This full text paper was peer-reviewed at the direction of IEEE Instrumentation and Measurement Society prior to the acceptance and publication.

On the use of soft continuum robots for remote measurement tasks in constrained environments: a brief overview of applications

L. Angrisani[1], S. Grazioso[2], G. Di Gironimo[2], D. Panariello[2], A. Tedesco[3]
[1]Department of Electrical Engineering and Information Technology, University of Naples Federico II, Naples, Italy
[2]Department of Industrial Engineering, University of Naples Federico II, Naples, Italy
[3]Department of Chemical, Materials and Production Engineering, University of Naples Federico II, Naples, Italy
Corresponding author: stanislao.grazioso@unina.it

***Abstract*—Soft continuum robots provide high dexterity in constrained spaces, while guaranteeing a compliant interaction with the surrounding environment. Over the last years, they have been used to improve many manipulation tasks, going from maintenance, inspection and repair in industrial–related environments to minimally invasive surgery in the medical field. This paper investigates the use of soft continuum robots for remote measurement tasks, and focuses on the following application scenarios where they have already demonstrated their benefits: space, aerospace, nuclear, marine and medical fields. The limitations of existing applications and perspectives of future directions are also discussed.**

I. INTRODUCTION

The successful execution of remote measurement tasks in environments which are difficult to reach by humans requires the use of robotics technologies. A class of robotic systems which is suitable for remote measurement applications is represented by flying robots. Indeed, by embedding sensors on drones, it is possible to convert the flying robot in a remote measurement system [1]. To date, drones have successfully demonstrated their use in a wide range of measurement applications: aerial photogrammetry, agriculture, monitoring of buildings, inspection of power lines [2]. However, reaching remote sites through constrained and small–scale spaces using drones is highly challenging as they require accurate and reliable sensing systems for navigation; indeed, developing methods for efficient navigation of drones in GPS–denied environments as indoor spaces is still an open issue. Furthermore, drones can not be used in such contexts which also require safe interaction with the surrounding environment (i.e. surgery).

One possible technological solution for enabling remote measurement tasks in constrained and high–risk environments is represented by soft continuum robots [3], namely robots with a continuously deformable mechanical structure. Their inherently compliant structure enhance the operational capabilities of traditional robots by offering the possibility to traverse cluttered spaces and conform their shape to nonlinear paths, while guaranteeing, at the same time, a compliant interaction with the environment. Furthermore, they can also be used to manipulate objects in complex environments; this is relevant as sensing the environment is often required for remote on–line execution of manipulation tasks. Therefore, having the same robotic platform which can be used as both measurement and manipulation system could be a great advantage.

The design of soft robots takes inspiration from continuum biological structures, as climbing plants, snakes, trunks of elephants and tentacles of octopuses. In order to replicate the motion of their natural counterparts, soft continuum robots are basically composed by one or more elastic elements, which can be actuated by intrinsic sources (as fluids) or by external motors which transmit forces to the robotic structure through transmission mechanisms (as tendons/cables). Despite more complex models are needed to describe and control their shapes [4]–[7], soft robots are relatively easy to fabricate.

In the literature, existing review papers on soft continuum robots have focused on: continuum robots in general [8]; bioinspired soft robots [3], [9]; design and fabrication of soft robots [10]; design and kinematic modeling of constant curvature robots [11]; medical continuum robots [12]; shape sensing techniques for medical continuum robots [13]; force sensing using fiber optic sensors [14].

However, none of these works is specifically focused on *measurement applications* enabled by soft continuum robots in constrained environments.

II. OVERVIEW OF MEASUREMENT APPLICATIONS USING SOFT CONTINUUM ROBOTS

Here we review the use of soft continuum robots for remote *measurement tasks* in the following environments: space, aerospace, nuclear, marine, surgical (see, e.g. Fig. 1 for some illustrative examples of robots used in these environments).

A. Space

In space environments, soft continuum robots have been used for in–orbit monitoring and inspection. Motivated by the need of reaching tight spaces through complex geometries in space systems, their design was mainly inspired by plant vines, which are natural, thin continuum structures.

The first developed robot of this kind is the NASA Tendril robot, which is capable to extend deep into crevasses and under thermal blankets which cover space instruments to

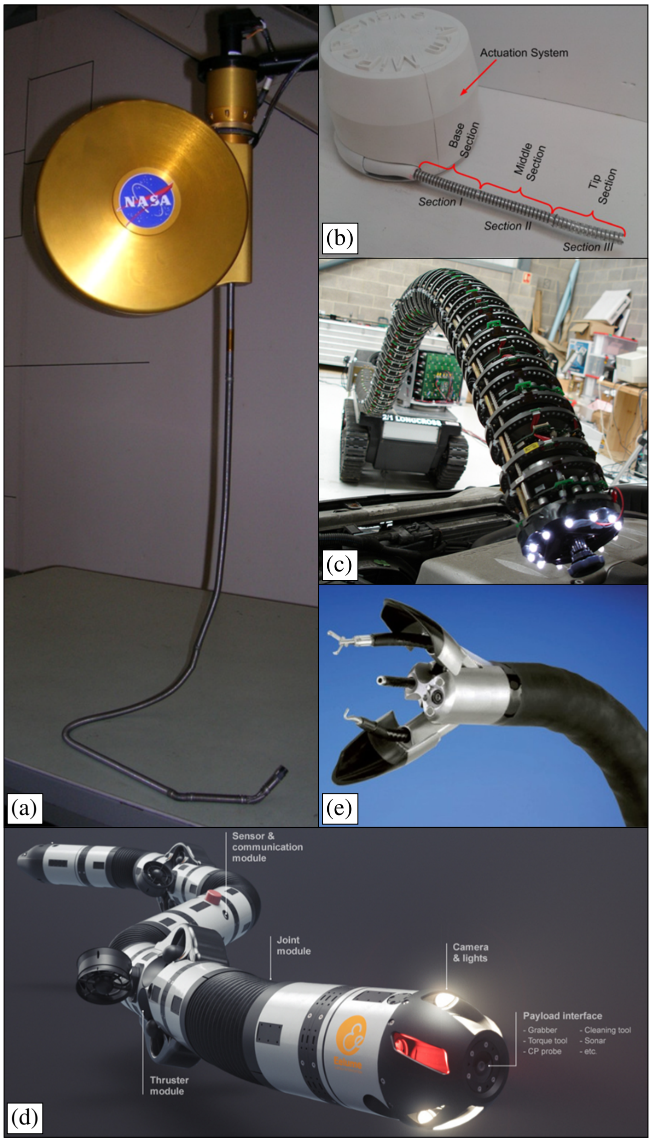

Fig. 1. Soft continuum robots used in measurement applications. (a) Tendril robot for in–space inspection developed by NASA's Johnson Space Center [15]. (b) Slender continuum for on–wing inspection of gas turbine engines developed by Rolls-Royce University Technology Center (UTC) at University of Nottingham [16]. (c) Snake–arm robot for nuclear applications developed by OC Robotics [17] (http://www.ocrobotics.com/). (d) Eel–like robot for subsea inspection developed by Eelume, a spin–off company from Norwegian University of Science and Technology [18] (https://eelume.com/). (e) ANUBISCOPE, a flexible endoscope prototype developed by Karl-Storz/IRCAD [19].

inspect areas largely inaccessible by astronauts and existing in–space tools [15]. NASA Tendril robot has a diameter–to–length aspect ratio of 1:100 (1cm:1m) and it is equipped with a tip mounted CCD camera for visual inspection. The robot structure is composed of passive springs interconnected by threaded links, and it only presents two actively controlled bending sections. This structure produces undesired effects while in operation, such as section buckling due to coupling of springs and spring twisting due to external loads. Since these aspects limit the control effectiveness, an enhanced concept based on concentric tubes actuated by a spring–tendon system was proposed in [20], [21]. Then, this design was enhanced by placing spines along the structure, which allow exploiting environmental contacts through local bracing. The novel design improved the overall stability and accuracy of the system; furthermore, it allowed increasing the maximum body length of the robot [22]. The novel vine–like robot was also used for environmental monitoring applications (remote sensor placement, data collection and analysis, imaging difficult–to–reach areas) in the 1 g Space Station environment at NASA's Johnson Space Center [23].

Most of research on continuum instrumentation for space applications has been funded by NASA.

B. Airplane industry

The need for minimizing jet engine downtime has recently pushed roboticists and technologists towards the development of remote robotic solutions to speed up boreblending procedures [24]. These procedures consist of machining stress–relief features on gas engine compressor blades which present mechanical defects. As it is simple to imagine, the aeroengine needs to be inspected from the inside, in order to identify the blades to repair. In the current airplane industry, boreblending procedures are still performed with manual tools and instruments inserted via borescope ports [25]. Due to their unique features, slender continuum robots represent a possible technological solution to automate boreblending. With this in mind, authors from University of Nottingham have developed a boreblending continuum robot for on–wing inspection and repair of aeroengines blades [16], [26]. This extrinsically actuated robot navigates into the compressor via borescope ports, and, as it is equipped with stereo cameras, it provides 3D point clouds of the surrounding environment; therefore, useful data as key measures, size and shapes of mechanical defects of aerofoils are obtained. These are then used for in–situ repairing tasks [27].

Most of research on remote boreblending technologies has been funded by Rolls-Royce, a world leader in gas turbine jet engines.

C. Nuclear reactors

Nuclear reactors are hazardous environments where humans can not access due to high levels of radioactivity. Continuum robots can be deployed inside reactor vessels through access ports. Their principal measurement application is the remote diagnostics of in–vessel components, as the latter need to be remotely replaced in case of damages and/or high activation [28]. When the high level of expected radiations inside the chamber prevent the insertion of survey systems from the vessel ports, continuum instruments are inserted through the piping system to provide remote inspection of the main vessel [29]. Another application in this scenario is the in–bore inspection of pipes, which is required for their remote cutting and welding [30]. It is worth noticing that these robots have to be equipped with special sensors devoted for such hazardous and demanding environments.

Remote nuclear operations are the oldest applications of robotics–related technologies for hazardous environments [31]. Born from the United Kingdom research on nuclear engineering, extrinsically actuated snake arm nuclear robots are currently manufactured and retailed by OC Robotics [17]. Initially tailored for nuclear applications, these robots have been used also in other industry–oriented domains [32]; currently, they represent the only commercially available solutions of general–purpose continuum–like robots.

D. Marine environments

The abilities to access and traverse confined spaces make continuum robots ideal candidates as explorators of those subsea sites which are difficult to reach with standard underwater robotic platforms [33]. A great example of continuum–like robotic platform for underwater applications is Eelume, an eel–like robot developed by authors from Norwegian University of Science and Technology [18]. Eelume is specifically targeted at inspection operations in constrained locations of subsea installation for oil and gas industry. Other existing underwater platforms are inspired by the natural octopus, as the one developed by authors from the Italian Sant'Anna School of Advanced Studies [34]; however, these platforms are mostly prototypes devoted to research studies.

Furthermore, since soft robots offer the possibility to safely interact with the surrounding environment, they can be used when it is required to delicately manipulate objects and/or biological species. Authors from Harward University have indeed developed a soft robotic gripper to sample fragile species on deep reefs [35]. Despite this application involves manipulation tasks (which are not object of this review), remote sampling can be seen in a broader sense as a measurement application, as scientific measurement studies can be carried out with the remotely-sampled organisms.

E. Medicine

The need for less invasive surgical procedures is driving the use of soft continuum robots in medicine. Indeed, soft continuum robots can allow access inside the human body through small incisions or natural orifices, and navigate along curvilinear paths, while providing safe interaction with the anatomic environment. They are the technological solution for the recent trends of natural orifice transluminal surgery [36] and single port laparoscopy [37]. Over the last decade, a huge amount of work has been done in medical continuum robots [12]. In the current work, we are only focused on continuum instrumentation used for aiding, from a measurement point of view, robot–assisted surgical treatments and/or simply medical diagnosis.

In minimally invasive robotic surgery, measurement applications of continuum instruments include: (i) enhanced visualization of the surgical site and surrounding anatomy; (ii) biopsy, i.e. sampling suspected cells or tissue for examination under the microscope; (iii) tissue characterization.

Flexible endoscopes with bendable tips are instruments aiding the surgical robot (which has to perform the intervention) by providing visualization of areas which are difficult to reach during operation [38]. They can be either equipped by the surgical robot [39] or integrated within it [40].

Biopsy continuum robots and flexible needles can reduce the risks of abrasion and injury to patients during biopsy, with respect to traditional systems. Continuum–like systems have been used in a wide spectrum of biopsy applications, including nasopharyngeal biopsy [41], maxillary sinus area biopsy [42], transthoracic lung biopsies [43], endoscopic tumor biopsy [44]. Biopsy involves a sampling task; as before, we consider it as a special case of measurement application, since the sampled biological structure can be used for measurement studies.

Soft tissues exhibit complex nonlinear, anisotropic, nonhomogeneous, time, and rate dependent behavior [45]. Material properties of soft tissues are challenging to measure and different approaches have been proposed in the past years [46]. Soft continuum robots might provide tools for remote characterization and measures of soft tissue, not only because they can access constrained sites and provide safe robot–tissue interaction for in–situ measurement tasks, but also for their intrinsic force sensing capability [47]. Indeed, authors in [47] have developed a method to estimate an unknown wrench at the tip by measuring the axial loads acting on the backbones of a multisegment continuum robot. This means that continuum robots might be used to sense contact forces with soft tissues, without using force sensors. This is of great advantage, as placing commercial force sensors at the tip of a surgical end–effector might be not always feasible, mainly due to side constraints and magnetic resonance imaging compatibility.

III. DISCUSSION AND FUTURE DIRECTIONS

Soft continuum robots have shown great potentials for measurement applications where humans and traditional means can not access due to constraints given by the environment. In these contexts, such systems act as tools transporting sensors for data acquisition, environment monitoring, visual inspection, diagnostics. Continuum robots used as measurement systems can indeed provide fundamental information to perform critical tasks, as the location and characterization of a damaged blade in a gas engine for a blending procedure or the visualization of anatomy for a surgical operation. Since most of current robotic systems working in hazardous domains are not fully autonomous (they either share a certain level of autonomy with humans, or they are full teleoperated), continuum measurement systems can be seen as tools for augmenting the human sensory system. As a matter of fact, in real applications, the environmental data that they provide are used by humans to take informed decisions and perform the remote task with a greater awareness. However, as data provided especially by continuum–like instrumentation lack of information, human experience still matters a lot in performing critical tasks. As an example in robotic surgery, flexible endoscopes, although being introduced since many years, still offer poor image resolution, if compared to rigid endoscopes.

Future research on continuum measurement systems in the listed applications should go in the direction of developing systems for enhancing human capabilities. Indeed, these systems can provide useful additional perception which goes beyond those provided by physical senses and classic instrumentation. Having a deeper knowledge of the surrounding environment allows taking more informed decisions for performing a critical task. To this end, emerging technologies for 3D visualization, 3D reconstruction and augmented reality implemented on continuum measurement systems could have a great impact. For instance, in the medical field, stereo cameras placed at the tip of a flexible endoscope could endow the physician with a 3D visualization of the surgical site, which is something that could bring great benefits as considered by the surgeon community. Furthermore, 3D scanning the internal anatomy of the patient could have a tremendous impact in delivering custom treatments to patients. Indeed, a virtual 3D reconstruction of the internal body could be used for off–line planning of surgical interventions, or even, for designing surgical instruments tailored for the patient anatomy. As the single port access surgery would become widespread, we believe that disposable custom–fit 3D printed continuum devices would become the common practice. Indeed, they can be much more cost effective than the current rigid instruments, which, despite having a useful life of about ten operations, are today really expensive.

In the application scenarios analysed in this work, soft continuum robots have already started in demonstrating their capabilities as remote measurement systems, despite the observed limitations. However, soft continuum robots could be used in many other applications of interest by the measurements community, where there is not yet a relevant scientific evidence of their use. Future applications might include: (i) power line inspection; (ii) remote power quality analysis [48]; (iii) monitoring of infrastructure sites which are difficult to access; (iv) structural health monitoring [49]; (v) in–situ diagnosis of electronic circuits; (vi) in–situ measuring of thin structures [50]; (vii) inspection of electrical cabinets and/or data center racks; (viii) remote ultrasonic–based nondestructive testing [51]; (ix) urban disaster operations, as they can bring sensors in a priori unknown and cluttered environment.

Another limitation of the soft continuum robots analysed in this work is that, in most of cases, they are robots with a fixed base. Therefore, despite their unique capabilities of going inside narrow spaces and adapt their shape to curvilinear path, they offer a limited workspace. To limit this problem, their design can be improved by using telescopic sections; however, even in this case, the workspace is limited, especially for such tasks that require inspection of large environments. There are two possible solutions to this problem: (1) coupling the continuum robot with a mobile or aerial robot; (2) giving locomotion and climbing capabilities to the continuum robot. In the first case, the mobile or aerial robot is used to bring the continuum robot in the inspection site, with the latter performing the measurement task. With the aim of enhancing the operational capabilities of traditional flying robots, two European projects have been recently funded for the developed of a robotic platform where a flying robot is coupled with a rigid articulated manipulator (AEROARMS, https://aeroarms-project.eu/) and a rigid hyper–redundant long reach manipulator (HYFLIERS, https://www.oulu.fi/hyfliers/). Despite these recent progresses, aerial manipulation and measurement tasks are still performed coupling a rigid manipulator to the drone [52]. Coupling a soft manipulator to the flying robot could be a possibility for future works in this domain. In the second solution, a continuum robot is endowed with internal locomotion and/or climbing. With this respect, there is an on–going research on different paradigms for soft robot locomotion, inspired by the locomotion of snakes and caterpillars [53]. On the other side, soft robots able to climb on different surfaces are inspired by geckos [54]. As an example, these robots can provide an alternative solution to drones for in–situ inspection of power distribution lines. In this context, it has been underlined that a robot able to climb along the conductor and overcome various obstacles on the power line might provide high inspection accuracy with respect to flying robots [55]. Another important aspect of soft robots is that they can exploit internal energy as additional source of actuation for locomotion/climbing purposes. Thus, soft robots designed considering this aspect can be more energy efficient, overcoming the current autonomy problem of traditional aerial robots. They could eventually become permanent residents of many sites, for their continuous monitoring.

In summary, in this preliminary work we have emphasized the features of soft continuum robots which are interesting for their use in remote measurement tasks. This first analysis underlines that soft continuum robots have been used as remote measurement systems mainly in the following environments: space, aerospace, nuclear, marine, surgical. However, their capabilities might benefit many other applications which are worth to be investigated in the future.

REFERENCES

[1] K. P. Valavanis and G. J. Vachtsevanos, *Handbook of unmanned aerial vehicles*. Springer, 2015.

[2] P. Daponte, L. De Vito, G. Mazzilli, F. Picariello, S. Rapuano, and M. Riccio, "Metrology for drone and drone for metrology: Measurement systems on small civilian drones," in *2015 IEEE Metrology for Aerospace (MetroAeroSpace)*. IEEE, 2015, pp. 306–311.

[3] S. Kim, C. Laschi, and B. Trimmer, "Soft robotics: a bioinspired evolution in robotics," *Trends in biotechnology*, vol. 31, no. 5, pp. 287–294, 2013.

[4] S. Grazioso, G. Di Gironimo, and B. Siciliano, "A geometrically exact model for soft continuum robots: The finite element deformation space formulation," *Soft robotics*, 2018.

[5] S. Grazioso, V. Sonneville, G. Di Gironimo, O. Bauchau, and B. Siciliano, "A nonlinear finite element formalism for modelling flexible and soft manipulators," in *2016 IEEE Int. Conf. on Simulation, Modeling, and Programming for Autonomous Robots*. IEEE, 2016, pp. 185–190.

[6] S. Grazioso, G. Di Gironimo, and B. Siciliano, "From differential geometry of curves to helical kinematics of continuum robots using exponential mapping," in *International Symposium on Advances in Robot Kinematics*. Springer, 2018, pp. 319–326.

[7] R. K. Katzschmann, C. Della Santina, Y. Toshimitsu, A. Bicchi, and D. Rus, "Dynamic motion control of multi-segment soft robots using piecewise constant curvature matched with an augmented rigid body model," in *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)*. IEEE, 2019, pp. 454–461.

[8] G. Robinson and J. B. C. Davies, "Continuum robots-a state of the art," in *Proceedings 1999 IEEE International Conference on Robotics and Automation*, vol. 4. IEEE, 1999, pp. 2849–2854.

[9] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," *Applied bionics and biomechanics*, vol. 5, no. 3, pp. 99–117, 2008.

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

[11] R. J. Webster III and B. A. Jones, "Design and kinematic modeling of constant curvature continuum robots: A review," *The International Journal of Robotics Research*, vol. 29, no. 13, pp. 1661–1683, 2010.

[12] J. Burgner-Kahrs, D. C. Rucker, and H. Choset, "Continuum robots for medical applications: A survey," *IEEE Transactions on Robotics*, vol. 31, no. 6, pp. 1261–1280, 2015.

[13] C. Shi, X. Luo, P. Qi, T. Li, S. Song, Z. Najdovski, T. Fukuda, and H. Ren, "Shape sensing techniques for continuum robots in minimally invasive surgery: A survey," *IEEE Transactions on Biomedical Engineering*, vol. 64, no. 8, pp. 1665–1678, 2017.

[14] F. Taffoni, D. Formica, P. Saccomandi, G. Pino, and E. Schena, "Optical fiber-based mr-compatible sensors for medical applications: An overview," *Sensors*, vol. 13, no. 10, pp. 14 105–14 120, 2013.

[15] J. S. Mehling, M. A. Diftler, M. Chu, and M. Valvo, "A minimally invasive tendril robot for in-space inspection," in *IEEE/RAS-EMBS Int. Conf. on Biomedical Robotics and Biomechatronics*, 2006, pp. 690–695.

[16] X. Dong, D. Axinte, D. Palmer, S. Cobos, M. Raffles, A. Rabani, and J. Kell, "Development of a slender continuum robotic system for on-wing inspection/repair of gas turbine engines," *Robotics and Computer-Integrated Manufacturing*, vol. 44, pp. 218–229, 2017.

[17] R. Buckingham and A. Graham, "Nuclear snake-arm robots," *Industrial Robot: An International Journal*, vol. 39, no. 1, pp. 6–11, 2012.

[18] P. Liljebäck and R. Mills, "Eelume: A flexible and subsea resident imr vehicle," in *Oceans 2017-Aberdeen*. IEEE, 2017, pp. 1–4.

[19] S. Perretta, B. Dallemagne, B. Barry, and J. Marescaux, "The anubiscope^ sup^ flexible platform ready for prime time: description of the first clinical case," *Surgical endoscopy*, vol. 27, no. 7, p. 2630, 2013.

[20] M. M. Tonapi, I. S. Godage, and I. D. Walker, "Next generation rope-like robot for in-space inspection," in *2014 IEEE Aerospace Conference*. IEEE, 2014, pp. 1–13.

[21] M. M. Tonapi, I. S. Godage, A. Vijaykumar, and I. D. Walker, "A novel continuum robotic cable aimed at applications in space," *Advanced Robotics*, vol. 29, no. 13, pp. 861–875, 2015.

[22] M. B. Wooten and I. D. Walker, "A novel vine-like robot for in-orbit inspection," in *45th Int. Conf. on Environmental Systems*, 2015.

[23] D. Nahar, P. M. Yanik, and I. D. Walker, "Robot tendrils: Long, thin continuum robots for inspection in space operations," in *2017 IEEE Aerospace Conference*. IEEE, 2017, pp. 1–8.

[24] D. Alatorre, B. Nasser, A. Rabani, A. Nagy-Sochacki, X. Dong, D. Axinte, and J. Kell, "Teleoperated, in situ repair of an aeroengine: Overcoming the internet latency hurdle," *IEEE Robotics & Automation Magazine*, vol. 26, no. 1, pp. 10–20, 2019.

[25] W. Lang, "The art of borescope photography," *Materials evaluation*, vol. 45, no. 12, pp. 1361–1364, 1987.

[26] M. Wang, D. Palmer, X. Dong, D. Alatorre, D. Axinte, and A. Norton, "Design and development of a slender dual-structure continuum robot for in-situ aeroengine repair," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2018, pp. 5648–5653.

[27] D. Axinte, X. Dong, D. Palmer *et al.*, "Mirorminiaturized robotic systems for holistic in situ repair and maintenance works in restrained and hazardous environments," *IEEE/ASME Trans. on Mechatronics*, vol. 23, pp. 978–981, 2018.

[28] S. Grazioso, G. Di Gironimo, and B. Siciliano, "Modeling and vibration control of flexible mechanical systems for demo remote maintenance: Results from the flexarm project," *Fusion Engineering and Design*, 2019.

[29] J. A. S. Rico, G. Endo, S. Hirose, and H. Yamada, "Development of an actuation system based on water jet propulsion for a slim long-reach robot," *Robomech Journal*, vol. 4, no. 1, p. 8, 2017.

[30] K. Keogh, S. Kirk, W. Suder, I. Farquhar, T. Tremethick, and A. Loving, "Laser cutting and welding tools for use in-bore on eu-demo service pipes," *Fusion Engineering and Design*, vol. 136, pp. 461–466, 2018.

[31] J. Trevelyan, W. R. Hamel, and S.-C. Kang, "Robotics in hazardous applications," in *Springer handbook of robotics*. Springer, 2016.

[32] R. Buckingham, V. Chitrakaran, R. Conkie *et al.*, "Snake-arm robots: a new approach to aircraft assembly," SAE Technical Paper, Tech. Rep., 2007.

[33] G. Antonelli, *Underwater robots*. Springer, 2014, vol. 3.

[34] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, and P. Dario, "Soft robot arm inspired by the octopus," *Advanced Robotics*, vol. 26, no. 7, pp. 709–727, 2012.

[35] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, and D. F. Gruber, "Soft robotic grippers for biological sampling on deep reefs," *Soft robotics*, vol. 3, no. 1, pp. 23–33, 2016.

[36] J. P. Pearl and J. L. Ponsky, "Natural orifice translumenal endoscopic surgery: a critical review," *Journal of Gastrointestinal Surgery*, vol. 12, no. 7, pp. 1293–1300, 2008.

[37] J. R. Romanelli and D. B. Earle, "Single-port laparoscopic surgery: an overview," *Surgical endoscopy*, vol. 23, no. 7, pp. 1419–1427, 2009.

[38] B. P. M. Yeung and T. Gourlay, "A technical review of flexible endoscopic multitasking platforms," *International journal of surgery*, vol. 10, no. 7, pp. 345–354, 2012.

[39] R. J. Hendrick, C. R. Mitchell, S. D. Herrell, and R. J. Webster III, "Hand-held transendoscopic robotic manipulators: A transurethral laser prostate surgery case study," *The International journal of robotics research*, vol. 34, no. 13, pp. 1559–1572, 2015.

[40] S. Can, C. Staub, A. Knoll, A. Fiolka, A. Schneider, and H. Feussner, "Design, development and evaluation of a highly versatile robot platform for minimally invasive single-port surgery," in *IEEE/RAS–EMBS Int. Conf. on Biomedical Robotics and Biomechatronics*, 2012, pp. 817–822.

[41] L. Wu, S. Song, K. Wu, C. M. Lim, and H. Ren, "Development of a compact continuum tubular robotic system for nasopharyngeal biopsy," *Medical & biological eng. & comp.*, vol. 55, no. 3, pp. 403–417, 2017.

[42] H.-S. Yoon, H.-J. Cha, J. Chung, and B.-J. Yi, "Compact design of a dual master-slave system for maxillary sinus surgery," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2013, pp. 5027–5032.

[43] L. B. Kratchman, M. M. Rahman, J. R. Saunders, P. J. Swaney, and R. J. Webster, "Toward robotic needle steering in lung biopsy: a tendon-actuated approach," in *Medical Imaging 2011: Visualization, Image-Guided Procedures, and Modeling*, vol. 7964. International Society for Optics and Photonics, 2011, p. 79641I.

[44] Y. Gao, K. Takagi, T. Kato, N. Shono, and N. Hata, "Continuum robot with follow the leader motion for endoscopic third ventriculostomy and tumor biopsy," *IEEE Transactions on Biomedical Engineering*, 2019.

[45] Y.-c. Fung, *Biomechanics: mechanical properties of living tissues*. Springer Science & Business Media, 2013.

[46] E. Samur, M. Sedef, C. Basdogan, L. Avtan, and O. Duzgun, "A robotic indenter for minimally invasive measurement and characterization of soft tissue response," *Medical Image Analysis*, vol. 11, no. 4, pp. 361–373.

[47] K. Xu and N. Simaan, "Intrinsic wrench estimation and its performance index for multisegment continuum robots," *IEEE Transactions on Robotics*, vol. 26, no. 3, pp. 555–561, 2010.

[48] L. Angrisani, P. Daponte, and M. D'Apuzzo, "A method based on wavelet networks for the detection and classification of transients," in *Proceedings of the IEEE Instrumentation and Measurement Technology Conference (IMTC/98)*, vol. 2. IEEE, 1998, pp. 903–908.

[49] L. Gallucci, C. Menna, L. Angrisani, D. Asprone, R. S. L. Moriello, F. Bonavolontà, and F. Fabbrocino, "An embedded wireless sensor network with wireless power transmission capability for the structural health monitoring of reinforced concrete structures," *Sensors*, vol. 17, no. 11, p. 2566, 2017.

[50] L. Angrisani and P. Daponte, "Thin thickness measurements by means of a wavelet transform-based method," *Measurement*, vol. 20, no. 4, pp. 227–242, 1997.

[51] L. Angrisani and R. S. L. Moriello, "Estimating ultrasonic time-of-flight through quadrature demodulation," *IEEE transactions on instrumentation and measurement*, vol. 55, no. 1, pp. 54–62, 2006.

[52] F. Ruggiero, V. Lippiello, and A. Ollero, "Aerial manipulation: A literature review," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 1957–1964, 2018.

[53] I. H. Han, H. Yi, C.-W. Song, H. E. Jeong, and S.-Y. Lee, "A miniaturized wall–climbing segment robot inspired by caterpillar locomotion," *Bioinspiration & biomimetics*, vol. 12, no. 4, p. 046003, 2017.

[54] G. Gu, J. Zou, R. Zhao, X. Zhao, and X. Zhu, "Soft wall-climbing robots," *Science Robotics*, vol. 3, no. 25, p. eaat2874, 2018.

[55] J. Katrasnik, F. Pernus, and B. Likar, "A survey of mobile robots for distribution power line inspection," *IEEE Transactions on power delivery*, vol. 25, no. 1, pp. 485–493, 2010.