Fiber-Reinforced hybrid Soft Robot: Integrating Suction cup for Anchoring and Kevlar-Enhanced method for locomotion on various challenging terrains

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***Abstract*— This study explores the development of a hybrid soft robot, using a fiber-reinforced process with silicone elastomer. The design incorporates a bell-shaped suction cup for anchoring system, added double Kevlar thread for elongation. The primary aim is to innovate a soft robot capable of efficient locomotion across different terrains, including smooth, and more challenging rugged surfaces such as wood.**

The approach is based on idea process for the robots design, electronics, software, and manufacturing processes. 3D modeling and printing techniques for the robots mechanical components, providing an optimal integration of mechanical and electronic elements. The electronic system, includes sensors and actuators, were designed to enable precise control and adaptability to various conditions. The software development was essential in achieving effective maneuverability and response to sensory inputs, including functions for motion control.

Experiments assessed the robots speed, elongation, and weight distribution. The results demonstrate that the hybrid design, includes an effective suction mechanism, Kevlar-enhanced elongation, and a robust electronic control system, significantly improves the robots performance on smooth surfaces. Future research should focus on refining the robots texture for enhanced locomotion, improving the suction anchoring system, and integrating more advanced sensory feedback systems for better environmental navigation.

I. Introduction

Soft robotics has emerged as a promising field with the potential to revolutionize various applications, particularly in environments that are challenging for conventional rigid robots. This study focuses on the development of a soft robot capable of self-elongation propulsion and turning, demonstrating the potential of soft robots for various tasks. A research question is thus born:

"Can a soft robot be developed with self-elongation propulsion and turning ability that can complete an obstacle course, that contains different surfaces like wood and sand as well get pass certain obstacles in order to complete the obstacle course?"

The primary mode of locomotion for the developed soft robot is self-elongation propulsion. This technique utilizes the elastic properties of the robots fiber-reinforced actuator to generate movement. By applying air pressure to the actuator, it elongates, propelling the robot forward. The actuator is made from Ecoflex 00-30 silicone elastomer, which provides the necessary elasticity and durability. A Kevlar string embedded within the actuator enhances its strength and allows for precise control of the elongation.

To further enhance the robot's maneuverability and adaptability, the suction cups are integrated with the self-elongation propulsion mechanism. This integration plan is to allow the robot to propel itself forward while simultaneously maintaining a firm grip on the surface, with possibility to traverse angled surfaces.

The robot's ability to turn is to be achieved using a servo motor and two strings attached to either side of the robot. The servo motor is controlled to generate a pulling force on the strings, causing the robot to turn to either side. This turning mechanism provides the robot with maneuverability, allowing it to navigate obstacles and change direction as needed. This research demonstrates the feasibility of developing soft robots with self-locomotion capabilities, paving the way for their adoption in various fields.

Conducted at University of Southern Denmark, Introduction to Soft Robotics. Special thanks to our supervisors: Jonas Jørgensen and Saravana Prashanth Murali Babu

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II. Methods

In this section, methodologies of the project used in the development of the hybrid soft robot are described. This includes design approach, manufacturing, electronic design, and software development.

A. Design

One bellow shaped suction cup was mounted on the front of the robot to provide adhesion to surfaces and enable climbing and self-propulsion. The suction cups were carefully selected for their compatibility with the robot's material composition and surface area to ensure optimal gripping performance. Several tests were conducted and recorded, but more about that in the in section **III**. The suction cup was mounted on the 3D printed armor part, as seen in the Figure 2. The armor provided a way to connect all of the

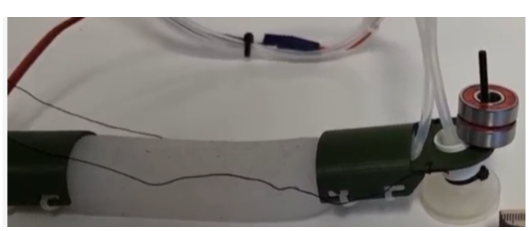
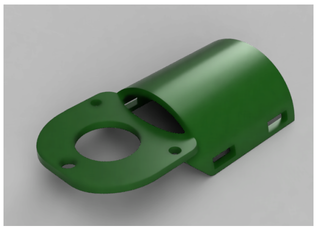
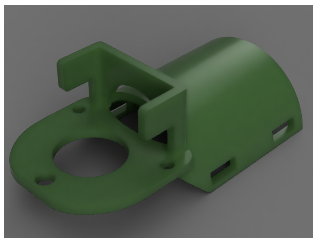


Fig. 1: Shows the suctions cup mounted onto the armor

components together as well as provided ways to add weight to each end of the robot, but more about that in section **III**. The armor part was modeled in Fusion 360 and later 3D printed using the prusa 3D printers. The image of the front and rear parts of the armor made in CAD can be seen in the Figure 2a and 2b.



(a) The front part of the armor



(b) The rear part of the armor

Fig. 2: A figure of the 3D models for the back and front brackets in the final robot design.

A servo motor was attached to the back of the robot on the back armor and connected to two steering lines attached to either side of the body to the front armor. The servo motor was controlled by an Arduino board, which provided precise control over the pulling force applied to the strings, enabling the robot to slightly rotate on its axis.

As for the design of the mold, initially the mold provided by the soft robotics toolkit [5] was used, but as certain parts of the mold did not work for the group it was redesigned. The things that were changed were mainly the size of the mold and the lid of the mold. The size was increased to suit the groups purpose and the lid was changed as the group kept getting bubbles on the actuator during the fabrication process and once air pressure was applied the actuator would pop. So, in the final mold the group chose to redesign the mold without the lid, that way the final product would have no bubbles. The image of the mold can be seen in the Figure 3.

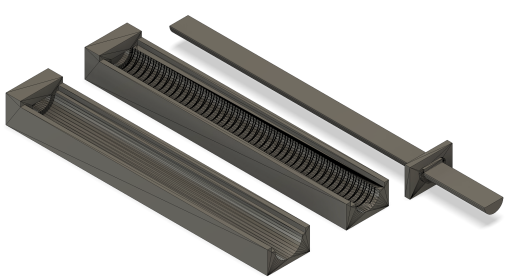


Fig. 3: Redesigned mold

B. Manufacturing

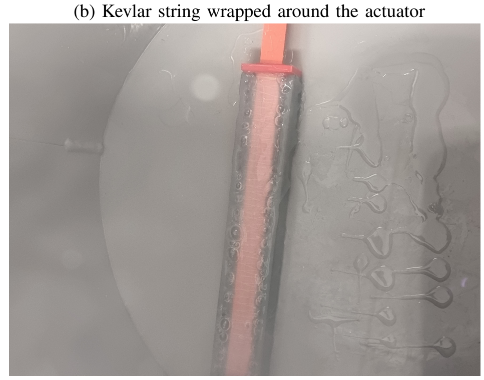
- Ecoflex 00-30
- Kevlar Thread
- Suction Cup
- Silicon Tubes
- Plastic strips
- Custom 3D Prints

Fig. 4: Soft Robot list

The fiber-reinforced actuator was fabricated by, following the guidelines from the Soft robotics toolkit [5], and the parts used during the manufacturing can be seen at list 4. In order to make the fiber-reinforced actuator that was embedded by a Kevlar string within a silicone elastomer tube. The Ecoflex 00-30 silicone elastomer was chosen for its elasticity and durability, while the Kevlar string provided strength and enabled precise control of the actuator's elongation. To fabricate the actuator, Ecoflex was mixed and put into the pressure chamber where the liquid mixture was rid of most bubbles see Figure 5a. Afterwards, the mixture was poured into the mold in order to create the inner tube of the actuator and then put into the oven at 45 deg.C. for around 30 minutes according [6].

(a) Mixing of Ecoflex

(b) Kevlar string wrapped around the actuator



(c) Outer casting of the actuator

Fig. 5: Manufacturing of the robot design.

Once the mold was taken out of the oven, the Kevlar string was then wrapped around that very same tube with a doublehelix wrapping without any strain limiting layers 5b in order to achieve the extendability of the actuator in the straight line.[7] Then a thin outer skin was molded in order to lock the fiber reinforcements in place, see Figure 5c Finally it was intended to lock one end of the actuator with Ecoflex, but due to troubles with this method, each end was sealed using zip-ties instead. The actuation was made possible using materials provided in list robot list 4 and electronic list 6.

C. Electronic

The hardware ensures safe and effective operation of the experiments and during the competition. In this section, an overview of the electronic controller circuit is described and an electronic diagram can be seen on Figure 7. A list of components is shown in Figure 6. These components are used for the presented operation of the electronic system and includes:

- SG90 Micro Servo
- 2ps Vacuum Pump
- Air Pressure Sensor
- 2ps Air Valve
- Jumper Wires
- Arduino UNO
- DFRobot Quad Motor Driver shield
- Breadboard
- 100SP5 on/off button
- 2ps 10 kΩ resistor
- 2ps 220Ω resistor
- Green Color LED Diode 5mm
- Red Color LED Diode 5mm

Fig. 6: Electronic list

The controller is made as extension of the Arduino UNO platform, combined with the DFRobot Quad motor driver. It incorporates several key features that enhance its functionality both during experiments and soft robotic arena [SRA] operation.

- **Start-Stop Button:** An implementation of start-stop button in the circuit, inspired by John Mains' 3-switch example [3]. This button enables us to initiate and stop the operation.
- **Suctions Button:** A special button in the circuit, this button enables a stop of the vacuum of the suction cup. This was a necessary step, to avoid contamination of the pump 2 during SRA, that potential could be exposed to suction on sand surface.
- **Status Indicator Light:** To monitor the status of the system, the circuit has a integrated status indicator lights, taking inspiration from The Robotics Backend's diode example [1], this project provide a modified version that are incorporated in the complete setup. This light provides visual feedback about the system.
- **Potentiometer Control:** Steering control is essential for the SRA competition. To achieve this, a potentiometer is implemented in order to have physical control buttons. By adjusting the potentiometer, it is possible to control a servo motor, that are connected to the 3D printed armor, described in section II-A. This setup allows us to steer the robot accurately using two steering lines attached to the front bracket.
- **Connection to External Sensors:** From the Arduino UNO platform and DFRobot Quad motor driver, the circuit is attached together with the board, where pumps, valves and sensors are all connected to digital and analog I/O, enabling integration with all components of the setup.

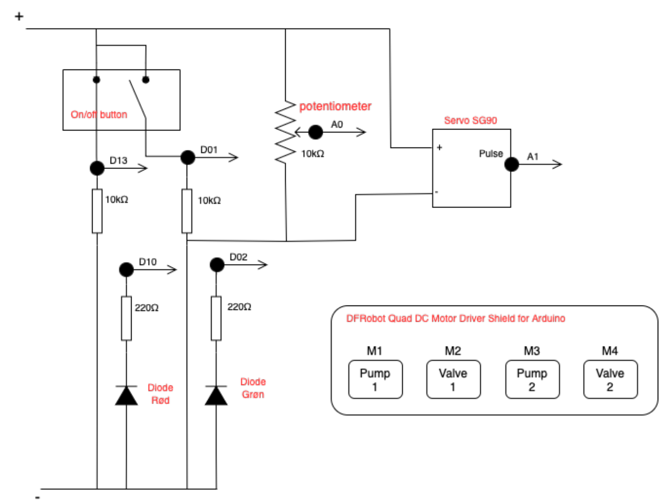


Fig. 7: Electronic diagram of the setup, showing digital and analog I/O

D. Software

The software couple an integration between the I/O and the additional circuit, where the code can be found at section V. The project is developed using C++ for the Arduino platform. The control system enables steering the robot, with its direction being adjusted based on potentiometer readings. The correct settings was found by testing the input from the potentiometer, and result in make an *right* turn by turning 180 degrees for condition of $avgPotValue > 682$, *left* turn towards 0 degrees $avgPotValue < 341$ and otherwise the servo is in the middle on 90 degrees. For the correct pressure for the pumps, a pressure sensor is integrated to monitor external forces, employing a filtering algorithm to ensure data accuracy.

The implementation are made with a state machine approach for managing various operational states, such as inflation, deflation, and suctions cup control. This structure simplifies the control logic, allowing for smooth transitions of the robots actions. Pump operation of the soft actuator are dynamically controlled based on sensor inputs and programmed logic.

The pressure calculations is based on raw sensor value reading, applying a gain, and then offsetting it to get the actual pressure reading. The pressure regulation is achieved with help from the resourceful course instructors during the lab work, and are based on filtering made to smooth out the pressure readings. The raw sensor value is obtained using Arduinos analog-to-digital converter (ADC), that reads the voltage across the sensor and converts it into a digital value.

By adding the Gain and offset, the raw sensor value is then adjusted to account for the specific characteristics of the pressure sensor.

$$FP = FP_{\text{prev}} + \alpha \times (P - FP_{\text{prev}}) \quad (1)$$

The filtered pressure value is calculated using a first-order low-pass filter and is shown at Equation 1. This filter smooths out the fluctuations in the pressure readings, which is useful for this noisy sensor input. The filtering can be represented by the following equation, where FilteredPressure is the current filtered pressure value, prevFilteredPressure is the previous filtered pressure value, pressure is the current raw pressure value, and α is the smoothing factor that determines the responsiveness of the filter.

III. RESULTS

The robot is evaluated by several experiment to measure the locomotive performance, which in the first experiment are conducted on counterweight distribution an second a speed analysis. The data in this section presents the results obtain form the FR soft robot. In the counterweight experiment the soft robot were tested on a smooth table, linoleum floor (ground) and wood surfaces, and its effectiveness are estimated with time and elongation towards a goal completion of 50 [mm] distance.

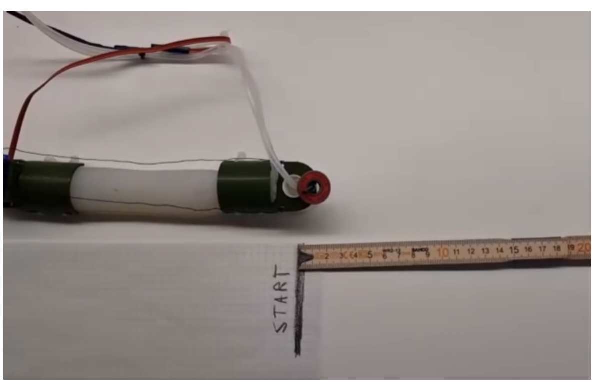


Fig. 8: Shows the speed test track

The raw data collected from the experiment is presented in table I. This data show time measurements, distances covered, and the robots performance on different surfaces. Useful information on the correlation of time and speed is shown, which help to understand the behavior of the robot by adjusting the weight distribution in the front and back. The *F* and *B* stands for front and back, and the number correspond to how many counterweight blocks that are used, one counterweight block weights 11[g]. The pronounce *DNF* stands for 'did not finish', which are used on data points where very limited or no performance was shown.

TABLE I: Speed Test Results on Different Surfaces

Surface	Configuration	Time (mm:ss)	Completion (50[mm])
Table	2F-1B	01:07	Finished
	1F-2B	00:45	Finished
	1F-1B	00:51	Finished
	0F-0B	00:47	20 [mm] - DNF
	1F-0B	01:10	Finished
Ground	2F-1B	01:42	20 [mm] - DNF
	1F-2B	00:00	0 [mm] - DNF
	1F-1B	01:00	10 [mm] - DNF
	0F-0B	00:55	10 [mm] - DNF
	1F-0B	00:55	20 [mm] - DNF
Wood	2F-1B	00:53	Finished
	1F-2B	00:54	Finished
	1F-1B	00:51	Finished
	0F-0B	00:55	Finished
	1F-0B	00:51	Finished

A. Data Analysis and Visualization

The data is visualized by plots made from the data points in Table I on different surfaces. The visualizations help to identifying patterns, comparing performance metrics across different surfaces, and understanding the effectiveness of the design implemented in the robot. First, a barplot in Figure 9 shows the average completion times for the soft robot. Error bars included in the plot represent the standard deviation, measure the variability in the robot. The plot shows a consistent performance on the wooden surface, as indicated by the relatively shorter error bars, suggesting that this surface may be optimal for locomotion. The data from the wood surface is cluttered together, and therefor the best performance was shown on the smooth table surface. The smooth surface is better suited for system that uses a suction cup, as the vacuum created is closed around the suction cup. During the project several suctions cups were tested to fine the best support for the anchoring feature, a short and bell-shaped suction cup gave best result.

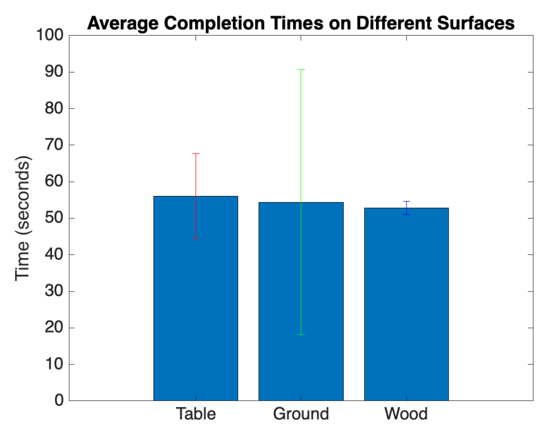


Fig. 9: Average completion times on different surfaces. Error bars show standard deviation.

Second, is a scatterplot that can be seen in Figure 10, which depicts the completion times for individual trials. Each point in the scatter plot corresponds to a specific trial, with blue points indicating successful completions and red points showing the instances where the robot did not finish

(DNF). This plot highlights the robot's challenges on certain surfaces, particularly the ground, where a higher frequency of DNF instances is observed, next to it the distance traveled within the specified time is mentioned.

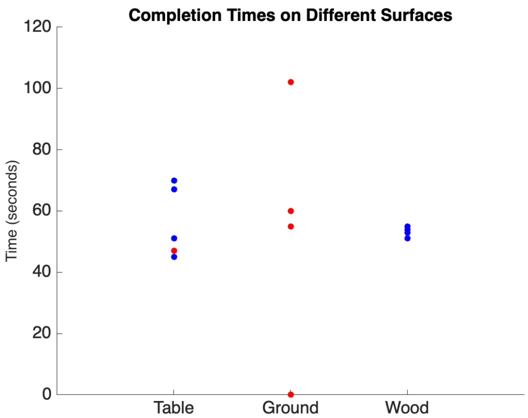


Fig. 10: Completion times for individual trials on different surfaces. Blue: Finished, Red: DNF.

B. Locomotion Analysis

In order to assess the locomotion behavior of the robotic design, a speed analysis were conducted. This was achieved through advanced video analysis software [2]. The video analysis tool was beneficial to evaluate the robot efficiency and understanding the dynamics of the locomotion in x-y direction.

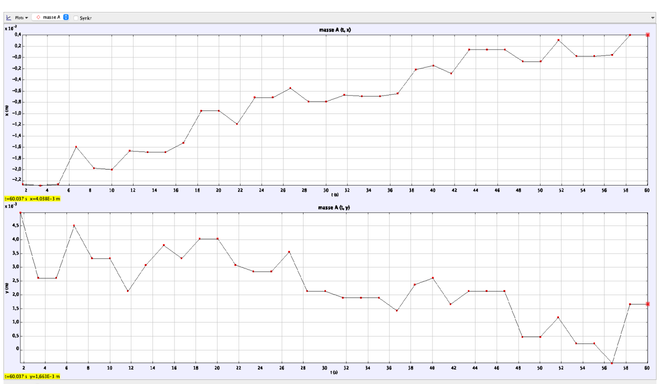


Fig. 11: Combined X- and Y-Axis Plot of the Robot's Speed

Figure 11 shows a plot output over the robots movement. The upper represents the motion along the x-axis, correlating to the robots forward movement. The lower part highlights movements along the y-axis, offering insights into lateral drifts that could be interesting to do a reevaluation of the robots design. To ensure accuracy in our measurements, a calibration stick was used. The standard point-mass tracker method was applied, analyzing the data at a granularity of 100 frames per point over the 60 [s] test video.

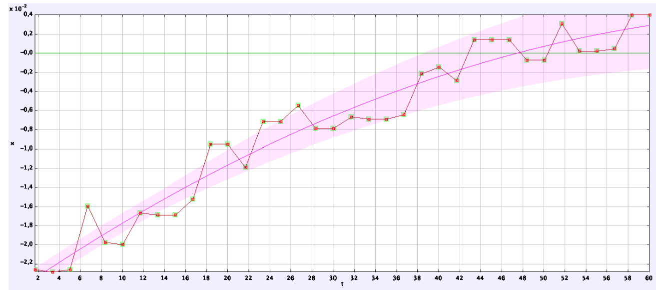


Fig. 12: Detailed X-Axis Plot of the Robot's Speed

A closer examination of the robots speed is presented in Figure 12. The X-axis plot gives a indication of the robots forward movement efficiency and can be used to benchmark against other performance metrics.

IV. Discussion

The project showcases certain findings in the FR design and inclusion of suction cup for anchoring, and it demonstrated promising good results for locomotion across various surfaces. There were unexpected results that indicated that future work is necessary, which will be discussed in this section. One notable problem was the varied performance of the robot on surfaces with different levels of rigid surfaces. While the design showed good result on smoother surfaces, its efficiency on hard, textured surfaces was not as high as anticipated. This variation could be attributed to the bell-shaped suction cup, which are optimized for mixed, more rugged surfaces. This change from suction cup indicates a potential area for future work in the design, suggesting an adjustment in mechanical design that can adapt to the surface rigidity. There were unexpected problems with the limited pressure the fiber-reinforced actuators could hold before popping the material. It was due to the used silicon(Ecoflex 00-30) for the fabrication of the actuator. For future work it is recommended to try making the actuator with a different material(e.g. Dragon-skin, Elastosil). Even though other materials were tried, the group was unsuccessful in the fabrication of a properly functioning actuator. During the design process the mold design process were difficult to archive promising results. There were many of trial and errors towards the development of the correct 3D mold. Inspiration for the mold design is made from a modified version of the example describe in the soft robotics toolkit [4]. During the manufacturing, some steps were discarded from the source example, due to the intensive testing in the lab, this includes removal of the lid, because it created too big of a surface tension when curing leaving behind bubbles that would pop when putting air pressure into the actuator.

A. Experiments

While the data provides valuable insights into the current capabilities of the soft robot, it also reveals areas for further development. Future iterations of the robot could focus on:

- Enhancing the texture of the base of the robot to increase elongation on various surfaces.

- Improving the robustness of the suction anchoring, and counter weight problem.
- Integrating advanced sensory feedback systems to better navigate and respond to environmental challenges.

V. Conclusion and Future work

In this study a soft robot was developed to demonstrate that locomotion in a linear motion can be achieved through fiber reinforced actuators and bellow shaped suction cups. This study shows that surface on which the robot travels on plays a major role in robot's locomotion and as seen in the test results, surface can also influence the speed of the robot.

The tests also revealed that configurations that are optimal for movement on one surface do not necessarily work well on other surfaces, as the friction is different on each surface, it can also be seen in the tests that weight on each end of the robot also played a huge role in its speed. Therefore, further need for in-depth study of fiber reinforced locomotion is needed, with the aim of increasing the speed and travel distance on different surfaces.

There is also a need to investigate a better alternative for bellow shaped suction cups as they are not able to perform well on certain surfaces, thus an alternative is needed in order to have a better grip of the surface with minimal speed reductions. Moving on certain surfaces and angled surfaces was a difficult task and the soft-robotics approach demonstrated in this study should have provided insights in order to aid the development of a whole new fiber reinforced robot with faster and more refined movement. Continued comparison with existing technologies will be crucial in advancing the field of soft robotics, paving the way for more versatile, durable, and intelligent robotic systems.

A. Future Research:

Based on these findings, future research should focus on optimizing the suction mechanism for varied surfaces, potentially incorporating adaptive technologies that allow the robot to adjust its anchoring strategy based on real-time feedback. Additionally, exploring integration with AI and machine learning could be beneficial for autonomous decision-making capabilities, further enhancing the robots utility in complex and dynamic environments.

Appendix

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https:
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https://github.com/stackovercode/
ISR_SoftRobot.git
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Daniel

1) **Project:**
   - Design
   - Fabrication
   - Testing
2) **Report sections:**
   - Introduction
   - Method: Design
   - Method: Manufacturing
   - Discussion
   - Conclusion

Emil

1) **Project:**
   - Software
   - Fabrication
   - Testing
2) **Report sections:**
   - Abstract
   - Method: Electronic
   - Method: Software
   - Result
   - Discussion

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