parameters is carried out and their influence on the weld seam quality is analyzed. The welding tool temperature is constantly held at 200°C. It is above the melting point of the material but below the maximum possible temperature of 260°C. For establishing a suitable contact force, the welding-tool-to-foil-distance is varied. The distance must be negative to ensure the required contact force, which is enabled by the compliance of the welding platform. The welding velocity, which affects the welding time, also impacts the local heat input. Lower speeds result in greater heat input and thicker weld seam, while higher speeds lead to lower heat input and thinner weld seams. The challenge is to find a good ratio between the weld seam thickness and a reasonable welding time. To achieve this, the same PAM (with a total seam length of 412.5 mm) is produced at different speeds. To assess the weld seam quality, each PAM is filled with pressurized air using a proportional pressure control valve (type VEAB, Festo SE & Co. KG, Esslingen, DEU). The gas pressure prevailing in the PAM is increased in 5.0 kPa steps starting at 35.0 kPa via the control valve. The settings are the

Tab. 1: Burst pressure of the weld seams manufactured using contact welding at different welding speeds.

Welding Speed [mm/min]	Burst Pressure [kPa]	Welding Time [min]
50	79	8.25
100	65	4.13
200	57	2.06
400	57	1.03
600	< 34	0.69

same for all PAMs tested. This standardized filling procedure ensures that each PAM is loaded under the same conditions until it fails (burst test).

3 Results

A welded seam between two layers of LDPE foil could be produced using both processes presented here.

laser welding: Despite systematic analysis of the parameter settings for laser welding and the clamping device designed ensuring foil contact during the welding process, no settings were found that consistently guaranteed the production of completely airtight PAMs.

contact welding: Contact welding allows for repeated manufacturing of airtight PAMs (see Fig. 3). Good values for the contact force are obtained with the welding-tool-to-foil distance set at -3.5 mm. In combination with the compliant welding platform, the foil is welded without holes and not pulled along with the welding tool. The results of the burst test can be found in Table 1. A speed of 100 mm/min is identified as a good compromise between the thickness of the weld seam and production time.

4 Discussion

In this work, two rapid prototyping approaches for the reproducible manufacturing of robust and airtight PAMs using LDPE foil were presented. However, the laser welding technique failed to produce reliable, leak-proof weld seams when using identical parameter settings that had previously yielded good results. One possible reason could be an insufficient contact between the foil layers despite the clamping device. Design changes in the clamping device could be made or the foils could be prepressed. Another possible solution to improve the welding results is the incorporation of a thin absorber layer into the structure, as highly reflective, transparent foils are less effective at absorbing energy and converting it into heat, which leads to an inadequate weld seam quality. To identify

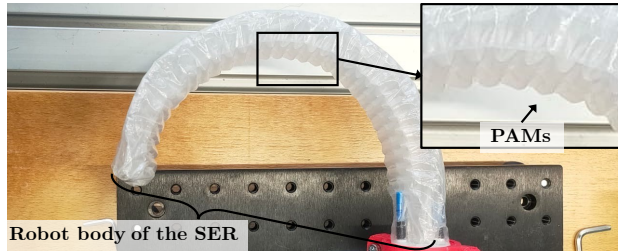


Fig. 3: Robot body with integrated PAMs of a SER, manufactured via contact welding.

the cause more precisely, the welding tests and seam analysis could be carried out with another, non-transparent material, such as TPU-coated ripstop nylon.

The contact welding technique offers a viable alternative to laser welding, relying on mechanical contact. However, its main drawback is the increased manufacturing time in comparison to laser welding, especially if longer PAM strings are to be welded. The maximum feasible length of a welding unit is determined by the length of the welding platform. For the manufacturing of longer PAM strings, several welding units must be performed in sequence with a manual advancement of the LDPE foils. Nevertheless, this technique has proven to be reliable and reproducible for creating airtight PAMs with consistent settings.

5 Outlook

Future work will focus on enhancing automation and reducing the production time for a robot body with integrated PAMs for the SER, using the CNC-based contact welding. Additionally, a directional control concept based on the PAMs will be developed. Prototyping methods will also be tested with alternative materials and further improved if necessary.

Author Statement

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