PARAMETER TUNING OF ADDICTIVE MANUFACTURING CONTINUUM FLEXIBLE MANIPULATOR SIMULATION

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Abstract: This work presents the process to simulate accurately a continuum flexible manipulator produced through addictive manufacturing (AM). A manipulator is an element capable of interaction with the space around it, a common example is a rigid robotic arm. The Finite Element Method (FEM) software adopted was the SOFA framework. The tuning process consists of adjusting the simulation parameters to achieve sufficient accuracy in the manipulator movement in space. A real manipulator was used, based on known input value application, the space position was measured, and compared with the simulated version. The simulated version achieved more than 240 % of improvement as compared to the nominal material parameters. The 3D positioning for steady-state study case reached 10 % of distance error, and a parameters surface was mapped to better understand the tunning process.

Keywords: continuum manipulator; simulation; SOFA; parameters calibration.

SINTONIZAÇÃO DE PARÂMETROS DA SIMULAÇÃO DE MANIPULADOR CONTÍNUO E FLEXÍVEL

Resumo: Este trabalho apresenta o processo de simular com precisão um manipulador contínuo flexível produzido em manufatura aditiva. Um manipulador é um elemento capaz de interagir com o espaço a sua volta, um exemplo comum é um braço robótico rígido. O *software* de elementos finitos adotado foi o *SOFA framework*. O processo de sintonia consiste em ajustar os parâmetros de simulação para atingir precisão suficiente no movimento do manipulador. Um manipulador real foi usado e aplicou-se sinais de entrada conhecidos, mediu-se a posição atingida e a comparou com a versão simulada. A simulação apresentou uma melhoria de mais de 240 % se comparada com os parâmetros nominais do material. O posicionamento 3D em estado estacionário para os valores testados alcançou 10 % de erro em distância, além disso, uma superfície dos parâmetros foi gerada para melhor entender o processo de calibração.

Palavras-chave: manipulador mole; simulação; SOFA; calibração de parâmetros.

1. INTRODUCTION

Continuum and soft manipulators represent promising technologies that have been developed to address tasks and challenges beyond the capabilities of rigid manipulators. These manipulators use flexible materials in their design that grants them high degrees of freedom and mechanical resilience, offering new options for robotics activities [1]. These characteristics offer several advantages, including adaptability to the environment, lighter weight compared to their rigid counterparts [2], lower construction costs, and reduced likelihood of causing injuries when interacting with humans and assets.

Simulation is a common step in robotics, offering benefits such as fewer design iterations, reduced time, and lower prototype costs [3]. However, simulating soft manipulators requires a higher level of detail, since the rigid robotics joint representation approach may not be sufficiently representative [4]. Among the accepted methods for soft robotic simulation, the FEM approach stands out for its greater representation capacity, heavily based on modeling the manipulator's geometry and material properties representation [5].

Additive manufacturing design creates the possibility to construct soft manipulators using materials not traditionally considered soft, exploring specific geometries to achieve elastic deformation like soft materials [6, 7]. This usage creates geometry dependent properties [8], which may result in a non-direct application on simulation environments. Soft robot simulation already demands a calibration step to enhance its accuracy, and because of the AM design, the calibration step increases this demand to compensate this geometry dependency. A calibration approach for soft robots' simulation is achieved in [9], addressing an accurately force sensing and position control through a vision-based method. The work of [4] proposes an inverse statics-based calibration process to determine model parameters for simulation, and orientation sensing is used to estimate the disturbances caused by external factors such as friction and gravity in a fiber-reinforced soft manipulator. Following these approaches, this article proposes a tuning procedure to improve accuracy in simulation for additive-manufactured continuum manipulator. The manipulator construction uses non-soft material to provide the compliance property, which demands parameters adjustment to correct the standard material values for simulation.

This work is organized as follows. Section 2 presents the system description, its simulation approach, and proposes the calibration guidelines that need to be followed. Section 3 presents the steps adopted for simulation tunning. Section 4 discusses the results, relating the calculated error and adjusted parameters. Section 5 concludes the paper.

2. SIMULATION OF CONTINNUM MANIPULATOR

To solve challenges associated with simulating soft robots, researchers have turned to the Simulation Open Framework Architecture (SOFA) due to its ability to model soft materials effectively. SOFA leverages the FEM to simulate soft bodies, which was the chosen approach in the current study. FEM relies on the geometrical representation of the soft robot model to accurately capture its behavior during simulations [12]. Furthermore, the availability of the Soft Robots plugin in SOFA enables the incorporation of actuation elements like cables and pneumatic chambers, which are common in this field. As a result, this framework becomes a powerful tool to simulate soft manipulators, providing insights into their complex interactions and behavior [13]. However, when aiming for high fidelity within the simulation environment, it becomes imperative to comprehend the limitations of the SOFA framework. One challenge arises when simulating additive manufacture soft robots with intricate structures. Computing material parameters may not suffice to achieve accurate results. Fine-tuning and meticulous adjustments become necessary to attain the desired level of precision in the simulations.

2.1. Tuning

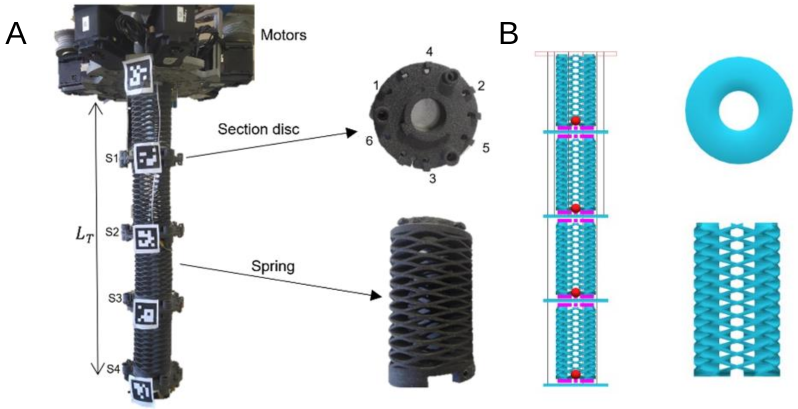
The physical characteristics of the material are the main tools to the soft material behavior in SOFA. For soft bodies, these characteristics are the Poisson ratio and the Young's Modulus, in conjunction they define how the forces applied in the bodies will deform it and how it will respond to these forces.

The presence of cable in SOFA raises the complexity of the scene requiring a close analysis of their behavior through the motion of the robot in the scene. It is important to understand the modes of operation of the cable, referred to as their value type. A cable with a value type set to displacement will keep its length constant no matter the magnitude of force. In the other hand, a cable with its value type set as force will keep the applied force on the cable constant varying its length if necessary.

3. METHODOLOGY

The tunning process of the simulation in SOFA framework was conducted based on real manipulator data, presented in Figure 1A was developed through additive manufacturing using HP Multi Jet Fusion (MJF) 3D printer, based on Powder Bed Fusion (PBF) technology. The system is formed by a base, section discs (S1 to S4) and springs, made of polypropylene (PP), whose material properties can be seen in [10, 11]. The manipulator's total length is $L_T = 425$ mm.

Figure 1. PP continuum manipulator, disc, and deformable spring, where A is the real manipulator and B is the simulated one.



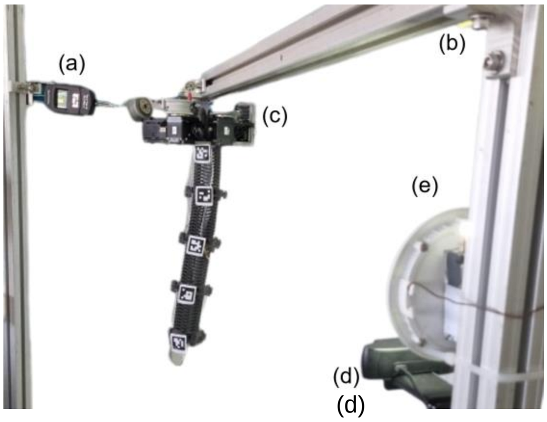
The manipulator is actuated by servomotors pulling steel cables, connected to section discs S2 and S4. Three cables are connected to the manipulator tip (cables 4, 5 and 6) whereas the other three are connected to the middle-section (cables 1, 2 and 3), as seen in Figure 1A. Each section cable is radially spaced at 120 degrees each, distributed around the section disc.

3.1. Data acquisition

The process to extract information from the real manipulator was conducted as shown in Figure 2, using (a) vertical weighing scale (0 to 50 Kg); (b) aluminum frame and supports; (c) real manipulator with ArUco fiducial markers [14]; (d) webcam Logitech C920 1080p; (e) light; a Notebook Intel® Core™ I7-11800H, 16 Gb of RAM; and OpenCV library.

The system input considered was the traction force applied manually pulling each cable, measuring by the vertical scale in kgf, and then converted to N. The resulting position of each section of the manipulator was measured using the ArUco markers, by the camera and the related OpenCV library. For each individual cable configuration, a resultant position was captured. Three tests for each cable were conducted, changing the intensity of applied force. The dataset created was used in the next step of tuning procedure.

Figure 2. Manipulator data measurement scheme.



(d)

3.2. Simulation

Using Blender, a model of the spring and discs were created with the same dimensions of the actual spring and converted to be inputted in SOFA simulation, as shown in the Figure 1B.

Each spring was imported to the software individually and can have different material characteristics if needed. The discs were imported as a single body to enable the actuation by cables. Constraints were applied to fix the base of the manipulators and to connect its parts, a low tolerance and a high value of iteration was set in the constraint solver to guarantee a stable fixing of the parts. The force was applied in the actuation cable slowly to ensure stability.

The velocity of the end effector was observed as the criterion to ensure the stabilization of the simulated manipulator. Once the movement stabilizes the Euclidean distance percent error between real position $\left(r_k^x, r_k^y, r_k^z\right)$ and simulated (k) position $\left(s_k^x, s_k^y, s_k^z\right)$ related to the manipulator length L_T is measured:

$$d_k = \frac{\sqrt{(r_k^x - s_k^x)^2 + \left(r_k^y - s_k^y\right)^2 + (r_k^z - s_k^z)^2}}{L_T} \cdot 100\%, \tag{1}$$

The simulation ran at a pace of 0.4 to 0.1 fps and takes an average of 60 to 120 animation steps to stabilize if the self-collision occurs or not.

3.3. Tuning

Once the scene was constructed an initial scenario was chosen at random. The scenario in case involved the cable 6 and an applied force of 19.62 N. The initial material parameters were a Poisson ratio of 0.5 and a Young's Modulus of 10 GPa. The values of Poisson ratio were decreased by 0.05 until the limit of 0.05, then the Young's modulus was decreased by 1 GPa. This process was repeated until the last combination of a Poisson ratio of 0.5 and a Young's modulus of 1 GPa.

4. RESULTS AND DISCUSSION

As indicated, the adopted calibration parameters were Young's modulus and Poisson ratio to adjust the material response and compensate the geometry material parameters dependency. The calibration mapping process to identify the adequate configuration for a better simulation was established as can be seen in Figure 3. For all sections it can be noted a strong influence of Young's module, especially around 0.8 GPa, and a weaker influence of the Poisson ratio. This region presents the lower error values, where its minimum is the operation point with Young's modulus of 0.8 GPa and Poisson ratio of 0.05. It should be noted that the minimum physically admissible value of this ratio is zero, also limited in the software. The nominal parameters are Young's module as 1.6 GPa and Poisson ratio of 0.43, which means it is out of the graph range, because for the values outside the graph window and in the regions without points, the simulation presents instability, not generating suitable data.

The nominal parameters led to a simulation response with a considerably high error (bigger than 40 %), as seen in Figure 4. The tuned version presented a reduction between 240 % to 1080 % (these results can be seen in the Figure 5) in the general error in relation to the nominal one, which confirms the idea of higher calibration necessity for AM manipulator. It can be noted also that the manipulator's tip presents bigger error, even for tuned case, as a function of accumulating each section error and the larger task space of this section. The final error of the tuned case is around 10 % of the manipulator length, which means a distance error around 4,25 cm.

Figure 3. Error distribution of the tunning parameters for each section.

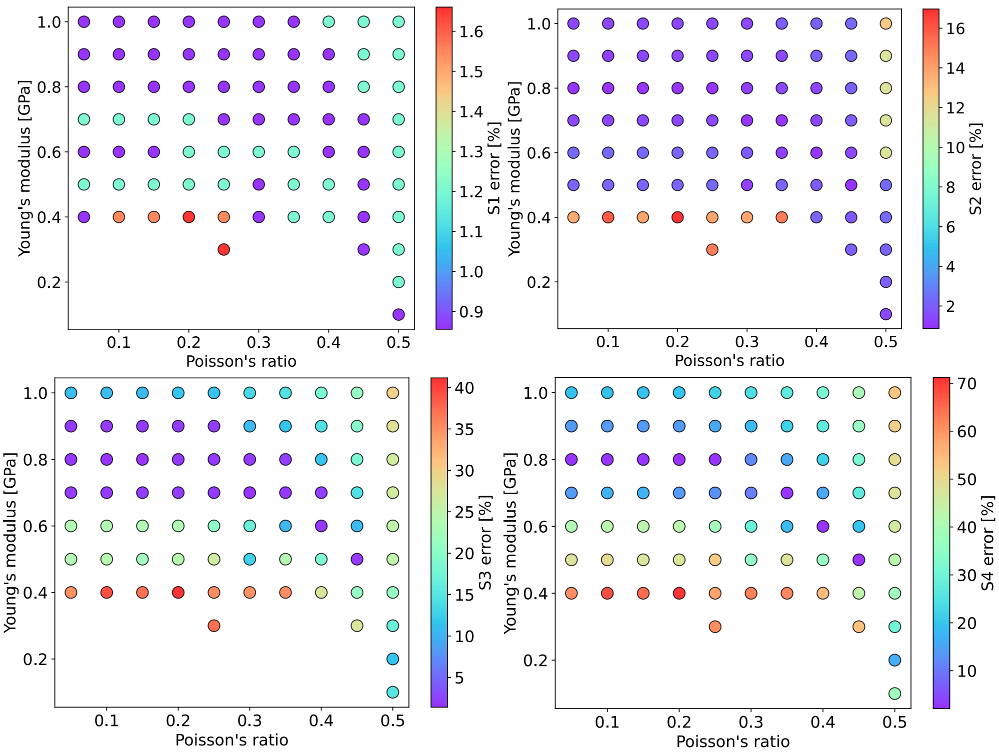


Figure 4. Error between nominal and tuned configuration for each cable input.

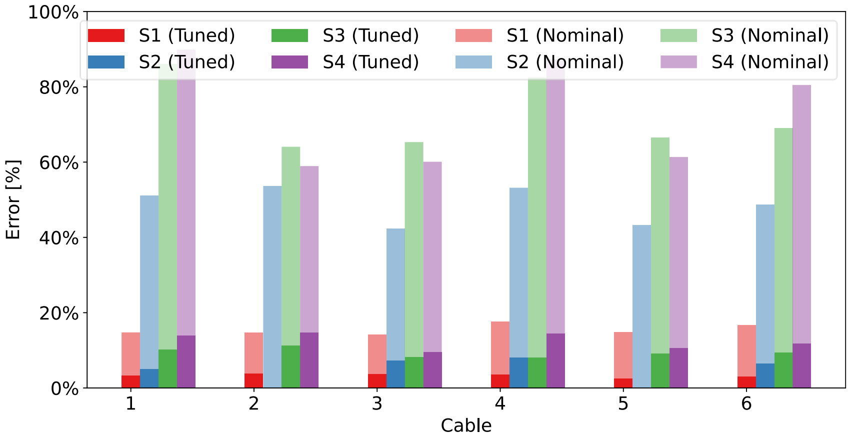
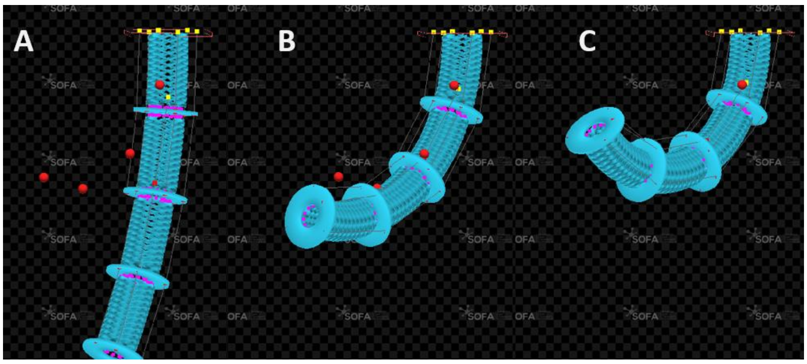


Figure 5. Calibration process test, with Young's modulus equal 10 GPa and Poisson's ratio for A: 0.5, B: 0.3 and C: 0.1, where C is the optimal calibration.



5. CONCLUSION

The continuum robot's simulation demands careful approaches to achieve accuracy. The nominal material parameters were insufficient to correctly configure the simulated material, even for a detailed 3D model, indicating a considerable gap between the simulation and the real manipulator made by AM.

The calibration procedure was able to substantially reduce the nominal error and resulted in a more notable dependence on Young's modulus, that need to be reduced to absorb the geometric dependence of the design, making the material more deformable, as expected with the use of rigid materials to produce materials. Even for a manual calibration, the simulation response achieved a notable operation point, considering the simulation complexity, but it will be more accurately in future improvements, like individually adjusting each spring parameters or using optimization approaches to numerically tuning.

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