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A Survey on the Current Trends and Applications of Design Optimization for Compliant and Soft Robotics

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Abstract— **This paper aims to provide a systematic review of the published results on design optimization techniques in the area of compliant and soft robots, with a focus on the manufacturing processes, actuation methods and application areas. The goal of this work is to provide a comprehensive view and categorization of recent efforts using optimization for improving the design paradigms of such robot technologies, while focusing on the popular methods of topology optimization and generative design. In addition, this paper provides insights into the technical and technological trends that could potentially steer this area towards widespread adoption in domestic and industrial settings.**

Index Terms— **Compliant Robots, Soft Robots, Robot Design, Topology Optimization, Generative Design**

I. Introduction

Soft and compliant robots have steadily gained research interest, due to their potential for safety in human-machine interaction with reduced maintenance needs and low development complexity, while retaining properties such as flexibility and shock absorption for adaptation when used in unstructured and complex environments. In their seminal review on the ”Design, fabrication and control of soft robots”, Rus and Tolley [1] define soft robots (SRs) as systems capable of autonomous behaviour while possessing materials whose Young's moduli are in the range of 10^4 and 10^9 Pa. This range of Young's modulus is in line with the moduli of soft biological materials. SRs are actuated through a number of different strategies ranging from fluidic (pneumatic and hydraulic), to thermal, magnetic, dielectric based, etc [2]. Structurally, SRs, i.e., robots composed of soft materials, need to be designed based on the level of required compliance, bending angle and other mechanical constraints like strength and fatigue.

On the other hand, compliant robots (CRs) made of monolithic or quasi-monolithic mechanisms are capable of producing large deformations in order to transmit motions and/or forces. Compliant mechanisms can be used to produce motions as a single part, in cases where achieving equivalent motion through numerous joints might be challenging.

Both types of robots are designed to be more adaptable and resilient than traditional rigid counterparts, and can be used in a wide range of applications, including manufacturing, healthcare, and search and rescue operations. One key difference between SRs and CRs is the materials used for their construction. SRs are typically made from flexible materials such as silicone, rubber, or other elastomers, while CRs can be made from a variety of materials including metals, plastics, and composites. As a result, SRs tend to have a more deformable and flexible structure, while CRs may be more rigid but still have the ability to adapt to their environment through the use of their structural properties.

Despite multiple advancements related mainly to the use of smart materials and fabrication processes, CRs and SRs require further technological advancements before seeing large-scale adoption in social and human-oriented applications. Challenges in the design and control of SRs are due to their low mechanical impedance, while CRs are characterized by design and manufacturing complexities, high rates of fatigue failure and inability to produce continuous motions. Furthermore, the large majority of these robots have been designed based on intuition and experience, following iterative processes or bio-inspired strategies, while a limiting factor for their establishment in real-life settings has been the lack of algorithmic design methodologies.

Structural design is largely governed by the expectation of specific outputs in terms of structural strength, material, shape, maximum deformation, etc. Given a specific set of constraints, structural design is a suitable candidate for optimization driven design. The need for optimization stems from the necessity of handling the definition of the robot's structural parameters, while addressing the trade-off between its degrees of freedom, their structural reliability and their actuators' performance. Thus, to satisfy the multiple design requirements posed by CRs and SRs, they need to be designed through an optimization driven approach.

Design techniques such as topology optimization and AI-enabled (generative) design, along with biologically inspired principles, have been modified and deployed for the cases of CRs and SRs, with the goal of producing systems that are application-optimized. Topology Optimization (TO) was developed to generate lightweight, innovative and high-performance structures that would otherwise be difficult to obtain through iterative testing [3]. This approach is an established optimization driven design method, since SRs and CRs require large deformation TO algorithms as opposed to rigid systems. Generative Design (GD), on the other hand, was more recently introduced as an iterative design technique that uses computer software to explore and find a design from a design space. Recently, the use of Artificial Intelligence (AI) and Machine Learning (ML) based techniques has allowed for the development of genetic and evolutionary algorithms that can deal with complex constraints [4], making

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them suitable for the design of robots characterized by high nonlinearities.

Although a number of survey articles related to CRs and SRs have been published in the last five years, none has sufficiently covered the applications and trends of utilizing optimization methods for the design of both these related robot categories. Specifically, Mazzoli et al [5] provide a large comprehensive review on the area of SRs, which acts as a roadmap covering the aspects of multi-functionality, adaptability and growth. While this work reviews design optimization, it does not cover this area in detail. Zhu et al [6] review the use of continuum TO for the design of compliant mechanisms, but do not cover its application on SRs. Conversely, Chen et al [7] explore design optimization methods applied towards SRs, but do not extend their analysis on CRs. Additionally, this study lacks the systematic review covering technological trends or providing a reasoning behind them.

This article aims to provide a systematic review of the trends and applications of CRs and SRs that utilize design optimization methods. Specifically, it provides novel insights related to the technical and technological evolution in the area, as it covers the different actuation technologies and manufacturing methods used to produce optimally designed CRs and SRs. Additionally, this article explores the application areas that incorporate design optimized CRs and SRs, in an effort to highlight the most dominant areas and identify others with increasing research interest and impact potential.

The rest of the article is organized as follows. Section II describes the methodology used in acquiring the references, and the process used in the elimination of certain references, and finally a list of categories used for organizing the references. Section III discusses and provides the results obtained through the methodical selection and categorization of the references, and are visualized using figures and tables. Section IV briefly summarizes and concludes the work.

II. Methodology and Literature Classification

For this review, a systematic search was conducted in the digital libraries of most major publishers in the areas of Mechanical and Electrical Engineering, namely: IEEExplore (Source A), SpringerLink (Source B), ASME Digital Collection (Source C), Science Direct (Elsevier) (Source D), SAGE Publishing (Source E), and Wiley Online Library (Source F).

Based on the fields identified in Section I, the following search strings were used, which will be hereafter referred to by their respective abbreviations:

- "Soft Robot*" (AND) "Topology Optimization" (SR + TO)
- "Soft Robot*" (AND) "Generative Design" (SR + GD)
- "Compliant Robot*" (AND) "Topology Optimization" (CR + TO)
- "Compliant Robot*" (AND) "Generative Design" (CR + GD)
- "Flexible Robot*" (AND) "Topology Optimization" (FR + TO)
- "Flexible Robot*" (AND) "Generative Design" (FR + GD)

TABLE I

Initial search results

Sources	A	B	C	D	E	F	Total
SR + TO	19	141	92	125	0	8	385
SR + GD	0	29	46	14	0	1	90
CR + TO	0	21	15	2	0	1	39
CR + GD	0	2	5	0	0	0	7
FR + TO	0	61	11	17	0	2	92
FR + GD	0	14	14	1	0	0	29
Total	19	268	183	159	0	12	641
Duplicates removed	19	201	150	147	0	10	527

In all above search strings, a wildcard character '*' was used to generate results with and without hyphenation and to include results with suffixes like '-s', '-ics' etc. The searches were explicitly performed for the whole search string rather than e.g. treating "Soft" and "Robot" as two individual terms. The quantification of results that were obtained from the aforementioned sources are provided in Table I.

Initially, the total search results amounted to 641, and after removing the duplicates within the same source and category, the resulting number of results was 527. Papers that meet at least one of the following criteria were removed: (1) survey papers, (2) non-peer reviewed work, (3) not published in the English language, (4) the search terms appearing only in the cited references. This led us to the final count of 52 papers evaluated in this study.

Furthermore, the analyzed papers were sorted into various categories in order to highlight their contributions and application areas, while analyzing the motivation behind the identified trends. This method allowed us to search, obtain, eliminate and classify the search results, which are presented and discussed in Section III. The papers were then sorted on the basis of the year of publication, optimization method, robot type, actuation method, application, fabricated (yes/no) and manufacturing process used.

III. Results and Discussions

An aggregated collection of all analyzed entries obtained through the search is presented in Table II, which provides the classification and sorting for each paper in chronological order, and Fig. 1 shows selected examples of design optimized CRs and SRs.

The trend in the publications over the years is shown in Fig. 2, which also indicates the number of papers that were hardware-tested. The earliest source dates back to 2008 [14]. This paper and other similar works from the same research group present optimal design techniques aimed towards designing SRs. No relevant publications were observed between the years 2009 to 2013 and in the year 2015, and there was one publication each year in 2014 and 2016.

The years following 2016 see a large upward trend in the publications. One of the reasons for this increase was the expiration of several patents related to 3D printing, for instance, Fused Deposition Modeling (FDM) in 2009 and Selective Laser Sintering (SLS) in 2014. These events led to widespread democratization of low cost plastic 3D printing. This spurred a large interest among the maker and research

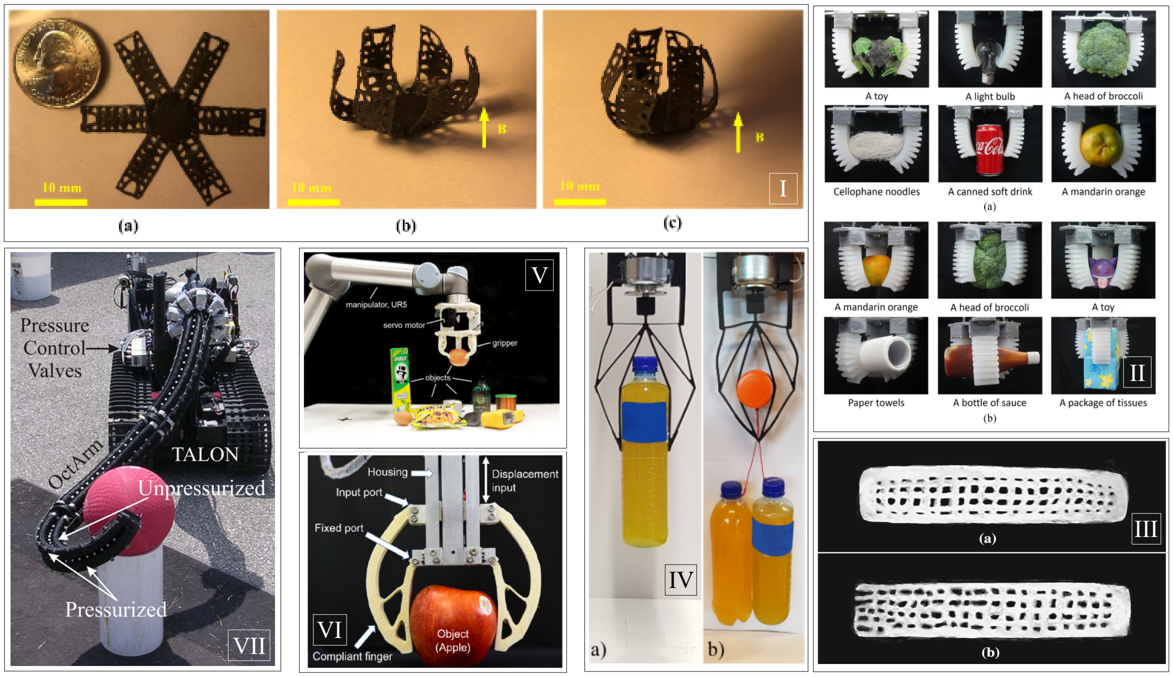

Fig. 1. Instances of manufactured design optimized soft and compliant robots. (I) A ferro-magnetic SR designed for grasping small objects [8]. (II) Example of an optimized penumatic soft actuator grasping various objects [9]. (III) A hydrogel based structure capable of morphing [10]. (IV) An optimized compliant gripper lifting heavy objects with a weight of (a) 520g and (b) 1.08 kg [11]. (V) A cable driven compliant gripper grasping objects and being manipulated by a rigid robot [12]. (VI) A compliant robot gripper designed for grasping fruits [13]. (VII) An articulating compliant robot amaking use of pneumatics and elephant trunk like actuators [14].

community where low-cost open-source printers, like Prusa [60], saw widespread adoption. The years after 2016 also saw a large number of Stereolithography (SLA) based printers being released into the market, which allowed for a widespread adoption of this technology for rapid prototyping of more complex structures with an increasing variety of materials of different properties.

A large number of hardware validated studies were conducted in 2018, which is largely attributed to the increased availability of low-cost FDM-based 3D printers around 2017-2018. A decline was observed in 2019, and in 2020 fewer hardware validated studies were observed, which could be a result of the COVID-19 pandemic effects. While there was a small decline in total related publications in 2021, this reduction is not deemed significant. A peak was observed in the year 2022, which together with the data from the previous years reveals a general upward trend in the area. Of all papers evaluated in this study, 59.6% have performed hardware validation of their results. Among the possible reasons for the rise in publications in the last several years, wthe following were identified as the most influential:

- Computational Resources: Moore's law has projected a continuous rise in the availability of computational resources. The evolution of GPU (graphics cards) increased distributed computing modules with parallelism. This allowed researchers to explore multiple research directions with a low cost on time [61], spurring an increase in research output and, therefore, subsequent publications in the area. It is important to note that the general rise in crypto-currency mining has led to an increase in graphics card prices, which may have affected their use in research [62].

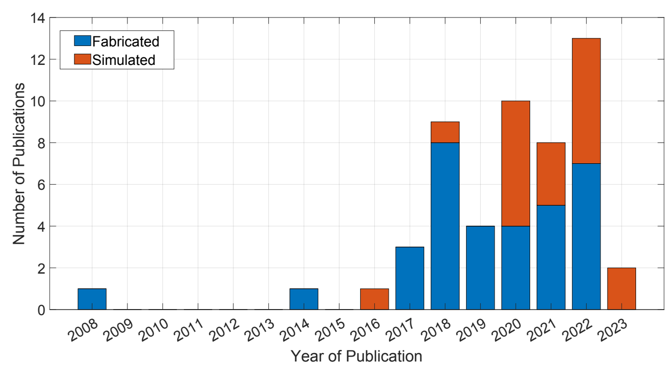

Fig. 2. Trend in publications over the years showing fabricated status

- AI driven acceleration: AI and data driven acceleration in GPUs and CPUs (advanced branch prediction) have reduced the required computation time for solving complex problems, and GPUs designed specifically for AI have led to the establishment of methods like GD [63].
- Availability of optimization methods: The open source revolution and democratization of code bases have allowed researchers easier access and replication of existing work. Indicatively, genetic algorithms have obtained large popularity in the field of GD, while the 99-line TO code [64] has served as the impetus for numerous papers in the area of TO.
- Additive manufacturing (AM): AM allowed researchers to design parts that may otherwise not be manufactureable by conventional processes. This has allowed re-

TABLE II

DISTRIBUTION OF SURVEY RESULTS ACROSS DIFFERENT DOMAINS

Ref	Year	Method	Robot	Actuation	Application	Fabricated	Manufacturing process
[14]	2008	TO	SR	Pressure and Cable Actuated	Gripping/Grasping	Yes	Multi-part
[15]	2014	TO	CR	Mechanical Force	Gripping/Grasping	Yes	Flexible material casted
[16]	2016	TO	CR	Agnostic	Application Agnostic	No	N/A
[17]	2017	TO	SR	Pressure	Gripping/Grasping	Yes	3D printed polyjet
[18]	2017	TO	CR	Mechanical Force	Gripping/Grasping	Yes	Flexible material machined
[19]	2017	TO	SR	Pressure	Gripping/Grasping	Yes	3D printed polyjet
[20]	2018	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printed FDM
[21]	2018	TO	SR	Agnostic	Locomotion	No	N/A
[12]	2018	TO	CR	Wire Driven Mechanical Force	Gripping/Grasping	Yes	3D printed FDM
[22]	2018	TO	SR	Pressure	Gripping/Grasping	Yes	3D printed FDM
[23]	2018	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printd FDM
[13]	2018	TO	CR	Mechanical Force	Gripping/Grasping Fruits	Yes	3D printed FDM
[24]	2018	TO	SR	Pressure	Gripping/Grasping	Yes	3D printed polyjet
[25]	2018	TO	CR	Mechanical Force	Gripping/Grasping	Yes	Flexible material casted
[26]	2018	TO	SR	Dielectric Elastomer Actuator	Indirect Locomotion	Yes	Dielectric membrane
[27]	2019	TO	SR	Electro-Active Polymer	Gripping/Grasping	Yes	PVDF strips
[28]	2019	TO	SR	Dielectric Elastomer Actuator	Application Agnostic	Yes	Dielectric membrane
[29]	2019	TO	SR	Pressure	Gripping/Grasping	Yes	3D printed FDM
[30]	2019	TO	SR	Pressure	Gripping/Grasping	Yes	3D printed multimaterial
[31]	2020	TO	SR	Ferro-magnetic	Gripping/Grasping	No	N/A
[32]	2020	TO	SR	Ferro-magnetic	Gripping/Grasping	No	N/A
[33]	2020	TO	SR	Pressure	Gripping/Grasping	No	N/A
[34]	2020	TO	CR	Mechanical Force	Force application	Yes	3D printed FDM
[35]	2020	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printed FDM
[36]	2020	TO	SR	Pressure	Locomotion	No	N/A
[37]	2020	TO	SR	Pressure	Gripping/Grasping	No	N/A
[10]	2020	TO	SR	Hydrogel	Application Agnostic	Yes	Hydrogel
[38]	2020	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printed FDM
[39]	2020	GD	SR	Polyeric Thermal actuation	Application Agnostic	No	N/A
[40]	2021	TO	SR	Ferro-magnetic	Gripping/Grasping	No	N/A
[11]	2021	TO	CR	Mechanical Force	Gripping/Grasping	Yes	Unclear
[41]	2021	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printed SLA
[42]	2021	TO	SR	Pressure	Gripping/Grasping	Yes	Flexible material casted
[43]	2021	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printed FDM
[44]	2021	TO	SR	Pressure	Gripping/Grasping	Yes	Flexible material casted
[45]	2021	TO	SR	Dielectric Elastomer Actuator	Application Agnostic	No	N/A
[46]	2021	TO	SR	Agnostic	Application Agnostic	No	N/A
[47]	2022	TO	SR	Penumatic	Gripping/Grasping	Yes	3D printed FDM
[48]	2022	TO	SR	Hydrogel in Isotonic Solution	Gripping/Grasping	Yes	Hydrogel
[49]	2022	TO	SR	Pressure	Application Agnostic	No	N/A
[50]	2022	GD	SR	Pressure	Locomotion	No	N/A
[9]	2022	TO	SR	Pressure	Gripping/Grasping	Yes	Flexible material casted
[51]	2022	TO	CR	Pressure	Gripping/Grasping	No	N/A
[52]	2022	TO	CR	Mechanical Force	Gripping/Grasping	No	N/A
[53]	2022	GD	SR	Pressure	Undersea Robots	No	N/A
[54]	2022	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printed FDM
[8]	2022	TO	SR	Ferro-magnetic	Gripping/Grasping	Yes	3D printed FDM
[55]	2022	TO	CR	Mechanical Force	Gripping/Grasping	Yes	3D printed FDM
[56]	2022	TO	SR	Electro-Active Polymer	Application Agnostic	No	N/A
[57]	2022	GD	SR	Penumatic	Gripping/Grasping	Yes	Multi-part
[58]	2023	TO	CR	Mechanical Force	Gripping/Grasping	No	N/A
[59]	2023	TO	SR	Pressure	Application Agnostic	No	N/A

searchers increased design freedoms and the ability to validate their models via rapid prototyping. The availability of multiple 3D printing materials of different properties has also fostered an increase in the adoption of this fabrication method.

The largest share of robots evaluated in this study are SRs with 33 instances, while CRs amount to 19 results. Of these, 29 relate to TO + SR, 19 relate to TO + CR, 4 to GD + SR and none to GD + CR.

From the design perspective, TO-driven approaches dominate the results with 48 instances, this is attributable to the large body of work already conducted in TO starting from the early 1990s [65]. This optimization method is widely studied in compliant mechanisms and many review articles have been produced on this subject [6] [66]. On the other hand, GD is a newer field and application towards rigid structures and mechanisms are rising [67]. However, GD-based approaches for flexible and compliant designs are starting to increase, since 4 works were identified in the years 2020 [39], and 2022 [50] [53] [57].

The distribution of the actuation technologies observed in all selected papers are depicted in Fig. 3. Pneumatic is the most used actuation method with 20 entries. Pneumatic actuation has been popular in SRs for enabling safe interac-

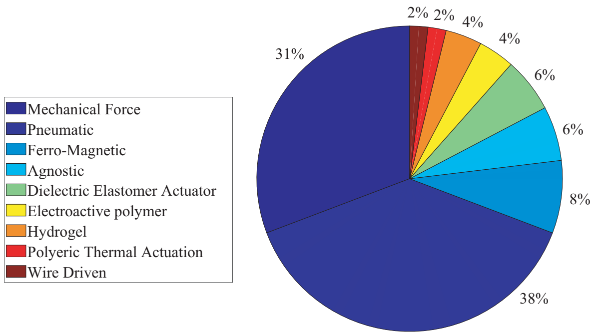

Fig. 3. Actuation technologies employed in the results

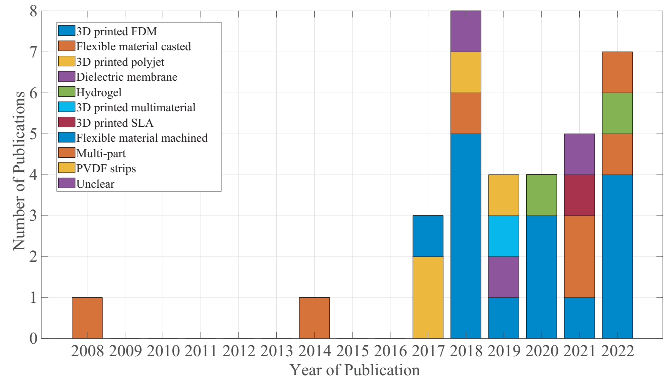

Fig. 4. Manufacturing processes across the publication results

tions due to air compressibility. The absence of mechanical or electrical parts makes them suitable for application in restricted and unstructured environments, but the challenge of producing untethered pneumatic SRs has been the main obstacle to their wide-scale adoption in real-life settings.

Mechanical actuation through the use of rotational or linear forces is observed in 16 entries. Typically, mechanical actuation is coupled to motors, which have allowed for easier untethered operation. Ferro-magnetically-actuated robots were identified in 4 entries, 3 of which are simulation based, and require the use of an external magnet to generate motion. The use of dielectric elastomeric actuators and electroactive polymers is described in three and two entries, respectively, while three entries are actuation agnostic as the papers focus more on the design method than actuation.

Moreover, 2 identified papers describe the TO of hydrogel based SRs. Hydrogels are increasingly popular due to their low voltage and current requirements, and hydrogel-based robots require the use of an isotonic solution to create an osmotic imbalance for producing fluidic motion. Last, wire-driven and thermally-actuated robots were identified in a single entry [12] [39], respectively.

The identified application areas of optimally designed CRs and SRs are represented in Table II. Generic grasping/gripping applications appear to be the most popular area with 36 entries. It is observed that most CRs designed for this application typically use linear actuation, usually provided by motors. This causes the gripper to deform and thereby close the gap between the fingers, leading to non-form contact with objects. On the other hand, gripping SRs mostly use pneumatic actuation that generates partial form contact of the gripper fingers with the object. It can be argued that soft or compliant grippers do not qualify as SRs or CRs, due to lack of integrated autonomy. However, soft and compliant grippers possess the potential to autonomously performing actions via their integration with a manipulation system. Most TO-based compliant mechanisms observed in this study are performed on similar designs replicating the compliant plier mechanism (Fig. 1(IV)–(VI)).

This study also highlighted 9 entries in which design optimization was deployed purely on a method-based approach, and therefore were classified as application-agnostic.

Locomotion is challenging for CRs and SRs, as it requires robust and untethered actuation. The difficulty is evident as only 3 entries were identified and all had only simulation results. The applications of SRs reported in these papers include constant force maintenance, fruit grasping, indirect locomotion, and undersea robotics. The fruit grasping SR deploys a typical compliant gripper that has been modified to create a large form contact for round fruits [13]. The indirect locomotion robot involves a hybrid morphing robot with a soft component, which does not directly contribute to its locomotion [26]. The undersea robotic application is a simulation only GD-based approach towards designing structural components for deep-sea SRs [53].

Of the 31 hardware validated entries, 3D printing as the manufacturing technique has the largest percentage and accounts for 58% of these papers. Among the 3D printing methods, FDM is the dominant method due to the generally low purchase, maintenance and material cost. Most works that use FDM for topology optimized soft and compliant structures, do not study the effect of factors such as infill, non-isotroposity, layer height and extrusion ratio.

Flexible material casting is employed in 5 of the 31 cases. Most designs use casted silicones of either Dragoskin, EcoFlex or Polydimethylsiloxane (PDMS). In some cases, the structures were additionally waterjet cut for post processing. 3D printed polyjeting is implemented in 3 cases and is a relatively more expensive manufacturing technique that produces near isotroposity. For CRs, no instances of metal 3D printing are observed. While there are examples of compliant mechanisms produced with metals, CRs designed through TO or GE through metal 3D printing are yet to be identified in related literature.

The manufacturing processes are also depicted in Fig. 4. which illustrates the various manufacturing processes used across the years, and also their distribution over the same calendar year. The only paper from 2008 [14] uses a multi-part design involving McKibben actuators and wire-driven segments to generate actuation forces. This is largely due to the fact that when this paper was published, the availability of 3D printing methods for flexible and compliant parts was very limited. The 2014 publication [15] uses casted PDMS and this could be attributed to similar reasons as the previous paper. The first research outputs using 3D printing are observed in 2017. Although they use polyjet printing, this is seen as the genesis of 3D printing in producing design optimized CRs and SRs, while another entry in the same year ([19]) uses a machined flexible material. In 2018, a large rise in 3D printing as a manufacturing technique was observed. This roughly co-incides with the availability of low-cost FDM printers and the mass production of flexible materials for such printers. Methods used for manufacturing are more evenly distributed in the results for 2019, while in 2020, FDM 3D printing is seen as the most popular method. In 2022 and by the time of writing this article, the majority of papers also use FDM 3D printing as the manufacturing process for their CRs and SRs.

IV. Conclusions

The emergence of soft and compliant robots (SRs and CRs) brings about challenges in ensuring repeatability and structural reliability owing to their non-algorithmic design based on intuition and experience. However, the advent of design optimization in the form of TO and GD has led to the possibility of enabling their widespread adoption. In this paper, a systematic review of the area was performed, with the goal of identifying the trends and applications of optimally designed SRs and CRs. The search process provided 52 original entries, which were classified based on design optimization, actuation methods, applications and manufacturing processes. The years following 2016 showed a large upward trend in the publications related to this field, due to the expiry of several patents related to 3D printing between 2009 and 2014. The increase of computational resources, AI driven acceleration, and availability of open-source coding are also important. 3D printing was identified as the most popular manufacturing process, as it enables rapid prototyping of complex flexible structures exported by design optimization algorithms. Pneumatic and mechanical sources were observed as the most utilized actuation methods, while most identified applications targeted gripping and grasping applications. The findings of this study support the identified trend of using TO techniques for producing reliable and versatile CRs and SRs, while foreseeing the increase in use of AI-based techniques such as GD towards an automated framework for optimized CR and SR designs.

References

[1] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.

[2] P. Boyraz, G. Runge, and A. Raatz, "An overview of novel actuators for soft robotics," *Actuators*, vol. 7, no. 3, p. 48, 2018.

[3] N. P. Van Dijk, K. Maute, M. Langelaar, and F. Van Keulen, "Level-set methods for structural topology optimization: a review," *Structural and Multidisciplinary Optimization*, vol. 48, no. 3, pp. 437–472, 2013.

[4] S. Krish, "A practical generative design method," *Computer-Aided Design*, vol. 43, no. 1, pp. 88–100, 2011.

[5] B. Mazzolai, A. Mondini, E. Del Dottore, L. Margheri, F. Carpi, K. Suzumori, M. Cianchetti, T. Speck, S. K. Smoukov, I. Burgert *et al.*, "Roadmap on soft robotics: multifunctionality, adaptability and growth without borders," *Multifunctional Materials*, vol. 5, no. 3, p. 032001, 2022.

[6] B. Zhu, X. Zhang, H. Zhang, J. Liang, H. Zang, H. Li, and R. Wang, "Design of compliant mechanisms using continuum topology optimization: A review," *Mechanism and Machine Theory*, vol. 143, p. 103622, 2020.

[7] F. Chen and M. Y. Wang, "Design optimization of soft robots: A review of the state of the art," *IEEE Robotics & Automation Magazine*, vol. 27, no. 4, pp. 27–43, 2020.

[8] J. Tian, M. Li, Z. Han, Y. Chen, X. D. Gu, Q. J. Ge, and S. Chen, "Conformal topology optimization of multi-material ferromagnetic soft active structures using an extended level set method," *Computer Methods in Applied Mechanics and Engineering*, vol. 389, p. 114394, 2022.

[9] C.-H. Liu, L.-J. Chen, J.-C. Chi, and J.-Y. Wu, "Topology optimization design and experiment of a soft pneumatic bending actuator for grasping applications," *IEEE RAL*, vol. 7, no. 2, pp. 2086–2093, 2022.

[10] A. Zolfagharian, M. Denk, M. Bodaghi, A. Z. Kouzani, and A. Kaynak, "Topology-optimized 4d printing of a soft actuator," *Acta Mechanica Solida Sinica*, vol. 33, no. 3, pp. 418–430, 2020.

[11] A. Milojevic, S. Linss, Z. Cojbasic, and H. Handroos, "A novel simple, adaptive, and versatile soft-robotic compliant two-finger gripper with an inherently gentle touch," *Journal of Mechanisms and Robotics*, vol. 13, no. 1, p. 011015, 2021.

[12] F. Chen, W. Xu, H. Zhang, Y. Wang, J. Cao, M. Y. Wang, H. Ren, J. Zhu, and Y. F. Zhang, "Topology optimized design, fabrication, and characterization of a soft cable-driven gripper," *IEEE RAL*, vol. 3, no. 3, pp. 2463–2470, 2018.

[13] C.-H. Liu, C.-H. Chiu, T.-L. Chen, T.-Y. Pai, Y. Chen, and M.-C. Hsu, "A soft robotic gripper module with 3d printed compliant fingers for grasping fruits," in *2018 IEEE/ASME AIM*. IEEE, 2018, pp. 736–741.

[14] D. Trivedi, D. Dienno, and C. D. Rahn, "Optimal, model-based design of soft robotic manipulators," *Journal of Mechanical Design*, vol. 130, no. 9, 2008.

[15] Y. Liu and M. Y. Wang, "Topology design of a conforming gripper with distributed compliance via a level set method," in *2014 IEEE ROBIO 2014*. IEEE, 2014, pp. 2191–2196.

[16] C.-y. Zhang, L.-k. Song, C.-w. Fei, G.-p. Hao, and L.-j. Liu, "Reliability-based design optimization for flexible mechanism with particle swarm optimization and advanced extremum response surface method," *Journal of Central South University*, vol. 23, no. 8, pp. 2001–2007, 2016.

[17] H. Zhang, Y. Wang, M. Y. Wang, J. Y. H. Fuh, and A. S. Kumar, "Design and analysis of soft grippers for hand rehabilitation," in *Volume 4: Bio and Sustainable Manufacturing*. ASME, 2017, p. V004T05A003.

[18] C.-H. Liu and C.-H. Chiu, "Optimal design of a soft robotic gripper with high mechanical advantage for grasping irregular objects," in *2017 IEEE ICRA*. IEEE, 2017, pp. 2846–2851.

[19] H. Zhang, M. Y. Wang, F. Chen, Y. Wang, A. S. Kumar, and J. Y. H. Fuh, "Design and development of a soft gripper with topology optimization," in *2017 IEEE/RSJ IROS*. IEEE, 2017, pp. 6239–6244.

[20] C.-H. Liu, C.-H. Chiu, T.-L. Chen, T.-Y. Pai, M.-C. Hsu, and Y. Chen, "Topology optimization and prototype of a three-dimensional printed compliant finger for grasping vulnerable objects with size and shape variations," *Journal of Mechanisms and Robotics*, vol. 10, no. 4, p. 044502, 2018.

[21] M. van Diepen and K. Shea, "A spatial grammar method for the computational design synthesis of virtual soft robots," in *Volume 2A: 44th Design Automation Conference*. ASME, 2018, p. V02AT03A012.

[22] H. Zhang, A. S. Kumar, J. Y. H. Fuh, and M. Y. Wang, "Topology optimized design, fabrication and evaluation of a multimaterial soft gripper," in *2018 IEEE RoboSoft*. IEEE, 2018, pp. 424–430.

[23] C.-H. Liu, T.-L. Chen, T.-Y. Pai, C.-H. Chiu, W.-G. Peng, and M.-C. Hsu, "Topology synthesis, prototype, and test of an industrial robot gripper with 3d printed compliant fingers for handling of fragile objects," in *2018 WRC SARA*. IEEE, 2018, pp. 189–194.

[24] H. Zhang, A. S. Kumar, J. Y. H. Fuh, and M. Y. Wang, "Investigation on developing a topology optimized and 3d printable multimaterial soft gripper," in *2018 IEEE 14th International Conference on Control and Automation (ICCA)*. IEEE, 2018, pp. 692–697.

[25] C.-H. Liu, G.-F. Huang, C.-H. Chiu, and T.-Y. Pai, "Topology synthesis and optimal design of an adaptive compliant gripper to maximize output displacement," *Journal of Intelligent & Robotic Systems*, vol. 90, no. 3, pp. 287–304, 2018.

[26] F. Liu, W. Sun, X. Zhao, C. Li, and J. Zhou, "Method towards optimal design of dielectric elastomer actuated soft machines," *Science China Technological Sciences*, vol. 61, no. 7, 2018.

[27] W. Zhang, J. Hong, S. Ahmed, Z. Ounaies, and M. Frecker, "A two-stage optimization procedure for the design of an EAP-actuated soft gripper," in *Volume 5B: 43rd ICMAR*. ASME, 2019, p. V05BT07A051.

[28] F. Chen, K. Liu, Y. Wang, J. Zou, G. Gu, and X. Zhu, "Automatic design of soft dielectric elastomer actuators with optimal spatial

electric fields," *IEEE Transactions on Robotics*, vol. 35, no. 5, pp. 1150–1165, 2019.

[29] H. Zhang, A. S. Kumar, F. Chen, J. Y. H. Fuh, and M. Y. Wang, "Topology optimized multimaterial soft fingers for applications on grippers, rehabilitation, and artificial hands," *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 1, pp. 120–131, 2019.

[30] L. Ding, N. Dai, X. Mu, S. Xie, X. Fan, D. Li, and X. Cheng, "Design of soft multi-material pneumatic actuators based on principal strain field," *Materials & Design*, vol. 182, 2019.

[31] J. Tian, X. Zhao, X. D. Gu, and S. Chen, "Designing conformal ferromagnetic soft actuators using extended level set methods (x-LSM)," in *Volume 10: 44th ICMAR*. ASME, 2020, p. V010T10A012.

[32] J. Tian, X. Zhao, X. Gu, and S. Chen, "Designing ferromagnetic soft robots (FerroSoRo) with level-set-based multiphysics topology optimization," in *2020 IEEE ICRA*. IEEE, 2020, pp. 10 067–10 074.

[33] B. Caasenbrood, A. Pogromsky, and H. Nijmeijer, "A computational design framework for pressure-driven soft robots through nonlinear topology optimization," in *2020 3rd IEEE RoboSoft*. IEEE, 2020, pp. 633–638.

[34] C.-H. Liu, M.-C. Hsu, and T.-L. Chen, "Topology and geometry optimization for design of a 3d printed compliant constant-force mechanism," in *2020 IEEE/ASME AIM*. IEEE, 2020, pp. 553–558.

[35] C.-H. Liu, F.-M. Chung, Y. Chen, C.-H. Chiu, and T.-L. Chen, "Optimal design of a motor-driven three-finger soft robotic gripper," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 4, pp. 1830–1840, 2020.

[36] Y. Luo, J. Xing, and Z. Kang, "Topology optimization using material-field series expansion and kriging-based algorithm: An effective non-gradient method," *Computer Methods in Applied Mechanics and Engineering*, vol. 364, 2020.

[37] E. M. de Souza and E. C. N. Silva, "Topology optimization applied to the design of actuators driven by pressure loads," *Structural and Multidisciplinary Optimization*, vol. 61, no. 5, pp. 1763–1786, 2020.

[38] R. Wang, X. Zhang, B. Zhu, H. Zhang, B. Chen, and H. Wang, "Topology optimization of a cable-driven soft robotic gripper," *Structural and Multidisciplinary Optimization*, vol. 62, no. 5, pp. 2749–2763, 2020.

[39] B.-E. Liu and W. Yu, "On-demand direct design of polymeric thermal actuator by machine learning algorithm," *Chinese Journal of Polymer Science*, vol. 38, no. 8, 2020.

[40] J. Tian, X. D. Gu, and S. Chen, "Multi-material topology optimization of ferromagnetic soft robots using reconciled level set method," in *Volume 8B: 45th ICMAR*. ASME, 2021, p. V08BT08A014.

[41] Y. Sun, Y. Liu, N. Zhou, and T. C. Lueth, "A MATLAB-based framework for designing 3d topology optimized soft robotic grippers," in *2021 IEEE/ASME AIM*. IEEE, 2021, pp. 1283–1289.

[42] S. Chen, F. Chen, Z. Cao, Y. Wang, Y. Miao, G. Gu, and X. Zhu, "Topology optimization of skeleton-reinforced soft pneumatic actuators for desired motions," *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 4, pp. 1745–1753, 2021.

[43] C.-H. Liu, F.-M. Chung, and Y.-P. Ho, "Topology optimization for design of a 3d-printed constant-force compliant finger," *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 4, pp. 1828–1836, 2021.

[44] S. Chen, Y. Wang, D. Li, F. Chen, and X. Zhu, "Enhancing interaction performance of soft pneumatic-networks grippers by skeleton topology optimization," *Science China Technological Sciences*, vol. 64, no. 12, 2021.

[45] R. Ortigosa and J. Martínez-Frutos, "Topology optimisation of stiffeners layout for shape-morphing of dielectric elastomers," *Structural and Multidisciplinary Optimization*, vol. 64, no. 6, 2021.

[46] N. Boddeti, T. Van Truong, V. S. Joseph, T. Stalin, T. Calais, S. Y. Lee, M. L. Dunn, and P. Valdivia y Alvarado, "Optimal soft composites for under-actuated soft robots," *Advanced Materials Technologies*, vol. 6, no. 8, p. 2100361, 2021.

[47] Z. Chen, H. Rahimi Nohooji, and C.-M. Chew, "Development of topology optimized bending-twisting soft finger," *Journal of Mechanisms and Robotics*, vol. 14, no. 5, p. 051003, 2022.

[48] Y. Qiu, S. Zhang, W. Zhang, H. Ye, H. Zhang, and Y. Zheng, "Coupling moving morphable voids and components based topology optimization of hydrogel structures involving large deformation," *Journal of Applied Mechanics*, vol. 89, no. 1, p. 011008, 2022.

[49] F. Lamping and K. M. de Payrebrune, "A virtual work model for the design and parameter identification of cylindrical pressure-driven soft actuators," *Journal of Mechanisms and Robotics*, vol. 14, no. 3, p. 031004, 2022.

[50] M. van Diepen and K. Shea, "Co-design of the morphology and actuation of soft robots for locomotion," *Journal of Mechanical Design*, vol. 144, no. 8, p. 083305, 2022.

[51] M. Maggi, G. Mantriota, and G. Reina, "Introducing POLYPUS: A novel adaptive vacuum gripper," *Mechanism and Machine Theory*, vol. 167, 2022.

[52] P. Kumar and M. Langelaar, "Topological synthesis of fluidic pressure-actuated robust compliant mechanisms," *Mechanism and Machine Theory*, vol. 174, p. 104871, 2022.

[53] S. Yin, Z. Jia, X. Li, J. Zhu, Y. Xu, and T. Li, "Machine-learning-accelerated design of functional structural components in deep-sea soft robots," *Extreme Mechanics Letters*, vol. 52, p. 101635, 2022.

[54] C.-H. Liu and P.-T. Hung, "Effect of the infill density on the performance of a 3d-printed compliant finger," *Materials & Design*, vol. 223, 2022.

[55] M. Mayyas, "Design characterization of 3d printed compliant gripper," *Meccanica*, vol. 57, no. 3, pp. 723–738, 2022.

[56] A. J. Gil, R. Ortigosa, J. Martínez-Frutos, and N. Ellmer, "In-silico design and computational modelling of electroactive polymer based soft robotics," in *Towards Autonomous Robotic Systems*. Springer International Publishing, 2022, vol. 13546, pp. 81–91, series Title: Lecture Notes in Computer Science.

[57] G. B. Mahanta, B. B. V. L. Deepak, A. Rout, and B. B. Biswal, "Optimal design optimization of a hybrid rigid–soft robotic hand using an evolutionary multi-objective algorithm," in *Applications of Computational Methods in Manufacturing and Product Design*. Springer Nature Singapore, 2022, pp. 63–72, series Title: Lecture Notes in Mechanical Engineering.

[58] E. Hermoza Llanos, M. Hüsing, B. Corves, and A. Saxena, "Compliant finger gripper based on topology optimization," in *Conference on Microactuators and Micromechanisms*. Springer, 2023, pp. 31–45.

[59] P. Kumar, "Towards topology optimization of pressure-driven soft robots," in *Microactuators, Microsensors and Micromechanisms*. Springer International Publishing, 2023, vol. 126, pp. 19–30, series Title: Mechanisms and Machine Science.

[60] J. Horvath, "A brief history of 3d printing," in *Mastering 3D Printing*. Springer, 2014, pp. 3–10.

[61] D. Blythe, "Rise of the graphics processor," *Proceedings of the IEEE*, vol. 96, no. 5, pp. 761–778, 2008.

[62] A. Nikzad and M. Mehregan, "Techno-economic, and environmental evaluations of a novel cogeneration system based on solar energy and cryptocurrency mining," *Solar Energy*, vol. 232, pp. 409–420, 2022.

[63] S. Oh, Y. Jung, S. Kim, I. Lee, and N. Kang, "Deep generative design: Integration of topology optimization and generative models," *Journal of Mechanical Design*, vol. 141, no. 11, 2019.

[64] O. Sigmund, "A 99 line topology optimization code written in matlab," *Structural and multidisciplinary optimization*, vol. 21, no. 2, pp. 120–127, 2001.

[65] H. A. Eschenauer and N. Olhoff, "Topology optimization of continuum structures: a review," *Appl. Mech. Rev.*, vol. 54, no. 4, pp. 331–390, 2001.

[66] J. A. Gallego and J. Herder, "Synthesis methods in compliant mechanisms: An overview," in *IDETC-CIE*, vol. 49040, 2009, pp. 193–214.

[67] E. Tyflopoulos, F. D. Tollnes, M. Steinert, A. Olsen *et al.*, "State of the art of generative design and topology optimization and potential research needs," *DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th-17th August 2018*, 2018.