Branch-Manoeuvring Capable Pipe Cleaning Robot for Aquaponic Systems[⋆]

Kristian Muri Knausgård[1][0000−0003−4088−1642] (✉),
Siv Lene Gangenes Skar[2][0000−0003−3567−7743],
Filippo Sanfilippo[1][0000−0002−1437−8368], Albert Buldenko[1], Henning Lindheim[1],
Jakob Lunde[1], Eligijus Sukarevicius[1], and Kjell G. Robbersmyr[1]

[1] Top Research Centre Mechatronics (TRCM),
University of Agder (UiA), 4879 Grimstad, Norway
[2] Norwegian Institute of Bioeconomy Research, NIBIO Landvik,
4886 Grimstad, Norway
`kristianmk@ieee.org`

Abstract. Aquaponic systems are engineered ecosystems combining aquaculture and plant production. Nutrient rich water is continuously circulating through the system from aquaculture tanks. A biofilter with nitrifying bacteria breaks down fish metabolism ammonia into nitrite and nitrate, which plants and makes the aquaculture wastewater into valued organic fertiliser for the plants, containing essential macro and micro elements. At the same time, the plants are cleaning the water by absorbing ammonia from the fish tanks before it reaches dangerous levels for the aquatic animals. In principle, the only external input is energy, mainly in the form of light and heat, but fish food is also commonly provided. Growing fish food is potentially feasible in a closed loop system, hence aquaponic systems can possibly be an important source of proteins and other important nutrition when, for example, colonising other planets in the future. Fully autonomous aquaponic systems are currently not available. This work aims at minimising manual labour related to cleaning pipes for water transport. The cleaning process must be friendly to both plants and aquatic animals. Hence, in this work, pure mechanical cleaning is adopted. A novel belt-driven continuum robot capable of travelling through small/medium diameter pipes and manoeuvring branches and bends, is designed and tested. The robot is modular and can be extended with different cleaning modules through an interface providing CAN-bus network and electric power. The flexible continuum modules of the robot are characterised. Experimental results demonstrate that the robot is able to travel through pipes with diameters varying from 50 mm to 75 mm, and also capable of handling T-branches of up to 90 degrees.

Keywords: Autonomous Aquaponics · Urban Agriculture · Pipe Cleaning · Continuum Robots · Space Colonisation.

[⋆] This work is part of the project *Smart integrated multitrophic city food production systems –a water and energy saving approach for global urbanisation* (CITYFOOD), which has received funding from the Horizon 2020 - JPI-Urban Europe, Belmont Forum and National Funding Organisations, grant agreement No 726744.

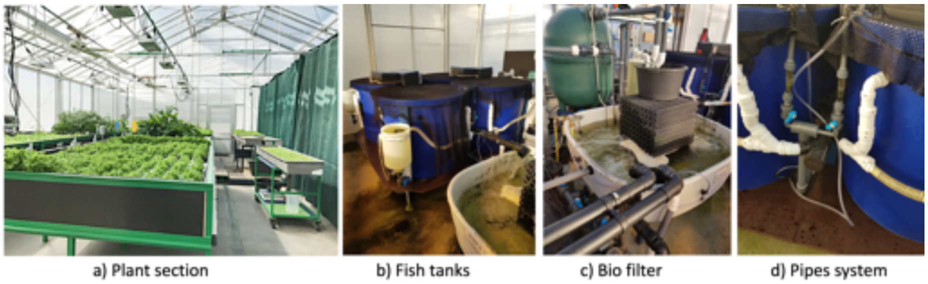

Fig. 1. NIBIO Living Lab aquaponic system.

1 Introduction

The potential of integrated aqua-agriculture systems (IAAC) for large commercial and smaller urban applications to contribute to sustainable development is promising. IAAC, like aquaponic circular-food-production-systems, can help solving the Food-Water-Energy Nexus challenge [29]. In aquaponic systems, fish excrement and fish feed remnants are composted and provides the plant crops with nitrogen, phosphorus and other essential nutrients. Elements that the plants absorb. This is a win-win situation since fishes do not tolerate some of these nutrients in large amount. As a result, the water can be reused and recycled for the fish production site, and a huge amount of water can be saved, coupled with an organic way of producing healthy and sustainable food.

When producing aquatic animals on-land together with plant production in water cultivation, floating trays are used to support the plants. Plant roots are hanging underneath these trays, directly into the fish wastewater. In this way plants are, partly through bacteria/biofilter, cleaning the water and removing ammonia from the fish tanks before it reaches dangerous levels for the aquatic animals. Water is continuously circulating through the system, and nutritious water is used as fertiliser for the plants. To give the optimal crop nutrition level, the water stream flowing from the aquaculture fish tanks can be controlled. In principle, the only external inputs are replacement of evaporated water and energy, mainly in the form of artificial grow light and heat, together with fish feed. Recirculated land-based aqua-agriculture food production systems may be possible in completely closed loops, hence aquaponic systems could be an important source to produce proteins and other important nutrition to people in urban areas or when for example colonising other planets in the future [2, 26].

Fully automatic and autonomous aquaponic systems are currently not available [32]. This work aims on removing some of the manual labour related to cleaning small and medium diameter pipes for water transport, to reduce man hours used on cleaning the system parts and therefore reducing costs. Due to the nutritious water circulating in an aquaponic system, microorganism such as algae and bacteria growth [7] leads to the need of regular cleaning of especially

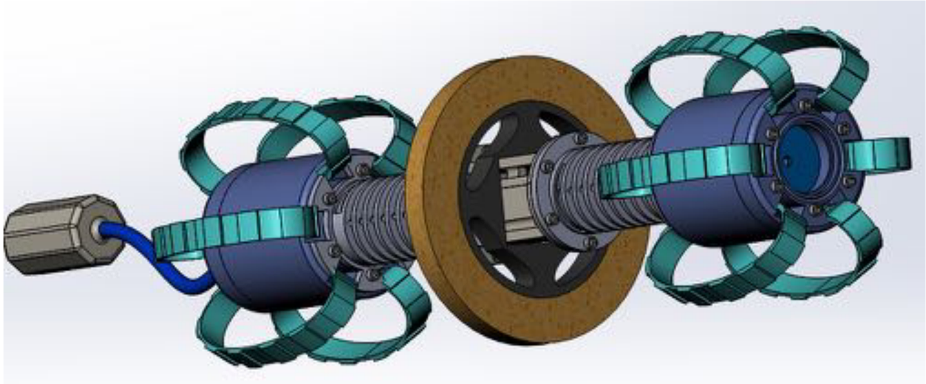

Fig. 2. Digital Mock-Up (DMU) of modular pipe cleaning robot with cleaning module as payload.

fish tanks and water transporting pipes. Cleaning has to be eco-friendly to both plants and aquatic animals, hence the decision taken to use pure mechanical cleaning for this project. A novel belt-driven continuum robot capable of travelling through small and medium diameter pipes and manoeuvring branches and bends is designed and tested.

This paper is organised as follows. The need for developing a pipe-cleaning robot is motivated in Section 2. A brief review of related continuum-robot research is given in Section 3. In Section 4, the main contributions of this work are presented, including robot concept development and detailed design of key components. In Section 5, preliminary results are outlined. Finally, conclusions and future works are discussed in Section 6.

2 Robotic Pipe Cleaning and The Need of Novel Solutions

Robotic pipe cleaning is an active research area, and a number of different principles and solutions was found during the initial phase of the project. However, to include a larger number of principles and prior art in the literature study, it was decided to include pipe inspection robots and some other robots capable of locomoting through narrow passages in general. This section is therefore not limited to pipes and pipe cleaning.

The existing research and technology will be presented and briefly discussed in the light of aquaponic-specific requirements given for this pipe-cleaning task. Firstly the robot must be capable of travelling small and varying diameter pipes with T-branches and bends, secondly the robot must be produced in bio-compatible materials to avoid contamination of the closed-loop aquaponic system. As a final requirement, the robot must be modular, to be extendable for future tasks, for example swimming and cleaning the main fish farming tanks in addition to pipes.

Existing pipe travelling robots can be divided into traditional- and non-conventional locomotion variants [19]. Traditional designs include belt driven, wheel driven, and fluid propulsion with propellers or other thruster designs. The non-conventional category is a bag for everything else, such as clamp-and-pull-designs, smart balls, inchworm-mimicking designs [19], and other bio-inspired concepts like legged robots, peristaltic earth-worm-like robots [28] and snake robots as presented in section 3 (Continuum Robots).

An example of traditional locomotion is the cylindrical elastic crawler mechanism for pipe inspection developed by Fukunaga and Nagase [17]. This amoeba-inspired tracked crawler design consists of a plastic screw inside a cylindrical outer shell, with multiple belts symmetrically positioned perpendicular to the shell, giving propulsion in longitudinal direction. The belts are directly driven by the screw, resulting in identical velocity on all belts, working similar to a locking differential in a car. In addition to the size-benefit of having only one motor, the synchronised movement is also expected to improve traction under slippery conditions. This robot is as a consequence not steerable, and therefore on its own not suitable for manoeuvring pipe branches. The original design from [17] is able to travel through pipes ranging from 30 mm to 100 mm in diameter.

Few existing pipe cleaning robots are found to be modular and steerable. One of the few existing modular and steerable designs is made for inspecting urban gas pipes, but is not suitable for pipe diameters below 160 mm [5]. The aquaponics pipe cleaning task is demanding when it comes to the small and varying diameter of pipes, T-branches and bends, and bio-compatibility. Due to the lack of available existing solutions viable for small diameter pipes, it was decided to develop a new, novel pipe cleaning robot concept. This concept is combining conventional crawling-belt propulsion modules with continuum robot elements for bending and steering. The pipe-crawling module design is strongly influenced by ground-breaking work of Fukunaga et al. on amoeba inspired propulsion [9, 17, 18], and inherits the ability to passively handle a sufficiently large span of pipe diameters. Continuum robots is a large research field on its own, and the next section will give an overview of important developments as seen by the authors.

3 Continuum Robots

The term continuum manipulator was first introduced in [3, 4, 21]. Continuum robots are continuously curving manipulators. They do not exhibit rigid linkages and distinct rotational joints. Instead, the structures bend continuously along their length due to elastic deformation and create motion by generating smooth curves, much like animal tentacles, or arms of an octopus, or tongues [14]. This notion is analogous to the continuous morphological manipulator described in [4], which is a snake/hyper-redundant robot idea pushed to its logical extreme. Namely, this group of robots has backbone architectures that have been pushed to their limits, with their number of joints tending to infinity and with their link lengths tending to zero [31].

Since the early 1960s, several designs of continuum robots have been proposed. One of the first implementation was the *Tensor Arm*, which was presented in [1], based on the original *Orm* concept of Leifer and Scheinman [22]. The *Tensor Arm* foreshadowed several later designs by having a flexible backbone bent by remotely powered tendons. However, synchronization of the inputs to exploit the robot's shapes proved challenging until the 1990s. Successively, experts like Shigeo Hirose [10] have made significant contributions to the field of continuum robotics.

How to actuate (bend and possibly extend/contract) the backbone is one of the most important design concerns of this type of robots. Actuation of continuum manipulators can either be intrinsic to the structure (e.g., pneumatic or hydraulic [8, 13]) or extrinsic through mechanical transmission (e.g., tendons [16, 20].

The structure design of continuum robots can also be approximated by adopting a modular approach. In this perspective, our research group recently introduced *Serpens*, a low-cost, open-source and highly-compliant multi-purpose modular snake robot with series elastic actuator (SEA) [24, 25]. Even though the proposed prototype was validated for achieving perception-driven obstacle-aided locomotion [23], it was not specifically designed to navigate pipes. Regarding robotic systems specifically designed for in-pipe inspection, recent works have proven the potential of multi-link robots to adapt to pipes with different diameters. For example, the design of an inspection robot with passive adaptation ability, which is used to inspect small size water supply pipeline was presented in [12, 35].

However, to the best of our knowledge, it is still an open challenge to build continuum robots capable of being resilient to uncertain environments, such as travelling through small and medium diameter pipes and manoeuvring through different debris and branches.

4 Pipe Cleaning Robot Design and Development

For proof-of-concept, a robot consisting of two belt-driven propulsion modules, a continuum bending actuator module, and the main computer module was designed. A digital mock-up is shown in Fig. 2. This design is resulting from a systematic and top-down product development process, breaking down top level functions into more manageable pieces, potentially in an iterative fashion, and then identifying technologies and solutions for fulfilling each derived function. Similar top-down design methods can be applied for both product development and systems engineering in general [6, 30]. A simplified breakdown structure for the top-level function of cleaning pipes in an operating aquaponic facility is shown in Table 1.

The continuum bending actuator module consists of two spine-style flexible actuators. One of the flexible actuators, resulting from the iterative design pro-

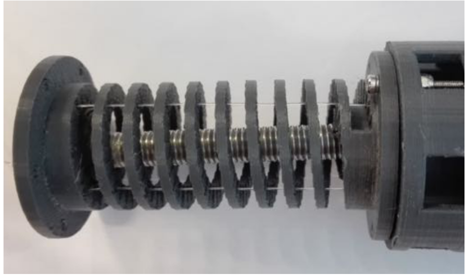

Fig. 3. Continuum bending module for pipe cleaning robot, detail with metal tension spring backbone visible inside the 3D-printed outer spring structure. Monofilament nylon strings for actuation.

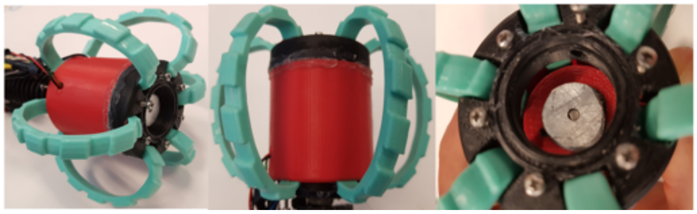

Fig. 4. Translation module assembly.

cess is depicted in Fig. 3. This can be considered an adaption and improvement of the design shown in [34]. In the design process multiple other variants were explored. Including a spineless flexible rubber structure and a vertebra spine-like variant mimicking human body [36]. These first variants did not behave well from a control system point of view, as motions ended up to be unpredictable due to the flexibility in all axis, and difficulty in controlling tension for the vertebra variant. A different principle, in the form of a spring actuator completely 3D-printed including a centre compression spring was also explored. This version was also too flexible in the longitudinal axis, due to the compression spring. Therefor this was replaced with a tension spring. However, printing tension springs requires too fine tolerances for a viable spring to be printed, and the fifth and final version therefore ended up with a metal tension spring backbone inside the actuated 3D-printed outer spring structure. The last version is the only tested configuration that behaved sufficiently well to be controllable and therefore applicable for the pipe robot steering function.

A key technology for implementing the propulsion concept inspired by [9], is production of bio-compatible and durable belts. A food-grade silicone material was selected for this purpose, and custom molds designed and 3D printed for belt molding and splicing/gluing. A housing and waterproofable motor compartment was designed for the propulsion module. The prototype is 3D printed in non-

Table 1. Top-down design approach with one top level function.

Top level function	Cleaning aquaponic water pipes				
Derived functions	Move robot	Navigate	Detect bends, junctions, and obstacles	Clean pipe	Avoid harming fish
Explored solutions	Fluid propulsion (propellers)	Acoustic	Force feedback	Passive brush	Passive safety
	Wheels	Odometry	Computer vision	Active brush	Active safety (Fish detecting AI [15])
	Belts	Inertial	Acoustic		
	Non-conventional	Pre-loaded map or SLAM			

waterproof ABS plastic, but with the possibility of gaskets in essential locations for later stage underwater tests. A complete translation module is shown in Fig. 4

The module interface is standardised at mechanical, electrical and logical level. This enables the robot to be quickly re-organised in different configurations and potentially with new modules. At the electrical and logic level, power is available for computers and actuators, while CAN-bus [11] is used for information flow. The module interface is shown in Fig. 6.

5 Testing and verification

Propulsion and bending modules was tested and verified separately during development. The final assembly was then tested at system level, to verify if the

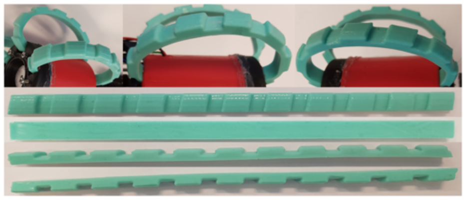

Fig. 5. Bio compatible silicone belts.

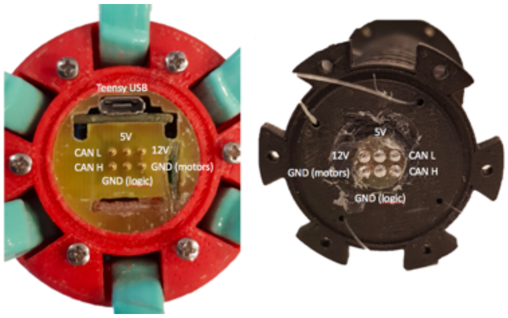

Fig. 6. Pipe cleaning robot electrical module interface.

requirements of crawling through both straight pipes and manoeuvring bends and T-junctions could be fulfilled.

The belt propulsion module design is shown to be viable, and able to provide necessary power and traction for pipe crawling by running the translation module assembly (Fig. 4) through a set of acrylic pipes. Friction between belts and the main propulsion screw is identified to be an issue with this design while running in air. Water immersion is expected to reduce this problem. Visible wear and tear on the belts was however more or less eliminated with lubrication, and food-grade lubrication is readily available if necessary. No further testing was performed on propulsion module-level.

Table 2. Monofilament nylon string pulled distance vs applied pulling force.

Step number	Force [N]	Measured pulled distance [mm]
0	0.00	0.0
1	1.01	1.0
2	2.02	2.0
3	3.03	2.9
4	4.04	4.0
5	5.05	5.3
6	6.06	8.0
7	7.07	12.0
8	8.08	19.0
9	9.09	21.0
10	10.10	23.5
11	11.11	25.2
12	12.12	28.0

Testing of the spring-based continuum actuators shows this design to be viable with improvements to durability. The nylon monofilament lines selected was susceptible to damage from sharp edges on the 3D-printed springs, an issue

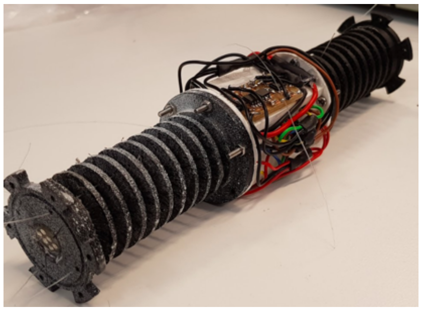

Fig. 7. Bending module with speckle pattern ready for Digital Image Correlation (DIC) measurements.

that still is not solved for long term use. It was also observed that the nylon lines lost some tension over time, but not to such extent that it posed a problem, and this issue was not looked into further. The modules overall perform well, and are expected to be closed-loop controllable using similar methods as developed for the universal joint-spine robot in [33]. The relation between force applied to one of the nylon strings and the deflection of the actuator was measured using Digital Image Correlation (DIC) with Vic-3D from Correlated Solutions Inc. This measurement method requires a speckle pattern to be used on the object under test. A flexible actuator module with speckle pattern is shown in Fig. 7. A reference measurement was first taken during no-load conditions. Then tension was increased in twelve steps of 1.01 N using small weights of approximately 101 g each. Results from this initial load test are summarised in Table 2. For each of the steps, the deflection was also measured using the DIC equipment, such that the raw data from this test is force versus pulled string distance, and deflection since last measurement. Based on the measured deflections and applied force, a relation between bending angle α resulting from a given string pull force input f_n can be calculated.

System level testing was performed in a dry but otherwise representative environment, consisting of acrylic pipes for observability. In the first test, the robot is crawling through a straight acrylic tube as shown in Fig. 8. As a final check of the manoeuvring capability, the robot was manually steered through a 90° T-junction, as shown in the same figure. No control system was developed for the characterised bending actuator, so these tests are open-loop only.

6 Concluding Remarks

Producing fish and vegetables together, in a fully automatic aquaponic system, is potentially achievable. Fish and vegetables are valuable sources for proteins among other nutritious human diets, also if or when colonising distant planets [2]. Today we see this concept as useful in cities and urban areas where

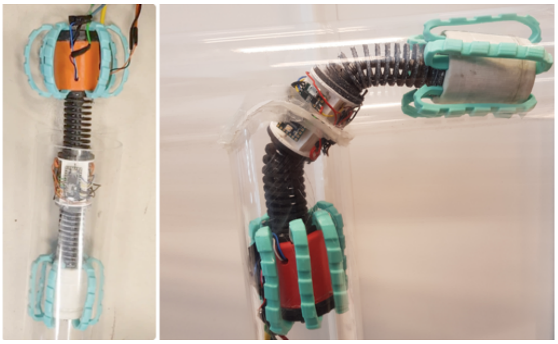

Fig. 8. Robot prototype manoeuvring through straight acrylic pipe and a 90° T-junction.

space comes at a premium. To get the system more sustainable, automation is necessary due to expensive man hours. Today, completely self-contained circular aqua-agriculture production systems e.g. aquaponics, are not available on the market [32]. One of the obstacles concerns cleaning and maintenance of the IAAC systems. Microbes like algae and bacteria thrives in the nutritious water circulating in these IAAC systems, and it is necessary with regular cleaning of fish tanks and water transportation pipes in particular. Both vegetation and aquatic creatures, must be protected throughout the cleaning procedure. For these reasons, a mechanical cleaning solution was proposed in this work. A novel belt-driven continuum robot capable of travelling through small and medium diameter pipes, was proposed. The robot is modular, and is ready to be expanded with for example various cleaning modules through a combined interface providing CAN-bus network and electric power. Preliminary experimental results were presented to illustrate the potential of the proposed design. The presented results include a one degree-of-freedom characterisation of the continuum actuator for steering, as a starting point for closed loop control system development. The robot is demonstrated capable of moving through pipes with a varying diameter from 50 mm to 75 mm, and is able to handle T-branches up to 90 degrees as demonstrated in Fig. 8.

As future work, the design of reliable control algorithms for the proposed robot will be investigated. Also a battery-module including inductive charging is planned, to make the concept even more suitable for underwater use. Another important area for improvement is software modularity and interfaces. Usage of micro-ROS [27] and similar light-weight frameworks will be explored. The current low-level software architecture of the robot must be supplemented with functionality for route planning and guidance, navigation, and control (GNC). This would make it possible to extend the robot capabilities towards autonomous operations in sustainable, circular food production facilities.

References

1. Anderson, V.C.: Tensor arm manipulator design. Trans. ASME **67**, 1–12 (1967)
2. Brown, L., Peick, J., Pickett, M., Fanara, T., Gilchrist, S., Smiley, A., Roberson, L.: Aquatic invertebrate protein sources for long-duration space travel. Life Sciences in Space Research **28**, 1–10 (2021)
3. Chirikjian, G.S.: A continuum approach to hyper-redundant manipulator dynamics. In: Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'93). vol. 2, pp. 1059–1066 (1993)
4. Chirikjian, G.: Theory and applications of hyper-redundant robotic mechanisms. Ph. D thesis, Dept. of Applied Mechanics, California Institute of Technology (1992)
5. Choi, H., Ryew, S.: Robotic system with active steering capability for internal inspection of urban gas pipelines. Mechatronics **12**(5), 713 – 736 (2002)
6. Clark, J.O.: System of systems engineering and family of systems engineering from a standards, v-model, and dual-v model perspective. In: 2009 3rd Annual IEEE Systems Conference. pp. 381–387 (2009)
7. Eck, M., Sare, A.R., Massart, S., Schmautz, Z., Junge, R., Smits, T.H.M., Jijakli, M.H.: Exploring bacterial communities in aquaponic systems. Water **11**(2) (2019)
8. Eder, M., Karl, M., Knoll, A., Riesner, S.: Continuum worm-like robotic mechanism with decentral control architecture. In: Proc. of the IEEE International Conference on Automation Science and Engineering (CASE). pp. 866–871 (2014)
9. Fukunaga, F., y. Nagase, J.: Cylindrical elastic crawler mechanism for pipe inspection inspired by amoeba locomotion. In: 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob). pp. 424–429 (June 2016)
10. Hirose, S.: Biologically inspired robots. Snake-Like Locomotors and Manipulators (1993)
11. ISO: Road vehicles — Controller area network (CAN) — Part 1: Data link layer and physical signalling . Standard, International Organization for Standardization, Geneva, CH (Dec 2015)
12. Kakogawa, A., Ma, S.: A multi-link in-pipe inspection robot composed of active and passive compliant joints. In: Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). pp. 6472–6478 (2020)
13. Kang, R., Guo, Y., Chen, L., Branson, D.T., Dai, J.S.: Design of a pneumatic muscle based continuum robot with embedded tendons. IEEE/ASME Transactions on Mechatronics **22**(2), 751–761 (2016)
14. Kier, W.M., Smith, K.K.: Tongues, tentacles and trunks: the biomechanics of movement in muscular-hydrostats. Zoological journal of the Linnean Society **83**(4), 307–324 (1985)
15. Knausgård, K.M., Wiklund, A., Sørdalen, T.K., Halvorsen, K.T., Kleiven, A.R., Jiao, L., Goodwin, M.: Temperate fish detection and classification: a deep learning based approach. Applied Intelligence (2021)
16. Li, M., Kang, R., Geng, S., Guglielmino, E.: Design and control of a tendon-driven continuum robot. Transactions of the Institute of Measurement and Control **40**(11), 3263–3272 (2018)
17. y. Nagase, J., Fukunaga, F.: Development of a novel crawler mechanism for pipe inspection. In: IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society. pp. 5873–5878 (Oct 2016)
18. y. Nagase, J., Suzumori, K., Saga, N.: Cylindrical crawler unit based on worm rack mechanism for rescue robot. In: 2012 19th International Conference on Mechatronics and Machine Vision in Practice (M2VIP). pp. 218–221 (Nov 2012)

19. Ogai, H., Bhattacharya, B.: Pipe Inspection Robots for Structural Health and Condition Monitoring. Springer (India) Private Ltd., 1st edn. (2018)
20. Oliver-Butler, K., Till, J., Rucker, C.: Continuum robot stiffness under external loads and prescribed tendon displacements. IEEE Transactions on Robotics **35**(2), 403–419 (2019)
21. Robinson, G., Davies, J.B.C.: Continuum robots-a state of the art. In: Proc. of the IEEE International Conference on Robotics and Automation (ICRA). vol. 4, pp. 2849–2854. IEEE (1999)
22. Roth, B., Rastegar, J., Scheinman, V.: On the design of computer controlled manipulators. In: On Theory and Practice of Robots and Manipulators, pp. 93–113. Springer (1974)
23. Sanfilippo, F., Azpiazu, J., Marafioti, G., Transeth, A.A., Stavdahl, Ø., Liljebäck, P.: Perception-driven obstacle-aided locomotion for snake robots: the state of the art, challenges and possibilities. Applied Sciences **7**(4), 336 (2017)
24. Sanfilippo, F., Helgerud, E., Stadheim, P.A., Aronsen, S.L.: Serpens: A highly compliant low-cost ros-based snake robot with series elastic actuators, stereoscopic vision and a screw-less assembly mechanism. Applied Sciences **9**(3), 396 (2019)
25. Sanfilippo, F., Helgerud, E., Stadheim, P.A., Aronsen, S.L.: Serpens, a low-cost snake robot with series elastic torque-controlled actuators and a screw-less assembly mechanism. In: Proc. of the IEEE 5th International Conference on Control, Automation and Robotics (ICCAR), Beijing, China. pp. 133–139 (2019)
26. Skar, S., Pineda-Martos, R., Timpe, A., Pölling, B., Bohn, K., Külvik, M., Delgado, C., Pedras, C., Paço, T., Ćujić, M., et al.: Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future. Blue-Green Systems **2**(1), 1–27 (2020)
27. Staschulat, J., Lange, R., Dasari, D.N.: Budget-based real-time executor for micro-ros. CoRR **abs/2105.05590** (2021), https://arxiv.org/abs/2105.05590
28. Tanise, Y., Taniguchi, K., Yamazaki, S., Kamata, M., Yamada, Y., Nakamura, T.: Development of an air duct cleaning robot for housing based on peristaltic crawling motion. In: 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM). pp. 1267–1272 (2017). https://doi.org/10.1109/AIM.2017.8014192
29. Thorarinsdottir, R.: Aquaponics guidelines. Tech. rep., University of Iceland (08 2015). https://doi.org/10.13140/RG.2.1.4975.6880
30. Ulrich, K.T.: Product design and development. McGraw-Hill Higher Education, New York, NY, seventh edition. edn. (2019)
31. Walker, I.D., Choset, H., Chirikjian, G.S.: Snake-like and continuum robots. In: Springer Handbook of Robotics, pp. 481–498. Springer (2016)
32. Yanes, A.R., Martinez, P., Ahmad, R.: Towards automated aquaponics: A review on monitoring, iot, and smart systems. Journal of Cleaner Production **263** (2020)
33. Yeshmukhametov, A., Koganezawa, K., Seidakhmet, A., Yamamoto, Y.: Wire-tension feedback control for continuum manipulator to improve load manipulability feature. In: 2020 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM). pp. 460–465 (2020)
34. Yoon, H.S., Yi, B.J.: A 4-dof flexible continuum robot using a spring backbone. In: 2009 International Conference on Mechatronics and Automation. pp. 1249–1254 (2009). https://doi.org/10.1109/ICMA.2009.5246612
35. Yuan, Z., Yuan, J., Ma, S.: Design and implementation of a pipeline inspection robot with camera image compensation. In: Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). pp. 6398–6403 (2020)
36. Zhou, Y., Asplund, L., Tsai, C.C., Georgilas, I., Tourassis, V.: From the human spine to hyperredundant robots: The ermis mechanism. ISRN Robotics (2013)