Soft Science

Review Article

A review of worm-like pipe inspection robots: research, trends and challenges

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Abstract

In recent years, the development of worm-like robots has increased significantly. These robots use peristaltic motion comprised of radial expansion and axial elongation to move leglessly through their environments. Soft worm-like robots have the advantage of conforming to their environment, making them ideal for confined spaces such as pipelines which are essential to societal infrastructure. Pipeline contamination and corrosion can be detrimental and costly and thus regular checking is vital. Some pipes are difficult to access due to size, access restrictions and harmful waste contamination (such as in nuclear power plants). This has led to an increase of research into soft worm-like robots for pipe inspection. This review will analyse the recent progress in this area to assess current robotic capabilities and where work may be further needed to ensure they are applicable to real-world applications.

Keywords: Worm robotics, pipe inspection robotics, soft robotics, inchworm, peristalsis

INTRODUCTION

Pipelines are relied on for their ability to transport substances economically and quickly such as water, gas, oil, and waste products. Any breakages or blockages in them can be incredibly harmful to businesses and infrastructures; hence, they are required to be well maintained. This typically involves periodic inspection for signs of damage and potential blockages. Often, these pipes are difficult and dangerous to access for

humans, and thus, a robotic solution is required. In recent years, considerable research has delved into the use of in-pipe inspection robots (IPIRs) to aid in this maintenance[1]. For large-diameter pipelines, (> 75 mm Ø) solutions such as pipe inspection gauges exist and have demonstrated their use in industrial environments[2]. However, smaller ones tend to be more difficult to access and require more manoeuvrable inspection devices. This has led to the development of small and more agile pipe inspection robots with smaller actuators and streamlined bodies[3]. Nevertheless, the miniaturisation of rigid robots remains challenging due to the bulkiness of traditional actuators such as motors; thus, research is looking towards smart and softer materials to create such devices[4]. Soft robotic design has taken a lot of its inspiration for structures and actuators from biological examples, and soft IPIRs are no exception.

Snakes and annelids use a wriggling or worming motion to shift their body through soil or uneven terrain and can form complex shapes to fit their surroundings. Hence, they are the common inspiration for soft robots designed to move in constrained environments such as pipe structures[5-9]. Another example of bioinspiration applicable to constrained environments is vine or everting robots, which can travel into confined spaces by growing through the tip[10]. Earthworms create forward movement by contracting and extending their body segments to create a wave-like motion[8] [Figure 1]. This pattern of contraction and extension from front to rear is called peristalsis and can be seen in other annelids and legless insects[11]. On the other hand, inchworms use an inching motion to propel themselves forward by anchoring the surface with the front of their body whilst contracting the middle and then extending their middle whilst anchoring the surface with the back of the body[12].

Both methods of worm motion rely on patterned anchoring and extension to create propulsion. To travel up a vertical pipe, robots must apply a traction force to the pipe to prevent falling or slippage, something that lends itself naturally to worm-like robotics. Furthermore, soft actuators, which tend to be made from high-friction materials such as rubber, are a natural choice for these worm-like robots[13]. Smart materials are also often used as constituents within these devices, such as shape memory alloys and dielectric actuators, or alternatively, they may use linear solenoids that bend the structures to create a force on the pipes[13,14]. Whilst worm-like robots have been developed for other uses such as exploration[15] and gastrointestinal inspection[16,17], this review will focus on their applications within pipework.

To analyse the applicability of worm-like robots to pipe inspection, we first must define what is important for a robot to carry out pipe inspection.
1. Locomotion: The robot must be able to effectively move through pipework. For most applications, this requires that a robot can move in any orientation around swept bends and tight turns.
2. Wall-press: The robot must be able to grip the pipe walls with enough force to hold its own weight and the addition of any sensors or loads required for inspection.
3. Steering: The robot must be able to turn left or right at junctions so that entire pipe networks can be explored.
4. Navigation and mapping: Thus, any areas of damaged pipe network or contamination can be located.

This paper will first discuss fabrication, wall-press ability and motion or earthworm mechanisms and inchworm mechanisms separately as their difference in locomotive strategy affects these areas. Then, control, navigation and mapping of worm-like robots will be discussed.

EARTHWORM MECHANISMS
Fabrication
Earthworm mechanisms are robots that move using peristaltic motion. These platforms are made from a
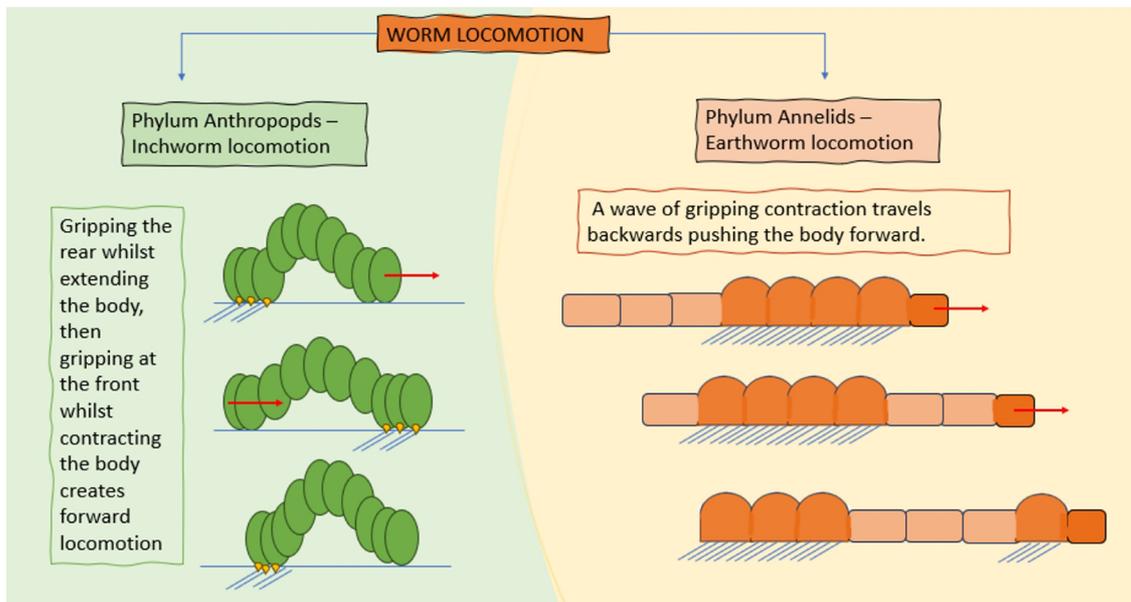
Figure 1. Demonstration of inchworm and earthworm locomotion.

series of identical actuators which anchor when contracted axially and extend when contracted radially. They contract actuators in waves moving from the front to the back in turn, resulting in forward movement imitating that of an earthworm. A demonstration of an Earthworm mechanism in a pipe can be seen in Figure 2.

The advantages of a modular design such as this are that the robot's length can be extended easily, multiple units can be gripped at once, increasing stability, and only one actuator unit needs to be designed. The units can be constructed using a variety of actuation methods; for example, Nemitz *et al.* used voice coils capable of creating 1 N of force to actuate a rubber muscle-like actuator[18]. These modules were connected in series. Gao *et al.* used shape memory alloy springs, and Das *et al.* developed an earthworm robot using a biomimetic actuator containing encapsulated fluid mimicking the coelomic fluid seen in earthworms[14,15] [Figure 3A]. In a study by Das *et al.*, the actuators have three states: (a) elongation from positive pressure; (b) partially relaxed with no pressure input; and (c) radial expansion from negative pressure[15]. This is advantageous as both actuation modes (a) and (c) are active. This contrasts with most worm robots that use pneumatic actuators such as Pneumatic Artificial Muscles (PAMs) which do not exert an active force during elongation[19], making their response slower and less predictable. Ikeuchi *et al.* and Tanise *et al.* overcame this issue by reinforcing PAMs with springs to create an active force on release[20,21]. To increase the actuator response further, Tanise *et al.* also included a pressure-driven valve at the air connection to each of the PAMs[20]; thus, the air was released directly to the environment, decreasing the elongation time of the unit from 3.4 to 1.1 s. By reducing the elongation or contraction time, the velocity of the robot can be increased. Whilst actuator response is crucial for the speed of the robot, other factors are important to consider when designing the actuator unit. To create motion in an earthworm mechanism, a sufficient contraction length to extension length ratio is needed. The larger this is, the further the robot will travel in a single cycle of motion. Theoretically, the distance travelled in a cycle should be the number of units multiplied by the extension length of a single unit. Tang *et al.* developed a pneumatically driven earthworm robot made from silicone chambers[13]. The 2-unit robot should theoretically move around 10 mm per cycle (though it was found to move only 5 mm practically). This difference between expected and real movement is due to slippage. This can be reduced by increasing the grip on the surface of movement. Not only is this important
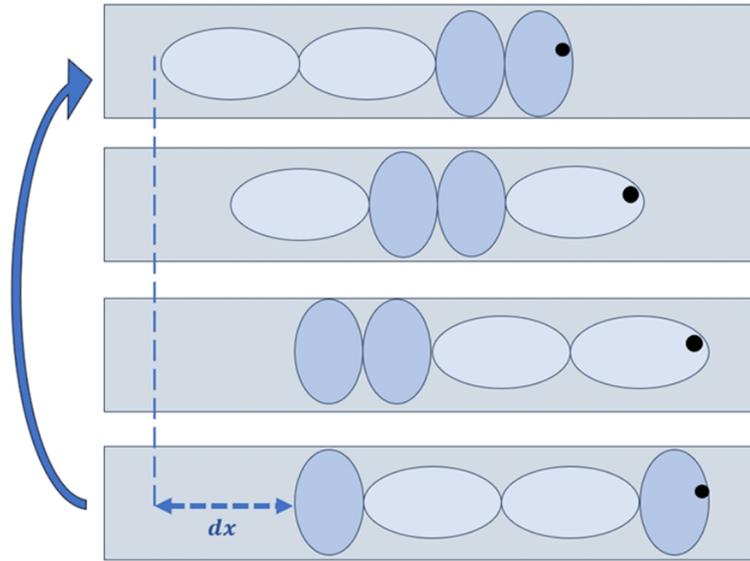
Figure 2. Diagram of an Earthworm mechanism moving through a pipe.
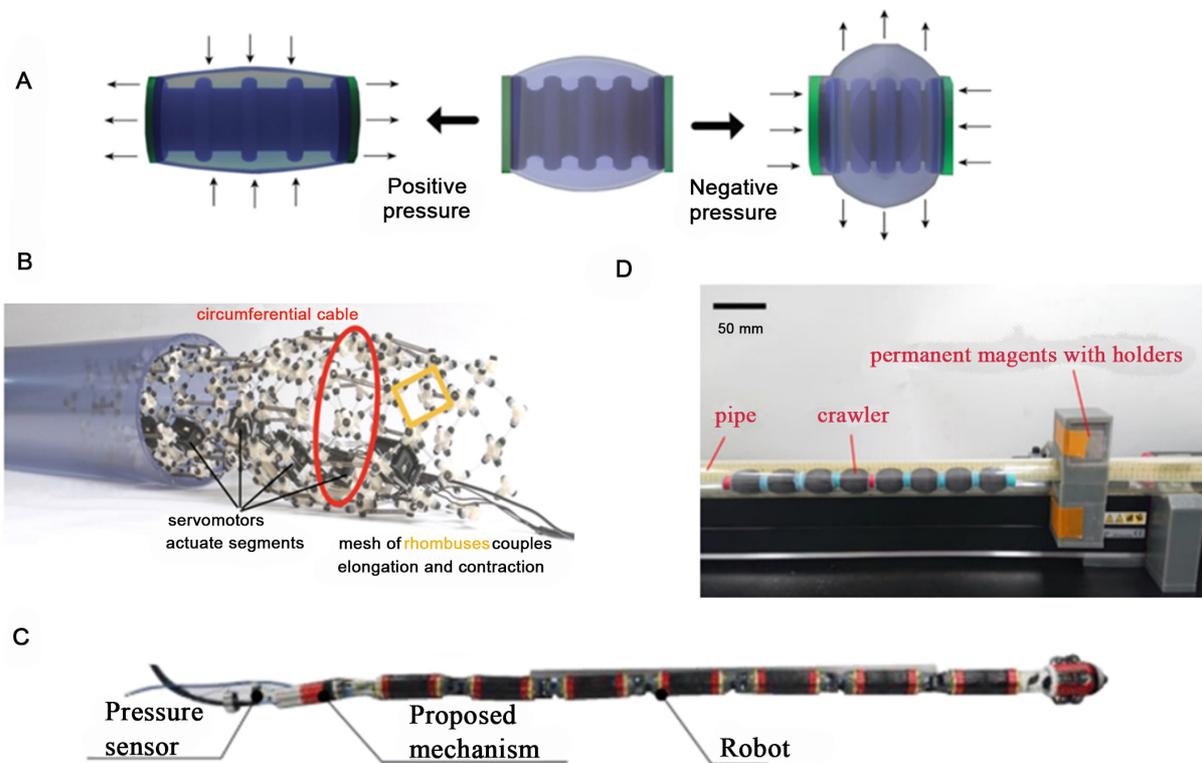
Figure 3. Examples of Earthworm Robots and actuators. (A) Fluid-filled pneumatic actuator under positive and negative pressure adapted with permission from Das *et al.*[15];(B) CMMWorm in a 15.2 cm Ø pipe developed by Daltorio and Kandhari. Provided by Daltorio *et al.*[24];(C) Earthworm robot made from pneumatic artificial muscles, reprinted with permission from Sato *et al.*[26];(D) Wireless magnetically actuated Earthworm Robot reprinted with permission from You *et al.*[30].CMMWorm: Compliant Modular Mesh Worm.

to maximise movement in a single cycle but also to render movement more predictable as the position of

the robot will be better known which is vital for mapping and navigation.

Mesh worms are a type of earthworm robot made from a single piece of mesh as opposed to a series of actuators. Such materials, akin to those seen in McKibben Actuators, elongate when their diameter is shortened due to the nature of their geometry. Mesh worms can use soft actuators such as Shape Memory Alloys and nickel-titanium wrapped around a mesh tube to create a smaller diameter and, hence, elongation at points along the mesh[22]. The sequence of this actuation around the mesh creates a peristaltic locomotion. Other mesh worms, such as the Compliant Modular Mesh Worm (CMMWorm)[23] presented in Figure 3B and Softworm presented in Daltorio *et al.*, make use of traditional actuators such as servomotors which use a cable-driven mechanism to contract the mesh[24]. Softworm was actuated using 12 hoop actuators pulled by a single motor. The hoop actuator contracts sections of a helical mesh which is reinforced with longitudinal springs to return it to its initial state after contraction. Daltorio *et al.* model each segment as a rhombus to calculate the lengthening under actuation whilst also using a spring-mass model to determine the forces acting on the pipe[24]. The size of the motors and mesh structures mean they are more suited for medium-sized pipes (> 75 mm Ø); CMMWorm was demonstrated for use in a 152 mm Ø pipe[23].

Wall-press ability

In pipe inspection robotics, the robot's capability to create sufficient friction with the pipe walls is called wall-press ability, which is vitally important for load carrying and vertical climbing. Ideally, a robot would be able to create enough force to carry its own weight and an additional extra load. Dai *et al.* developed an earthworm made from tensegrity structures that were actuated using linear solenoids which bent the structures to create a force on the pipes, with the resulting earthworm mechanism capable of traversing 155 to 195 mm pipes with a gripping force of 55 N in the 155 m pipes and 30 N in the 195 mm pipe[25]. Dai demonstrated the robot's ability to carry an 850 g load in a 195 mm pipe. It is more common for earthworm robots to be made from pneumatic actuators such as PAMs akin to the one developed by Sato *et al.*[26] [Figure 3C]. Sato *et al.* used axially reinforced PAMs where a single unit is capable of a 300 N traction force in a 102 mm pipe[26]. The robot, by contrast, only weighed 6.3 kg, and thus, it could carry a load vertically. However, creating as much traction force in smaller pipe diameters is more difficult as friction is proportional to contact area and smaller actuators in smaller pipes will create less contact area. One way to enhance wall-press ability in smaller earthworm robots is to increase the number of units contracted at a time. However, this action can affect the robot motion by decreasing its speed.

Motion

When considering peristaltic motion in earthworm mechanisms, speed is not just a question of fast actuation but also of optimising the motion. For an Earthworm mechanism, the motion can be defined in terms of "Wavelength", "Propagation speed" and "Number of waves" [Figure 4]. At any time within a peristaltic Earthworm mechanism cycle, some number of units will be elongated, with this number referred to as "Wavelength" (l). To move, the number of units gripping the pipe will shift back by a set number of units referred to as the "Propagation Speed" (s). Lastly, an Earthworm mechanism can have more than one group of gripping units actuated at a time, a number referred to as "Number of Waves" (n). By convention, an Earthworm motion pattern can be described by l-n-s[20,21,27]. For example, the motion pattern in Figure 4 may be described as 4-1-1.

We can use these values to calculate the speed of the robot. If we know the length of contraction of a single unit r, and the time each unit takes to contract t, then for N unit-long robots, the distance moved is d_w. As a wave of gripping units propagates from head to tail, d_w and the time taken T_w can be given by Equations (1) and (2).
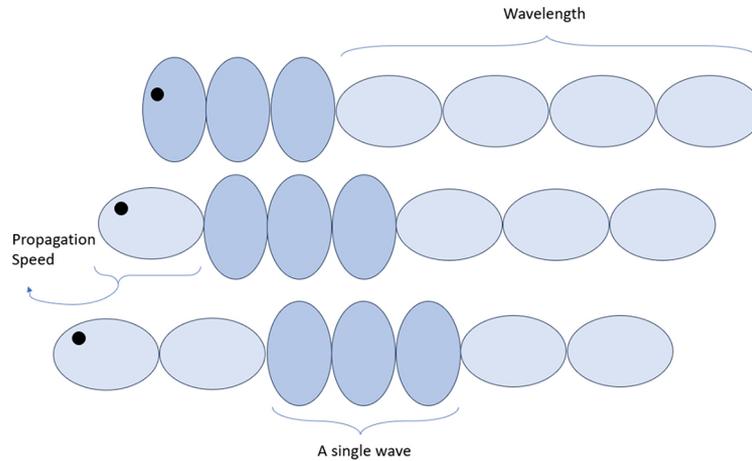
Figure 4. Graphic explaining the terms used to define the wave motion in peristaltic motion. Here, Wavelength = 4, Propagation Speed = 1, and the Number of Waves = 1.

$$d_w = rnl \tag{1}$$

$$T_w = \frac{Nt}{s} \tag{2}$$

We can derive the speed of the robot as:

$$v = \frac{rnsl}{Nt} \tag{3}$$

Ikeuchi *et al.* found that the fastest motion sequence varied in different pipe sizes due to the contraction time differing across pipe diameters[21]. As in Equation (1), the speed of the earthworm robot can be increased by increasing the number of elongated units l, propagation speed s and number of waves n. All these values are constricted by the number of modules in the design, suggesting that, by increasing the length of an Earthworm mechanism, the speed can be increased.

Mano *et al.* demonstrated this experimentally by creating 4-module and 7-module earthworm mechanisms and comparing their speeds[28]. Whilst the 7-unit worm could reach a speed of 42.8 mm/s, the 4-unit module was only capable of reaching 11.6 mm/s [Figure 5]. As evidenced by Equation (3), other ways to increase the speed of earthworm robots include increasing the length of contraction or reducing the contraction time. In pneumatic robots, the modules require a pressure input into the bellows which is often controlled externally via valves connected to the modules through pneumatic tubing[13,17]. The number of modules is thus limited by the volume of tubing the design can accommodate, posing limitations on speed. However, not all designs require a large amount of tubing. Yamamoto *et al.* developed a peristaltic robot design that used only two air inputs regardless of length[29]. As opposed to creating a peristaltic motion through segments, the design uses a slide roller. As seen in Figure 6A, a gripping unit can be moved and activated by varying the pressure inputs from either side. Another advantage of this design is that it can move in two directions. The robot can be of any length, which is correlated with the size of the stroke from a cycle of motion. The demonstrated robot was 90 mm long and 38 mm wide and could produce speeds of 100 mm·s⁻¹ horizontally and 40 mm·s⁻¹ vertically.

A 7-unit Earthworm mechanism
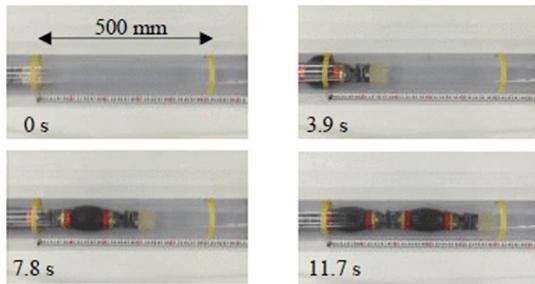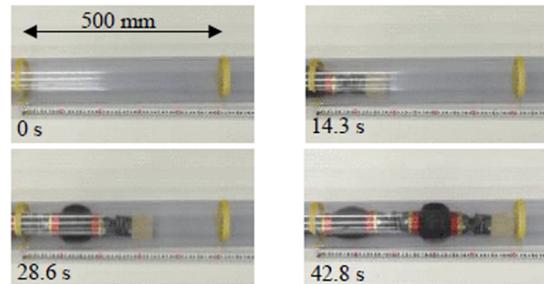
B 4-unit Earthworm mechanism

Figure 5. Comparison of the speed from a 7-unit Earthworm mechanism (A) and a 4-unit (B). Reprinted with permission from Mano *et al.*[28].
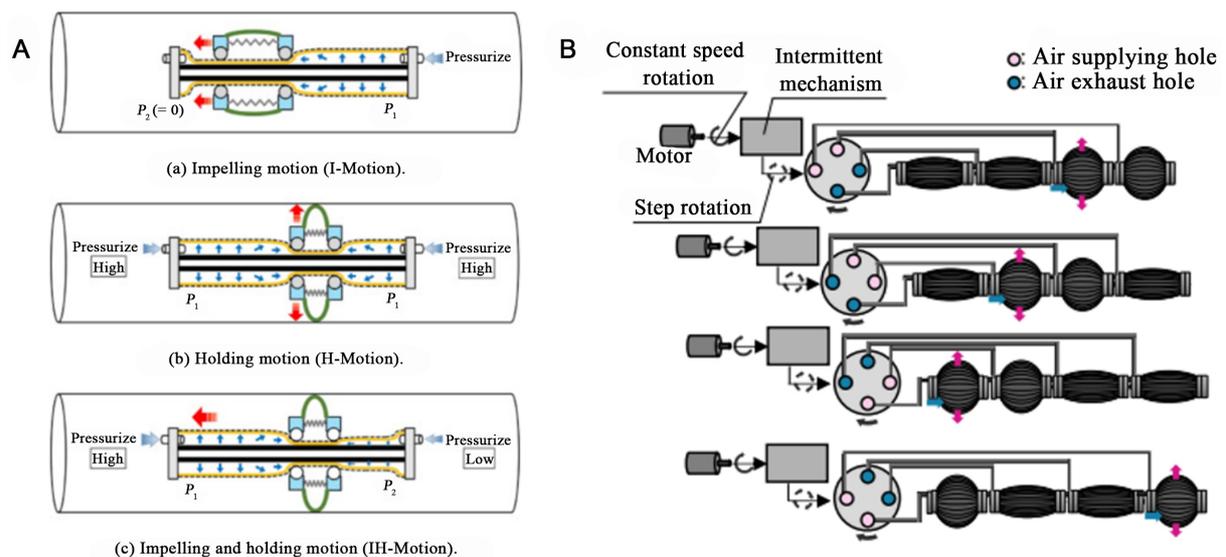

Figure 6. (A) Bi-directional sliding mechanism robot. Reprinted with permission from Yamamoto *et al.*[29]; (B) Sequential actuation of earthworm mechanism by use of a novel rotational flow control valve, reprinted with permission from Sato *et al.*[26].

Sato *et al.* developed a novel Compact Pneumatic Valve (CPV) controlled by rotational motion of a single motor[26]. The valve can be supplied by a single source and periodically rotates an outlet hole supplying air to a different actuator in turn, while simultaneously, an outlet valve is periodically rotated too. The CPV was used to control a 7-module earthworm In-Pipe Robot (IPR) [Figure 6B]. The placement of the inlet and outlet valves was two actuators apart, resulting in a 5-1-1 earthworm robot. This streamlines the design since an external valve system is not needed and only one tube needs to be connected to the robot, though tubing between the individual actuators is still required.

Sato *et al.* integrated solenoids directly into the actuators, meaning they could release air directly from the actuator to the environment and hence, only one supply line was required[26]. This was used to create a 6-unit robot capable of traversing 150 mm pipelines. Rigid valves can be quite large meaning that by integrating them directly into the robot, miniaturisation potential is limited. A wireless and tubeless earthworm mechanism [Figure 3D] is demonstrated by You *et al.*[30]. The robot is made from magneto-

active elastomers which expand radially and contract when exposed to a magnetic field. Though the robot manages to navigate straight pipes without tethering, it does require a magnetic field to be created and moved to create actuation which is impractical in most pipe inspection environments.

Seok *et al.* determined the speed of a mesh-based earthworm robot using Equation (3), supposing that if all other variables were kept constant, speed would be proportional to the wavelength (l)[22]. However, experimentally, they found that the shorter wavelength motion was faster at 3.47 mm·s⁻¹. It was observed that for longer wavelength (l), fewer units are in a gripping state, so less friction is being created which can result in slippage. Equation (3) may be considered an accurate calculation of speed for the robot if the number of units gripping at a moment is enough to keep the robot stable. Hence, it may be argued that the speed of a robot may be most adjustable if the gripping force of a single unit is sufficient to prevent slippage. This is particularly difficult in robots made from mesh material as their lattice-like structure does not create significant contact area with the pipe when actuated, and they tend to be made of low-friction materials such as nylon[23] further reducing their wall grip ability.

Many worm-like pipe robots do not have any active bending actuation facility. These platforms rely on their compliance and the constraints of the pipe environment to guide their movement. However, this can only work in pipe structures that do not contain complex junctions such as Y and T-bends where the robot is required to actively steer itself. To create active steering in the robot, soft bending actuators need to be integrated into the design. Soft bending actuators are made from a variety of materials ranging from elastomers[31] to electroactive polymers[32] and shape memory alloys[33]. Their actuation can be driven by pressurised fluids, electric stimuli, or even chemical reactions. Pneumatic bending actuators tend to be the most popular in worm robots due to their low cost and high power-to-weight ratio.

As earthworm robots tend to be modular or are made from a single piece of material, it is difficult to integrate steering into the modular design without adding a separate steering unit. Omori *et al.* designed a pipe inspection earthworm robot made from two plates connected by flexible belts[34]. Two motor crank systems inside the units were used to extend and contract the motor creating expansion and elongation.

To create steering, one side of the robot is extended more than the other [Figure 7], creating a planar turning motion. While the active turning method was not practically tested in a pipe environment, the robot was capable of navigating bends of up to 90 degrees by using forward peristaltic motion alone. Multiple actuators were required for a single unit to enable steering. This design makes miniaturisation difficult; consequently, the robot had a contracted width of 82.7 mm. In pneumatic earthworm mechanisms, steering may be integrated by splitting the units into chambers to create a force imbalance. Tang *et al.* also developed an earthworm robot with turning capabilities built into the modules by fabricating a single earthworm unit from three pneumatic chambers[13]. Three modules were used to create a full robot, and when contracted, the Tang *et al.* platform had a diameter of 32 mm[13]. However, when placed vertically, each module could only produce a bending angle of 7-9° which could affect its suitability in pipe networks with sharp turns.

The integration of full body steering into the actuation units of an earthworm robot may not always be required. Zhang *et al.* demonstrated that a mobile pipe robot can successfully traverse multiple bends, including vertical T-junctions, using a steering mechanism at the head of the robot[35]. Hence, if there is enough driving force from the robot body, steering at the head may be sufficient. This was demonstrated by Liu *et al.* who added a soft bending unit onto the top of a modular inchworm robot[36]. The robot was then able to navigate more complex junctions such as Y-junctions.
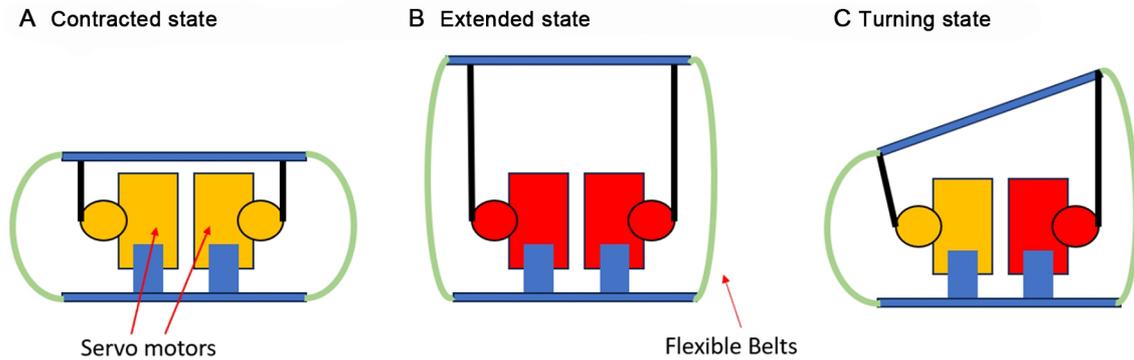
Figure 7. Diagram of the turning mechanism used in the study of Omori *et al.*[34].

INCHWORM ROBOTS

Fabrication

Inchworm robots are defined by having two gripping units on either side of a central extension unit, though they may also have a separate bending unit or have bending integrated into the extension unit. These robots may be connected in series to make such a modular device resemble an earthworm robot[11]. The units can be connected by rigid parts or the whole robot can be made from flexible material. Bertetto and Ruggiu created one of the first inchworm robots for pipe inspection in 2001[37]. Here, the gripping units were constructed from expanding pneumatic bladders whilst the extension unit was made from a stiffening actuator which shrunk when pressure was applied. Modern inchworm robots use similar actuators to those presented in this early paper, with expanding pneumatic bladders being one of the most common types of gripping units still seen in recent inchworm robots. The materials used to create the actuators are vital in terms of creating robust and reliable gripping and propulsion units that can be characterised and controlled. Design considerations for soft actuators are made to control the behaviour of the actuator when supplied with an air input or vacuum, where fabric sleeves[21], fibre reinforcements[27,28], carbon fibre reinforcement[38], and the shape of the actuator[10,26,29] can all be used to restrict and direct the motion.

Basem and Bastaki made an inchworm robot with micro-DC motors alongside several compliant structures that bent to create a desirable force or motion[39] [Figure 8A]. The clamping unit was made from metal sheets that bent with motor-driven linear contraction. Further, the central module was developed to drive and steer the robot and was made from three nylon rods that could be extended or shortened to create turning or movement. The robot demonstrated its ability to move through 100 mm diameter pipes with 90-degree elbow turns.

Wall-press ability

Kusunose *et al.* created a gripping unit made from a silicone tube covered in a ruffled fabric sleeve that was connected end to end to create a circular shape[40] [Figure 8B(i)]. The fabric sleeve constrained it to expand radially while silicone tape was added to the actuator to create more grip. This unit could hold a force of around 40 N when supplied with a pressure of 300 kPa, a figure which was later improved to a holding force of 160 N at 100 kPa when the gripping unit was redesigned as an O-shaped rubber tube that inflated to grip the pipe as seen in Figure 8B(ii)[41]. The difference between the two actuators had to do with the contact area between the actuator and the pipe as frictional force F_f is directly proportional to surface area A. Rubber is capable of deforming into the cavities of hard surfaces to create a large contact area, and thus it is ideal for such actuators[42]. Hence, one of the most common gripping units seen in pneumatic inchworm robots is radially expanding bellows of air made from elastomer[17,37,40,41]. The contact area is an important part of
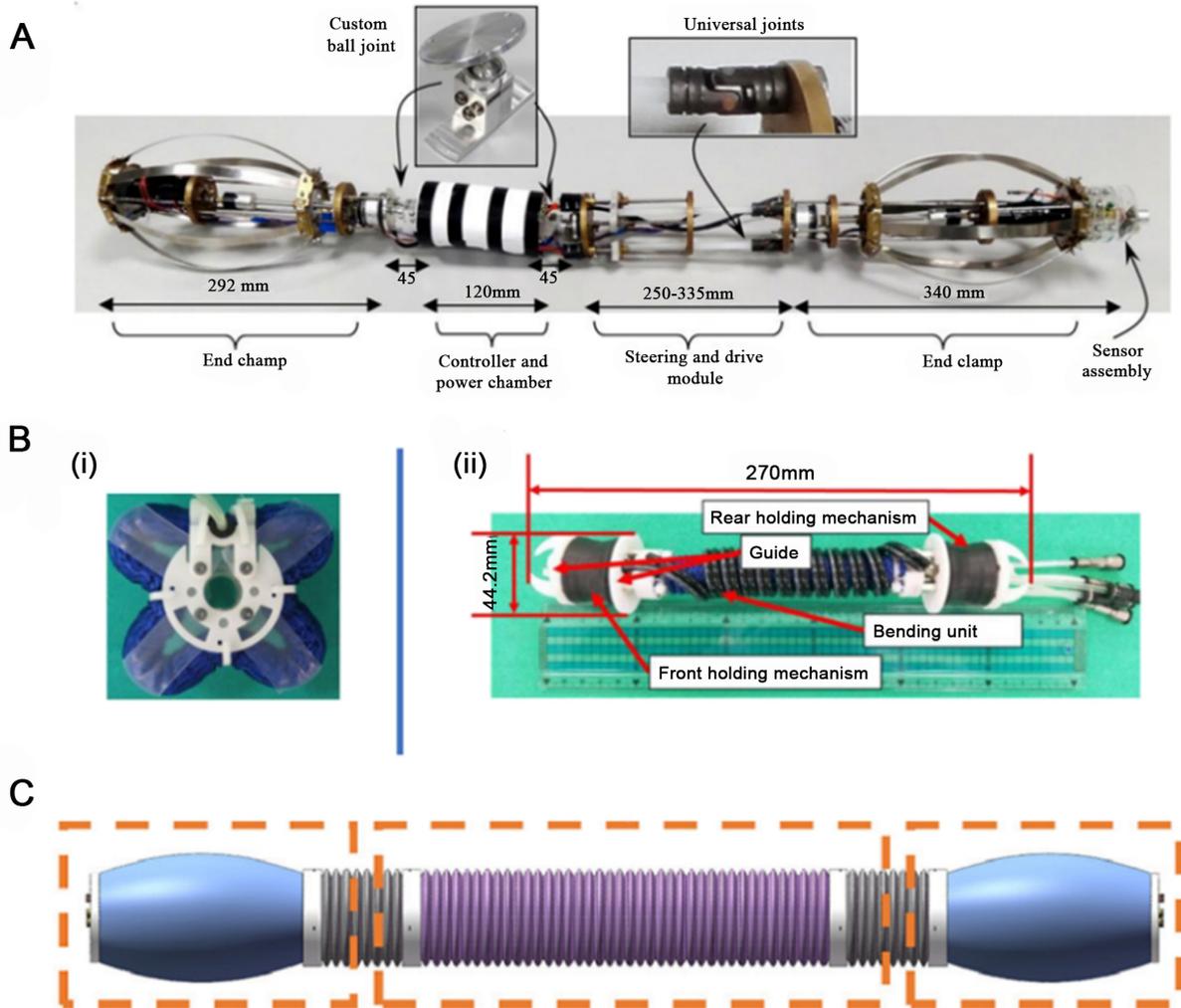
Figure 8. (A) Inchworm mechanism made using traditional rigid actuators. Reprinted with permission from Basem and Bastaki[39]; (B) Comparison of the initial gripping unit developed by Kusunose *et al.*[40]. (i) The improved mechanism integrated into the whole robot by Hayashi *et al.*[41], (ii) Both images printed with permission from Hayashi *et al.*[41]; and (C) Inchworm robot developed by Li *et al.* reprinted with permission[44].

designing an inchworm robot as it determines how much load can be carried and hence if the robot will be capable of carrying sensors/tools required for inspection. The gripping unit in the study by Fang *et al.* was placed between two rigid plates limiting the contact length to the displacement between the plates[43] [Figure 9]. They[43] determined the relationship in Equation (4) between the maximum load F_{max} given pressure p, the pipe diameter D_p, and the minimum contact length L_s.

$$F_{max} = \mu F_n = p\pi D_p L_s \qquad (4)$$

Fang *et al.* found that for a 25 mm diameter pipe, the gripping units would be sufficient with a 32 mm contact length, whereas for a 40 mm pipe, a 24 mm contact length was sufficient[43]. The robot was demonstrated in vertical and U-bend pipes of 90 mm diameter. Generally, a smaller gripping length allows a robot to navigate a turn more easily. In the case of robots where the contact length of gripping units is set between rigid plates, this may limit whether the robot can approach a bend or create a limit on minimum
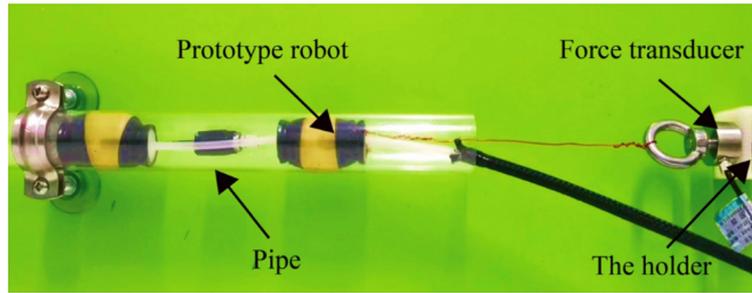
Figure 9. Image of the robot produced by Fang *et al.* being tested for force analysis. Reprinted with permission from Fang *et al.*[43].

pipe diameter. If a gripping unit expands longitudinally and axially, then the contact length when it is not inflated is less of a burden. For less constrained actuators, more mechanical analysis may be used to determine the contact length under expansion and, hence, confirm whether the gripping force is sufficient.

Li *et al.* created an inchworm robot with ellipsoid-shaped gripping actuators capable of extending both radially and axially[44] [Figure 8C]. To determine the contact area, Li *et al.* used strain relationships at the contact boundary[44]. The strain on a thin-walled pressure vessel can be given by latitudinal (σ_1) and longitudinal (σ_2) stress, as given in Equations (5) and (6).

$$\sigma_1 = \frac{pr}{\delta} \tag{5}$$

$$\sigma_2 = \frac{pr}{2\delta} \tag{6}$$

Where p is the gauge pressure, r the radius of a thin-walled cylinder resembling that shown in Figure 10, and δ the thickness[45]. If we consider a pipe wall of diameter d with an expanded balloon in it, we can calculate the latitudinal strain at the boundaries of where the balloon contacts the pipe under expansion x_b and $-x_b$. Using the stress-strain relationship, we can also derive Equation (7):

$$\sigma_2 = E\varepsilon \tag{7}$$

Where E is the elastic modulus and ε the expansion which can be expressed in terms of $\varepsilon = d/y\,(x_b)$ where $y\,(x_b)$ is the equation of the unexpanded ellipse. Setting the two equations of longitudinal stress to be equal, it is possible to derive x_b, which, in turn, can be used to determine the length of contact between the balloon and thus the frictional force. Li *et al.* derived these calculations for the gripping units of an inchworm robot and used them to optimise the actuator parameters for a given pipe diameter to provide the most gripping force[44]. Less restriction on the gripping actuator means that more contact area can be covered as the gripper will expand both radially and axially. However, this can make the modelling more complicated and the determination of ideal parameters less simple; Li *et al.* managed to determine the ideal parameters using geometry and strain relations due to the simplicity of design[44].

Not all inchworm robots are actuated using pneumatics; examples of other softworm in-pipe robots actuated through other means have been researched. Tang *et al.* developed an inchworm robot capable of inspecting 9.8 mm Ø pipes using Dielectric Actuators (DEAs) to create propulsion units and an anchoring unit made from smart composite microstructures[46]. DEAs are electroactive polymers that deform through the induction of an electric field. They created the elongation unit from a single DEA, whereas the anchoring unit [Figure 11], was made from a DEA between a mechanism whose diameter decreases when
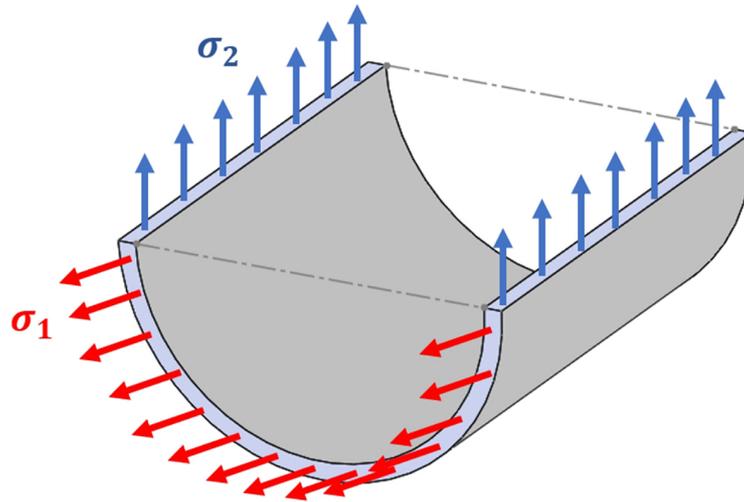
Figure 10. Diagram of longitudinal and latitudinal stress on a thin-walled cylinder.
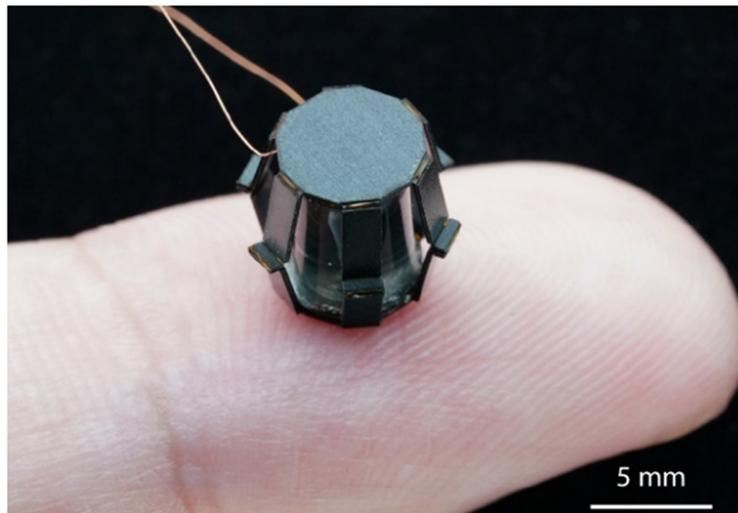

Figure 11. Millimetre scale gripping unit that uses Dielectric Actuation reprinted from Tang *et al.*[46] with permission.

the DEA itself elongates[46]. The Youngs modulus of the DEA in the elongation unit was much lower than that in the anchoring unit (100 kPa at 100% strain compared to 420 kPa). This ensured that the anchoring unit had a stronger energy transfer for a smaller movement creating more force on the mechanism. Tang *et al.* investigated the best activation voltages and phase cycles to actuate the inchworm robot in order to create efficient and fast peristaltic motion[46].

Calculating the optimised activation voltage or pressure to use in the actuators is vital in order to know that the robot is secure during elongation/contraction and to ensure that the robot produces a suitable elongation. Liu *et al.* created a modular worm-inspired soft robot using radial expansion, elongation, and spatial bending pneumatic actuators[36] [Figure 12A]. Here, a Magnetostrictive Displacement Sensor (MDS) was used to measure the deformation of the axially expanding pneumatic actuator, thus demonstrating that the elongation of the actuator was linear for deformations < 60 kPa[36]. Radially Expanding Pneumatic Actuators (REPAs) used force sensors to gauge when sufficient grip is present to achieve the target goal. At
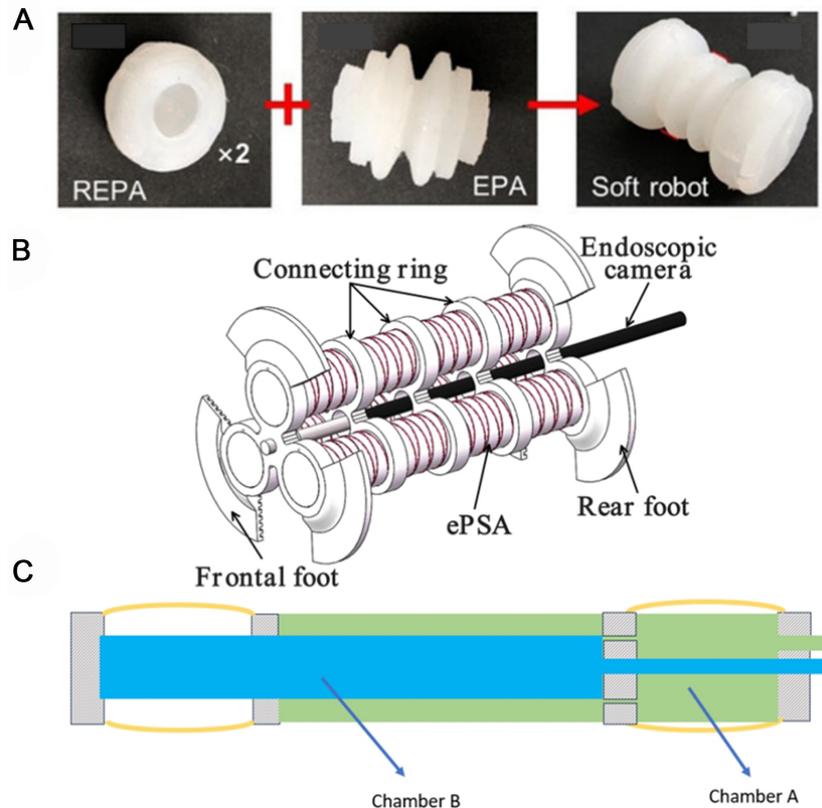
Figure 12. (A) Soft inchworm robot developed by Liu *et al.*[36], reprinted with permission; (B) Soft inchworm robot made from three eSPAs and two flexible feet. Reprinted with permission from Zhang *et al.*[55]; (C) Internal structure of duplex chamber inchworm mechanism based on that presented in the study of Yamamoto *et al.*[58]. REPA: Radially Expanding Pneumatic Actuator; EPA: Expanding Pneumatic Actuator; eSPAs: Extensible Pneumatic Soft Actuators.

250 kPa, the robot has enough grip to hold a load of 240 N more than the weight of the robot, meaning it can move vertically against gravity. The inchworm robot demonstrated its ability to move through straight pipes and U-bends at a variety of inclines.

Motion

Similar to an earthworm mechanism, the amount of movement produced in a cycle depends on the extension that can be created by an actuator. Producing a large determinable amount of contraction is desirable to increase movement and speed and make the behaviour of the robot more predictable. Within a typical inchworm mechanism, the extension unit typically consists of one or more pneumatic actuators. Extension units should create a driving force capable of lifting the body's full weight and any friction from the pipe, whilst creating a reasonable displacement. Extension units can range from elastic bladders covered in sleeves to prevent radial expansion to creased pneumatic bellows[44], unfolding/origami actuators[47,48], vacuum-actuated buckling mechanisms[49,50], traditional rigid linear actuators, and smart materials. The structural considerations ensure the expanding behaviour of the bellows is more predictable and constrained to the axial direction.

PAMs with folds or pleats can be modelled using geometric force models[51,52], whereas other methods include biomimetic models that model pneumatic actuators akin to muscles[53,54] and force-spring models[55-57]. Zhang *et al.* created a robot consisting of three parallel PAMs (modelled biomimetically as muscles) and two flexible feet[55]. Unlike force-spring models, biomimetic models also consider the force

axially that causes the pneumatic actuator to expand radially. The relatively simple robot [Figure 12B] presented by Zhang *et al.* has gripping units which do not require inflation, and thus, it can reach speeds of 18.7 mm·s⁻¹ forwards and 17.7 mm·s⁻¹ backwards[55].

Pneumatically inflated robots face the same difficulties as earthworm ones, where miniaturisation and high speeds can be difficult to achieve when there are a lot of air supplies to consider. Usually, an inchworm mechanism will feature at least three inputs to control each unit. Yamamoto *et al.* reduced this by creating such a robot made from two chambers[58] [Figure 12C]. The two chambers can be used to inflate corresponding grippers at low pressures and both the corresponding gripper and the elongation units at high pressures. By switching between high and low pressures in each chamber, the robot can achieve inchworm locomotion. It can produce speeds of 45.5 mm·s⁻¹ in horizontal and 23.7 mm·s⁻¹ in vertical 25 mm pipes, albeit not as fast as the robot presented in Yamamoto *et al.* though within a significantly smaller diameter[29].

Lim *et al.* managed to produce an inchworm robot using one pneumatic line with the rear gripping unit, elongation unit and front gripping units separated by holes of different sizes[59]. Each hole required a threshold pressure for the air to pass through; hence, the inflation of each chamber travels from rear to front with the deflation from rear to front the same [Figure 13]. This creates the desired peristaltic motion where higher pressure leads to less time required for a cycle of motion.

The robot developed by Lim *et al.* can achieve high-speed motion reaching 50 mm·s⁻¹ attained in a 16 mm pipe, which is significantly smaller than the pipes used in the study of Yamamoto *et al.* although unlike this robot it can only perform one directional motion[58]. Gilbertson *et al.* made an inchworm robot driven by hydraulics, similar to the study of Lim *et al.*[59,60]; the robot is driven using only one supply line; however, in this case, the supply is water. Gilbertson *et al.* use passive valves that release water into the next chamber when a certain pressure threshold is reached managing a speed of 13.5 mm·s⁻¹[60].

From Table 1, the conclusion can be drawn that the speed at which the actuation method can be delivered to the robot influences the overall speed of the robot. Fluid-driven robots can increase speed by introducing passive valves, reducing tubing, and removing the reliance on solenoid valves. This means that the fluid must travel less distance to pressurise or depressurise the actuators, reducing the overall time required to complete a sequence of movement. Passive designs may increase the speed of an inchworm robot but control over the individual chambers is lost. If more gripping power was required in an inchworm mechanism where the two gripping chambers were actuated by separate supply lines, the pressure in these chambers could be increased simply by increasing the inflation time. However, in a passive design, the entire mechanism would need to be redesigned. This leads on to a larger implication that the robot may be less adaptable to its environment. Even if sensing were included, the robot would not be able to change its motion when required due to the over simplicity of its design. Hence, it is difficult to design a stable high-speed fluid-driven inchworm robot for small-diameter pipe navigation. To overcome this imbalance between speed and stability, one solution may be to use a different method of actuation altogether. Tang *et al.* present an inchworm robot made from dielectric actuators that is considerably smaller than the pneumatically actuated alternatives whilst maintaining a fast speed[46].

This suggests that electrical actuation of soft materials may be required to push the boundaries of speed and size reduction in worm-like pipe robotics. Soft electric actuation methods are difficult and expensive to fabricate which may be why there are only a few examples of their use in pipe inspection worm robots.

Table 1. Examples of high-speed inchworm robots

Robot	Actuation connection	Pipe diameter	Speed (Horizontal)
Zhang et al.[55]	3 pneumatic tubes	46 mm	18.7 mm·s^{-1}
Tang et al.[46]	Electrical (wiring)	9.8 mm	55.93 mm.s^{-1}
Yamamato et al.[58]	2 pneumatic tubes	25 mm	45.5 mm·s^{-1}
Lim et al.[59]	1 pneumatic tube	16 mm	50 mm·s^{-1}
Gilbertson et al.[60]	1 hydraulic tube	19 mm	13.5 mm·s^{-1}
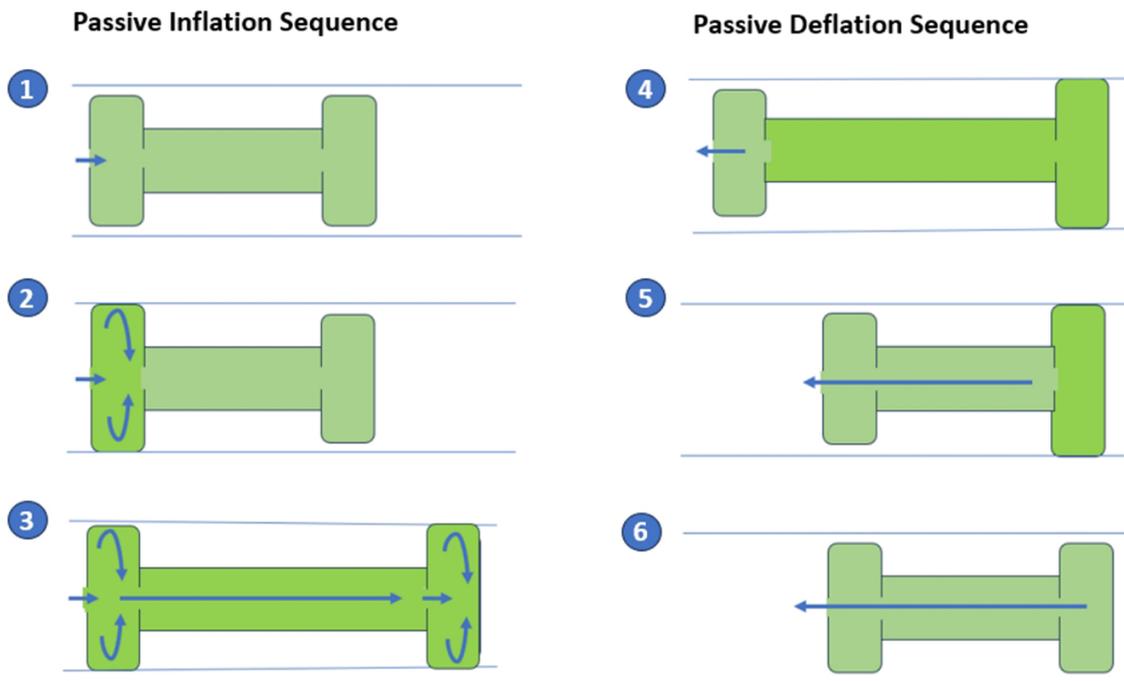
Figure 13. Inflation sequence of a passive valve inchworm mechanism, similar to that seen by Lim *et al.*[59].

Many pipe networks contain junctions where the robot may be required to steer. To steer in a desired direction at junctions, the inchworm robots must bend. To cause bending, the soft actuator must create an unbalanced force under inflation through methods such as fibre reinforcement[31], asymmetric design[61], or the addition of fins (as seen in the popular PnueNets actuator[62]). Hwang *et al.* showed that in ballooning actuators, the addition of fins creates a more linear response of the bending angle to input pressure, a characteristic that is desirable for controllability[63]. Xavier *et al.* analysed fluid-driven actuators specifically for their use in inchworm robots[64]. They found that for bending, a semi-circular ballooning actuator reaches a higher bending angle fastest and that fibre reinforcement made little difference. Xavier *et al.* subsequently developed a worm-like robot using soft pneumatic actuators[64]. A semi-circular ballooning actuator was placed at the tip to guide the robot around corners. However, this bending only appears to occur in one dimension.

Creating bending actuation in three dimensions can be executed by placing multiple linear actuators of varying lengths around a central axis. This method is commonly seen in continuum robotics but can also be used in worm-like soft robots. Zhang *et al.* used a worm-like robot with a bending and extending actuator in the middle[65]. It was composed of three chambers, where creating a difference between the pressures in each chamber would cause bending [Figure 14]. Pressure values for different bending angles were found
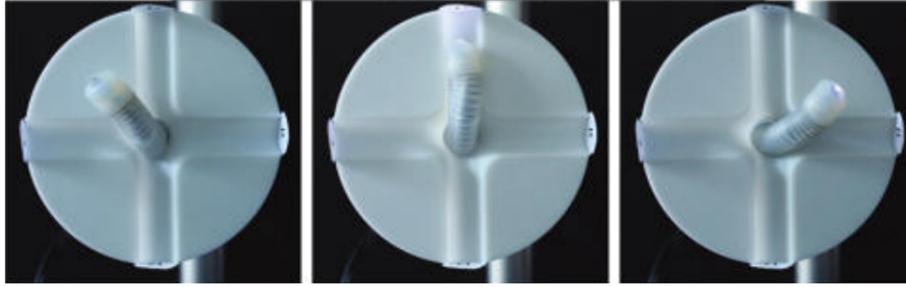
Figure 14. Example of three-chamber (PBA) inchworm robot turning its head in multiple directions. Reprinted with permission from Zhang *et al.*[65]. PBA: Parallel Bellows Actuator.

experimentally, and the robot was demonstrated to actively turn around 45-degree junctions. The middle unit used in the research of Zhang *et al.* is referred to as a Parallel Bellows Actuator (PBA) and is a popular design in soft robotics[65]. The PBA consists of three soft actuators placed in a triangle configuration around a central axis. The kinematics of such an actuator can be modelled using a constant curvature assumption. The constant curvature model says that the tangent angle to the imaginary backbone of the actuator is a constant. Whereas, in their study[65], the bending unit is part of the extension unit. In some inchworms, the turning mechanism is placed at the head of the robot, and the rest of the robot is guided by its movement. To improve the robot's agility, Liu *et al.* added a steering module containing a REPA and a Soft Bending Pneumatic Actuator (SBPA)[36]. The SBPA uses three chambers placed symmetrically around the axis allowing it to bend in any direction in space. The addition of more modules is desirable as it can increase the speed and stability of the robot, as gaps in the pipes and obstacles are more easily avoided.

Especially in the case of a T junction, the robot cannot rely on the guidance of the pipe walls for direction. To ensure successful operation, it should be able to assess the desired position of its end effector or gripping unit and use this to calculate the actuation inputs for its bending mechanism.

Zhang *et al.* developed a kinematic model for an inchworm robot with a parallel actuator and two "feet" based on the following assumptions[55]:
(1) The robot features constant curvature.
(2) The gripping actuators are stationary during inflation and deflation.
(3) The inflating parallel actuators keep a constant radius under inflation.
(4) The robot can be assumed to have no load or be affected by gravity.

From these assumptions and using the forward kinematics relationships defined in Webster and Jones[66], Zhang *et al.* can map the lengths of a 3-bellow actuator to configuration space variables (curvature) and hence task space (the end position)[67]. A static model of actuator variables (pressure in this case) can be used to calculate the required actuator inputs. Zhang *et al.* can predict the position of the robot gripping units after extension and then again after contraction by using this model and hence map the trajectory of the robot[55]. This trajectory plan is tried and tested in this work for an L bend where computations calculate the fastest trajectory. The robot does manage to navigate the L bend, but the trajectory is not the same as expected due to inconsistencies between the pipe conditions in simulation and real life.

As demonstrated in Table 2, the robots with the best turning capabilities all use three bellows actuators and are pneumatically actuated. There are no obvious advantages between integrating turning actuation into an inchworm propulsion unit or placing it at the head of the robot, but this may be due to a lack of examples.

Table 2. Comparison of bending abilities in worm-like pipe robots and demonstrated ability

Robot	Bending method	Actuation	Angles	Demonstrated ability in pipes
Integrated inchworm[50]	Three vacuum actuators	Pneumatic	40	Navigation of straight pipes
Earthworm[13]	Three pneumatic chambers are arranged axially	Pneumatic	7-9 degrees per segment	Navigation of straight pipes
Inchworm with bending actuator at the top[64]	Semi-circular bending actuator	Hydraulic (Safe in medical applications)	90 degrees Also presented a PBA that could do 85	Navigation of straight pipes and two unconnected planar tubes placed at 90 degrees to each other
Earthworm[34]	Length control from servo	Electric, motor driven	n/a	Navigation of straight pipes and L Bends
Inchworm Integrated[55]	Parallel Bellows Actuator	Pneumatic	Not recorded	Navigation of straight pipes and L Bends using trajectory planning
Inchworm with bending actuator at the top[36]	Three pneumatic chambers	Pneumatic	25	Navigation of straight pipes, pipes with gaps, pipes of variable diameter and Y junctions
Inchworm Integrated[65]	PBA	Pneumatic	120 degrees (two actuated chambers) 90 for one	Navigation of straight pipes and a pipe with multiple branches, but no evidence of a 90-degree sharp turn

It should be noted that "Navigation" here simply means the robot was able to move through and does not suggest autonomy. PBA: Parallel Bellows Actuator.

There are few examples of worm robots that can navigate two-directional junctions, and though some of the robots are able to turn L-junctions, there are also many examples of worm-like robots without active turning also being able to achieve this by simply relying on compliance alone. Moreover, there is yet to be a robot that demonstrates autonomous sensing to guide turning.

COMPARISON OF MECHANISMS

As shown in Figure 15, there is much similarity between the capabilities of Earthworm and Inchworm mechanisms. Earthworm mechanisms offer a solution for small-diameter pipe inspection for straight and bent pipelines in any orientation with little complexity. They have demonstrated a variety of speeds and an ability to travel in two directions. Their relatively simple design makes them easy and cheap to fabricate and control, as more than one unit can be actuated at a time. Moreover, sensors such as cameras could easily be added to the head of the robot to aid inspection purposes. These could be used to identify typical distress indicators required in pipe inspection[68]. These devices could further be used to inspect underground gas pipes which are currently inspected using manually operated instrumentation such as ground penetrating radar inspection and walkover beacon systems[69]. Earthworm robots offer a remote semi-autonomous cheap alternative to this manual method. Without steering, straight pipe mapping is relatively simple for a tethered robot as the distance travelled can be indicated by the length of the tether. Alternatively, a visual SLAM algorithm could be used on the camera head. The use of earthworm mechanisms in more complex pipe networks is limited by difficulties in steering, as the units are optimised for both contraction and extension; thus, steering is difficult to work into the design. Inchworm robots demonstrate a similar ability to traverse small-diameter straight pipes vertically and horizontally. However, unlike earthworm robots, they have the advantage of superior turning ability as the extension unit in an earthworm can be created in the form of a three-bellow actuator. Nevertheless, there are only a few examples of inchworm robots navigating pipe networks with sharp turns, and it is unclear in these experiments whether the steering motion is precalculated given knowledge of the setup or preprogrammed for a known environment. Both mechanisms rely on the control of expanding or contracting soft actuators in sequence. Though the motion sequence differs, the control strategies can be considered similar enough to discuss together.
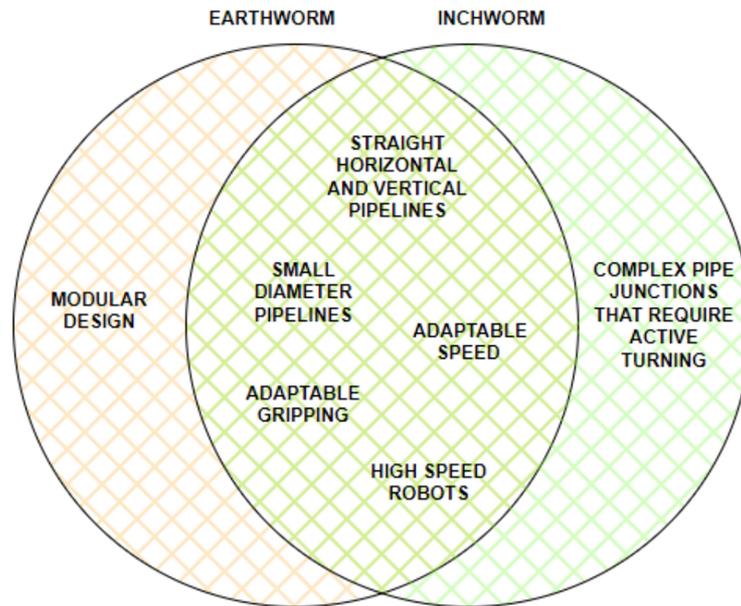
Figure 15. Comparison between Earthworm Mechanism and Inchworm.

CONTROL AND NAVIGATION

Control and shape sensing

Worm-like robots mimic the peristaltic motion seen in worms in nature by triggering actuators in a sequence. In pneumatic worm robots, this is usually done using external solenoid valves which release and input a constant pressure for a set amount of time to each actuator in sequence[36,41,47,49,50]; an example of this on/off control method can be seen in Figure 16. This has also been shown to be done using onboard pneumatics[37]. The same method can be applied to electrically actuated robots with set voltages being supplied to soft actuators in sequence[46]. The phase cycles for each actuator are key to the speed and efficiency of the robotic platform.

Zhang *et al.* used a Central Pattern Generator (CPG) to fine-tune the motion of their robot[67]. CPGs are based on behaviour seen in nature where animals can create rhythmic actions without input[70]. The CPG network connects all the valves into a central network where each one, i, is controlled by a trajectory function $f_i(r)$ where $r = 2\pi\delta$ where δ is the oscillator frequency. For valve control, $f_i(r)$ is a square wave where phase shifts for each actuator control the sequence of actuation and varying pulse widths control the amount of inflation. An example of a CPG network is shown in Figure 17.

The advantages of CPG networks include ease of ability to change inflation times, phase shifts, and frequencies. Not only does this mean the user can easily adjust the travel speed but also turning can be implemented. Zhang *et al.* created an inchworm robot with a 3-actuator turning mechanism in the middle[67]. By varying the pulse width of the actuators in the CPG network, the length of the three actuators varies creating a turning motion. This was demonstrated in a 90-degree swept pipe bend. Pneumatic robots that use passive valves or single actuator movement have smaller motion cycles and, hence, simpler control systems. Zhang *et al.* reduced the cycle of the robot by using flexible "feet" as the gripping units[67]. Some of the feet grip the pipe while the propulsion unit moves the others. This results in a 2-step cycle of movement that increases the robot's speed to 15 mm·s⁻¹. Other single actuation soft IPIRs use a similar 2-step cycle[71]. Though simpler to control, these systems pay little attention to gripping force and stability, making them
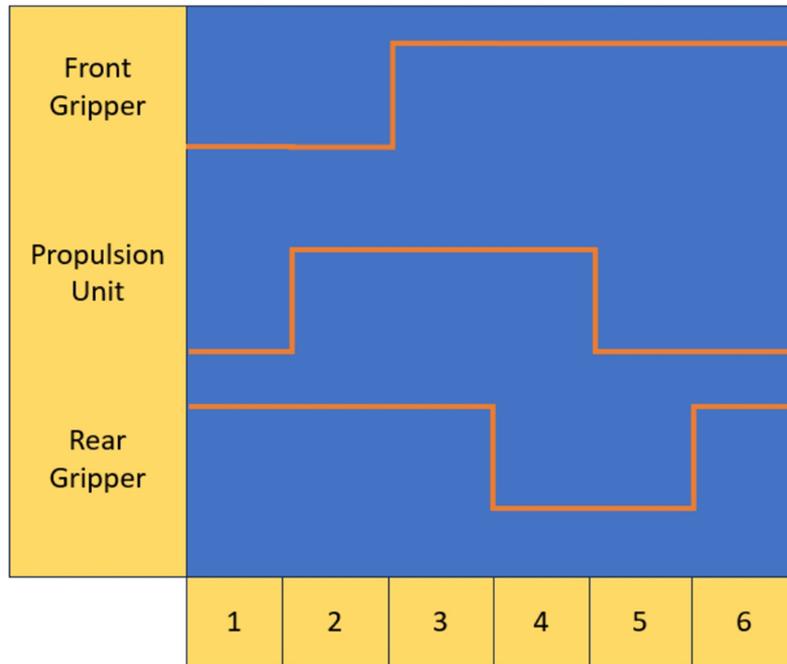
Figure 16. Example of on/off control for an inchworm robot. For a three-actuator robot, a cycle of motion can be achieved in 6 steps.
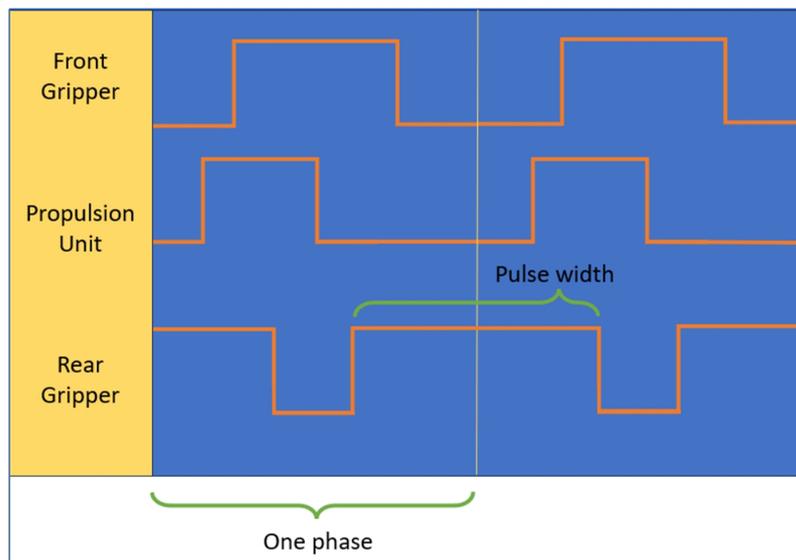
Figure 17. An example of inchworm actuation using a CPG network. CPG: Central Pattern Generator.

less suitable to carry the loads that may be required for inspection.

Earthworms exhibit rhythmic behaviour similar to that made via the open loop systems discussed above, although they use stretch stimuli to achieve this[72]. Whilst open loop control is generally shown to be reliable, most experiments utilise dry uniform pipes and do not account for slips or obstacles expected in real-world applications. To improve the robustness of the robot, feedback can be used to create closed-loop solutions that can account for such occurrences. Kandhari *et al.* developed a cable-driven mesh worm with

the cables pulling and causing the segments to expand, with slackness occurring on contact with the wall[73]. Kandhari *et al.* detected this by analysing load data from the cables and identifying peaks with a median filter[73]. This work was further developed by Kandhari *et al.* who added 36 force sensors to the robot and developed a closed-loop control system where the robot could estimate its shape and environment during movement[74]. The robot expansion was controlled by a desired force setpoint, whilst the contraction was controlled by stretch sensors. This resulted in the prevention of high-force interaction and reduced forward slip improving the motion. Calderón *et al.* created two robots: the first being a basic pneumatic inchworm robot and the second the same except for Stretchable Liquid Circuits (SLCs) integrated into the gripping units[75]. These extra features provided strain sensing, meaning they could determine when enough force was being applied to the pipe walls. The control system for the robots can be seen in Figure 18.

The Multiple Input Multiple Output (MIMO) controller uses the same sequential on-off locomotion rules observed in other inchworm mechanisms. In the first robot without integrated strain sensors, the actuators are expanded/deflated until a set pressure is reached using PID control, whereupon, locomotion rules determine the next action. In the second robot, a setpoint pressure is still used to guide the PID inflation of the actuators, although readings from the strain sensor are used to monitor whether the robot has made contact with the pipe surface. Calderon *et al.* found that when the gripping actuators are expanding without external compression from the pipe wall, the resistance of the SLCs increases linearly, whereas, once under compression, the behaviour is non-linear[75]. Therefore, the actuator can be said to have made contact with the pipe wall when the change in voltage with time no longer approximates to a constant. In the second robot controller, the voltage from the sensors is used to indicate pipe wall contact. If detected, the pressure supply to the actuator is stopped and the setpoint pressure is updated to the current value. Adaptive control systems such as this allow robots to move through less predictable environments. Calderon *et al.* used this control system to efficiently move the second robot through a pipeline of changing diameter[75].

As demonstrated by Zhang *et al.*, the constant curvature model can be used to model how an inchworm robot may approach a T or Y junction, although better sensing would be required for this to be considered robust[55]. The robot should be able to
(a) Identify its desired position in task space.
(b) Control its movement towards the goal position.

To achieve (a), the robot would be required to detect a junction and determine the relative position of the junction relative to its body so that it can move in that direction, something that could be done using machine vision or other environmental sensors[76]. To tackle (b), live sensing of movement is required. Goldoni *et al.* made stretchable nanocomposite sensors that could be integrated into robot design[77]. These were demonstrated to provide identifiable readings for bending, interaction with obstacles and stretching. To facilitate this, a pair of sensors are placed on either side of each other on the soft actuator [Figure 19], with the readings compared to infer the state of the actuator. This works well for a planar robot; possibly, similar methods could be used for 3D movement.

Navigation
Sensing of the environment is vital for the facilitation of movement control, mapping and navigation. Pipe inspection robots are most effective when robots can autonomously or semi-autonomously navigate pipework whilst feeding back information about conditions[78]. To do this, the position of faults or hazards must be determined, usually with Serial Localisation and Mapping (SLAM)[76]. Currently, a few worm robots have successfully demonstrated SLAM. Ishikawa *et al.* developed an odometry method to help determine the shape of the pipe the robot was travelling through[79]. A sensing unit was placed at the tail of an
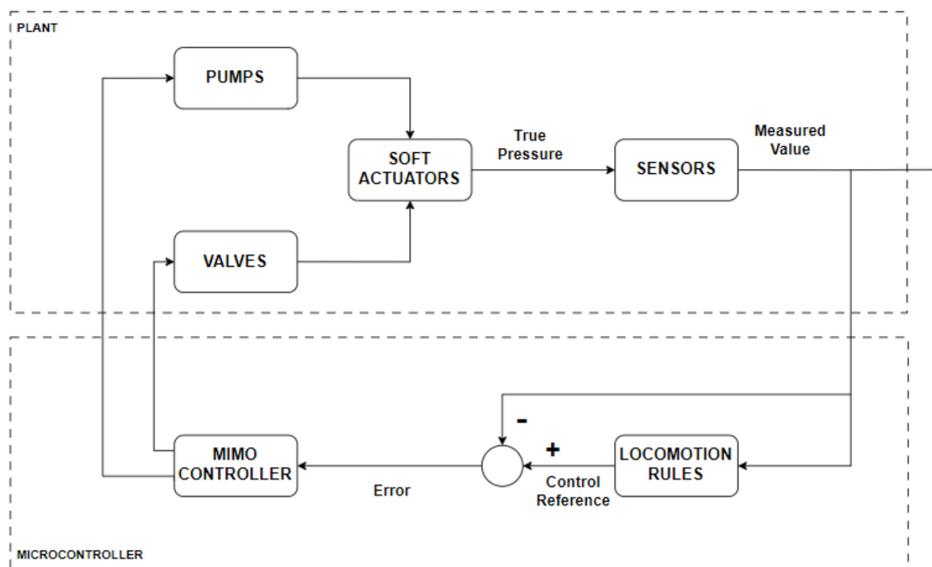
Figure 18. Flow chart demonstrating the control system used in the study of Calderón *et al.*[75].

Figure 19. Reprinted with permission from Goldoni *et al.*[77]. Copyright 2024 American Chemical Society.

earthworm mechanism that consisted of two accelerometers placed on either side of a passive joint. The passive joint has a potentiometer at the joint to indicate when the robot is passing through a turn. The posture angle can be calculated by comparing the two accelerometer readings, and hence, the angle of the pipe turns determined. The robot also had a distance measurement unit that was placed at the entrance to the pipe which used an encoder to measure the length of cable (attached to the robot) that had travelled in the pipe. These measurements were used to build a 3D estimation of the pipe the robot had travelled through. The distance was measured with an uncertainty of 2.6%, whilst the angles of the pipe structure were measured with uncertainties of up to 50% when the direction of turning was parallel to the direction of gravity. The angles of measurement perpendicular to gravity were smaller due to the slack of the cable causing disturbances on the accelerometer when the robot was travelling downwards.

Improvements and advancements in worm robot mapping are required to enhance their applicability to real pipe inspection although many robots have been demonstrated with cameras at their heads[24]. Image processing could be used to create a global SLAM algorithm using landmark recognition[80], though as pipe environments are quite uniform in appearance, local information from IMU sensors and ultrasonic sensors may be needed to improve positional estimations[81]. Although, in some respects, pipe environments make visual SLAM difficult, the uniform geometry of the pipes can aid odometry. Zhang *et al.* showed that as feature detection is performed in a cylindrical environment of known diameter, it is relatively simple to calculate the distance moved between frames[82]. Worm-like robots tend to explore smaller pipelines (< 70 mm), although not much research has been conducted into small-diameter pipe SLAM due to the size and rigidity of sensors, making them difficult to integrate. Lim *et al.* developed a robotic system where a sponge was propelled through 15 mm pipes using hydraulics as the driving force[83]. The Sponge pulled a CMOS camera and a sensor unit behind it which were used to build a map of the pipes. An accelerometer and single-axis gyroscope were used to measure the roll of the camera with image processing employed to detect the direction of forward movement. This data was all used in combination to create a map of the pipelines. However, Lim *et al.* found that the camera algorithm was unreliable as pipe conditions changed[83]. SLAM in worm-like pipe inspection robotics remains an open challenge which is required to broaden the applicability of worm-like robot inspection.

CONCLUSION AND OUTLOOK

Recently, the application of worm-like robots for pipe inspection has seen significant development. Currently, there exist many worm-like robots capable of traversing small-diameter pipes both vertically and horizontally and around tight bends. Many have also presented their ability to carry a small load such as a camera, raising the possibility of using them for inspection. However, the robots presented in this work have not been demonstrated in realistic pipe set-ups and have not been shown to exhibit specific capabilities that may be required to carry out inspection tasks. To be specific, the pipe set-ups that the robots have been tested upon are, in most cases, plastic pipes, whereas the pipes used in the industry tend to be made from a metal such as steel. Steel may pose a problem for worm robots as they present a more frictional surface, and worm robots rely on pushing their body along the pipe environment. Moreover, autonomous navigation and mapping of complex pipework has also not been demonstrated, likely due to two areas of difficulty. The first of these is the turning in a soft robot. The controlled curvature of soft actuators and robots is a complex control problem, and the pipe environment provides both guidance (in the case of swept bends) and obstruction (in the case of junctions such as T-junctions). Hence, a control system that can effectively predict the robot state and sense the robot's environment is required. Worm robots have demonstrated their ability to turn, although a control method that could be considered robust enough for real pipe environments remains an open challenge. The other area of difficulty comes with mapping the pipe environment. Though this has been demonstrated in several non-worm-like pipe robots, there are few examples in worm robots. This is likely as estimations of robot shape and movement are required to create effective mapping algorithms and as worm robots are generally made from soft actuators this presents a significant difficulty. On top of these difficulties, there are also the problems associated with attaching sensors to small compliant robots. For the pipe inspection capabilities of worm-like robots to be realised, demonstrations of worm-like robots with more sophisticated sensing and inspection abilities are required.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of study, found and analysed the relevant literature for interpretation: Blewitt G

Provided administrative and material support as well as assisting in editing of the paper: Monk S, Andrew J, Cheneler D

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