Folding mechanism for a remotely deployable robotic vehicle

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Abstract

An innovative design for a folding robotic vehicle is presented that can deploy through small openings into crawl spaces and underfloor voids to survey and carry out operations within them. The mechanism employs a four bar linkage, enabling the axles to be extended away from the chassis and the axle to be deployed in line with the chassis, thus producing an elongated but small cross sectional area. In its low cross-sectional area form the device can be fed in through a small opening and once in position, the axles can be rotated into their functional position and locked in place. To remove the robot the mechanism works in reverse, with the axle is unlocked and rotated in line with the chassis This transformation is a key enabler for deployment and practical applications of this type of robot. The mechanism has been commercially developed and used for both survey and applying treatments in a wide range of building applications, although other uses are possible. This paper describes the practical aspects of the mechanism as an enabler for the transformation of a robot chassis for accessing confined spaces.

1 Introduction

Underfloor cavities, voids and crawl-spaces are commonly found in buildings. These spaces elevate the floor above the uneven ground below and enable ventilation or they may be used to carry services such as water, heating and energy. An unintended consequence of these spaces can be a source of energy loss, especially for suspended concrete and timber floors at ground level. A potential solution is to install some form of thermal insulation within such spaces in order to reduce the heat transfer. Access however can be challenging. In order to address this challenge a series of robotic devices have been developed that survey the spaces and undertake a series of tasks within the voids such as spraying thermal insulation materials on one or more of the internal surfaces associated with the void. To access the void, the robots would ideally have minimal cross sectional area, in order to avoid the need to make extensive openings. This paper presents the application, design requirements, process and solution developed for a folding robotic vehicle that can deploy through small openings into crawl spaces and underfloor voids to survey and carry out operations within them. The requirements for a simple, robust and inexpensive platform has emerged that can be easily used by construction workers and can be applied across a wide range of buildings and applications. This led to the design challenge for a novel robotic platform that uses a folding mechanism to deploy through restricted openings remotely from the operator and the solution to this is presented here. The robot has been developed by Q-Bot Ltd which was formed in 2012.

1.1 Application

In Northern Europe there are many buildings that have underfloor voids and crawl spaces. Typically these voids are between 200-600 mm high and can contain services, ventilation ducts and other infrastructure [1] and [2]. These spaces are typically too small for a human to access, requiring disruptive and expensive work to remove floor coverings and uncover the void. Even when they are large enough for a human to access they may contain hazards such as asbestos, protruding nails or brads, and wiring in poor condition, preventing safe access.

The use of robots to survey and inspect hard to access environments is not new. Generally these applications tend to have well defined characteristics such as the inspection of pipes, ducts and sewers [3][4] [5], or are highly specialised e.g. inspection of power lines or within nuclear reactors to carry out decommissioning [6] [7]. There are few industrial robots designed to cope with constrained spaces, highly variable, rough terrain and which can not only survey the void but also carrying out other operations. A particular challenge associated with floor voids is the variability in terrain that can be encountered ranging from sand, dusty and debris strewn rubble, to wet clay and mud. For the particular application that was the focus of this development a compounding challenge is the need for the robot to be able to climb over a brick, and also pull an umbilical hose supplying compressed air, power and chemicals to form the insulation.

At the start of the design process more than 100 voids were surveyed to build up a picture of the physical constraints of the space and create a requirements specification. These voids (an example is shown in **Figure 1**) typically are 400 mm high, and split into corridors around 1 to 1.5 m wide, and can be accessed through an air vent in the external wall or an access hatch in the floor made from within the property.

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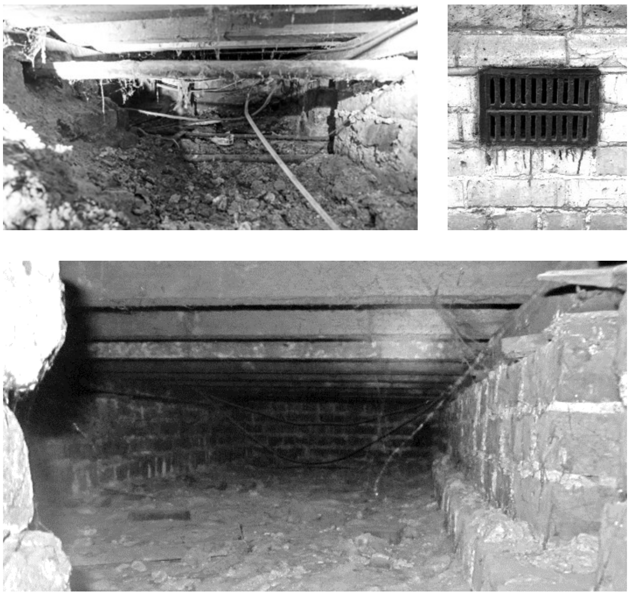

Figure 1: Images of typical voids and an air vent.

When negotiating rough and uneven terrain a wide platform is beneficial for stability and traction. Similarly for robots that use slip steering to turn on the spot, rather than steering of the individual wheels, a wider, square wheelbase improves manoeuvrability. However this increases the size of the opening required for the robot to access the void.

Therefore the requirements for a simple, robust and inexpensive platform that can be easily used by construction workers and can be applied across the wide range of buildings and applications has led to a unique design challenge for a novel robotic platform that uses a folding mechanism to deploy through restricted openings remotely from the operator.

1.2 Robots for use in confined spaces

A significant number of robot development programmes have been undertaken to produce devices that can be used within confined operational envelopes or have the potential to be deployed. Examples include robotic arms that can be folded and articulated, key hole surgery platforms [8], planetary rovers [11], snake robots [12], cockroach platforms [9], welding robots [10] and drones. Each type of application has its own specific requirements, such as performing any operation, through a natural orifice or single incision successfully and safely in the case of surgery, but some principles may be common, such as minimisation of the device, robustness, sensing and safety. Aspects of specification relevent to the deployment of thermal insulation in underfloor voids are described in Section 2. The design solution developed and deployed is given Section 3. Testing of the robotic platform is described in Section 4.

2 Design requirements

The design requirements included the following principal aspects:

1. Survey – Properties need to be surveyed in order to check; the most suitable means for access, whether the floor can be insulated and the likely benefits, whether existing services need to be treated or repaired, e.g. mains, waste and central heating pipes, electrical cables, damp, infestation or structural issues. A program of works, estimated savings and the cost of installation can then be developed.

2. Entry - Access can be gained through a number of methods; removal of an air vent on the outside of the property, drilling a hole or removing a brick in a wall, or through access points from within the property, e.g. cellars, by lifting floorboards, etc. Any robots developed may fold, stretch and bend through small gaps in order to fit through relatively small access holes (e.g. a 150 mm diameter core drill or standard air vent which in the UK is 225mm wide by 150mm high).

3. Deployment – Once inside the void the robot must deploy and then explore and traverse sand, rubble, bricks, rocks and other obstacles.

4. Treatment – The robot must apply insulation to the underside of the floorboards forming an airtight barrier and adding a layer of insulation 100-150 mm thick. In applying insulation to the underside of the floorboards the ventilation gap is maintained, allowing the ground to breath and moisture to escape, while the floorboards remain on the warm dry side, reducing condensation, damp and extending their life.

5. Retrieval – The robot must be able to return to its starting point with its umbilical hoses and cabling, navigating over or through any obstacles, and without entangling the umbilical or causing any damage to the environment. At the entry point the robot needs to be removed through the opening

A full product design specification using a standard proforma tabulated format [13] was developed accordingly.

3 Design and development

A stage-gate approach to design and development was utilised for this project with phases of information gathering, specification, ideation, review, prototypiing, detailed design, review and issue of engineering drawings. A characteristic of the ideation process was use of functional analysis diagrams [14] combined with a design through making approach [15].

A survey was conducted of different robotic platforms that might be able to operate in these environments, were robust and cost effective. Snake or worm like robots were investigated but due to the complexity and cost of many of the platforms, they were initially ruled out. The robot needs to be able to pull heavy loads over distances of up to 20 m in order to access the far end of a void under a building, which for snake like robots meant a very powerful device with articulation required along its length (>25 m). A number of more unusual approaches were also evaluated including using rails and deployable structures. Wheeled robots were eventually selected over tracked robots due to their simplicity and reliability, while also presenting the most options for how they might be made to fold up and fit through restricted openings.

The project methodology for the Q-Bot described here follows three Specific Objectives:

1. Develop a Fully Working Demonstrator (Product Development) - This will allow a robotic device to be constructed that meets customer requirements, is robust and reliable, and can be deployed at scale.
2. Customer and Partner Trials - Full scale trials with customers and installers to demonstrate the business model and validate the value proposition of the service.
3. Sales and Delivery Channels – Q-Bot will engage with sales and delivery channels, in order to validate the commercial model and prepare for market launch.

Specific areas of development identified within the project planning included:

- Refine the design of the folding chassis, drive mechanism, spray system and sensor module in order to minimise size, maximise performance and to meet the design criteria.
- Miniaturisation of electrical systems, improved power handling and traction.
- Integrate sensing and mapping algorithms for floor pitch, void height, etc., and create a 3D texture map.
- Refine the spray and sensing algorithms that govern the pattern, angle and speed of the spray gun.
- Test and refine the user interface to ensure it is easy to use and effective.

This paper focuses on the folding aspects of the chassis.

3.1 Overview of the robot

The basic robot configuration is shown in **Figure 2** and consists of a small 4 wheeled platform with a 450 x 600 mm wheelbase. Each wheel is individually driven by an internal gearbox and motor, a pivoting rear axle ensures all 4 wheels remain in contact with uneven surfaces. The robot is controlled by a front mounted camera, an IMU and an actuated camera-laser system (3D scanner) mounted on a turret at the back of the robot. The ROS framework is used over a distributed system between an on-board computer and an external operator station [16].

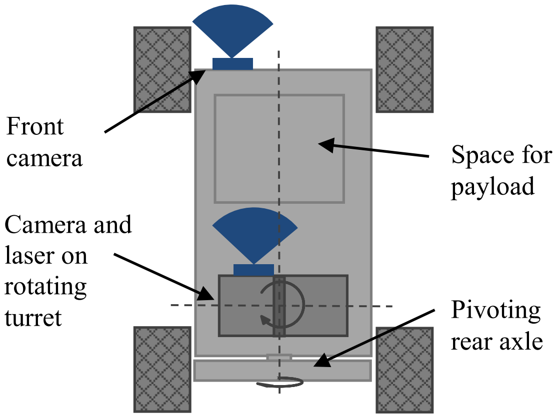

Figure 2: Top view of the robotic vehicle.

The original concept for the folding mechanism is shown in **Figure 3**. Each axle can rotate from perpendicular to parallel to the direction of travel (labelled 1-5). A connecting link moves the axle away from the chassis so the wheel can tuck into the resulting space. This allows a robot chassis that has a wheelbase 450 mm wide to still fit through an opening 200 mm wide and then deploy within the void. Each drive wheel can also be rotated 90 degrees relative to the axle, so when in a configuration (3) the robot can still drive forwards.

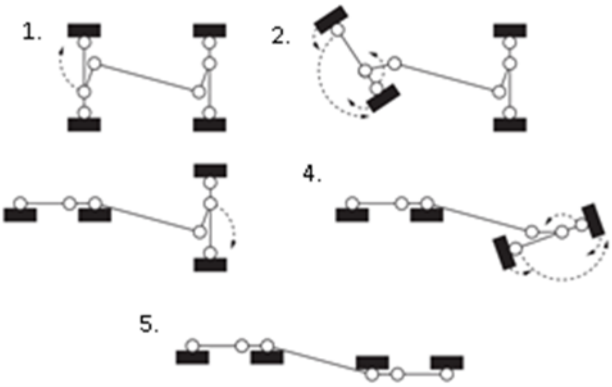

Figure 3: Initial proposed folding mechanism.

As the mechanism needs to be actuated remotely from the operator different solutions were explored. Initially the design was prototyped using eight actuators, one for each pivot point to provide the required control and movement. This created a number of challenges to robustly miniaturise the mechanical and electrical systems while still providing the required torque. Therefore it was decided to simplify the approach and rather than allowing the wheels to pivot, they would be fixed to the axles and the robot could be pushed or pulled through the opening.

The resulting mechanism uses a four bar linkage, the chasis and axle form two of the links while two short pivoting

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links connect and control the motion. The use of two unequal length links between the axle and chassis controls the angle of the axle, to chasis, rather than allowing the axle to rotate freely which makes the deployment easier to control. **Figure 4** shows the axle partly rotated with the drive wheels driven in opposite directions proportional to the perpendicular distance to the resulting centre of rotation, until in the fully folded position shown below. This allows the mechanism to be driven by the existing drive wheels rather than requiring additional actuators.

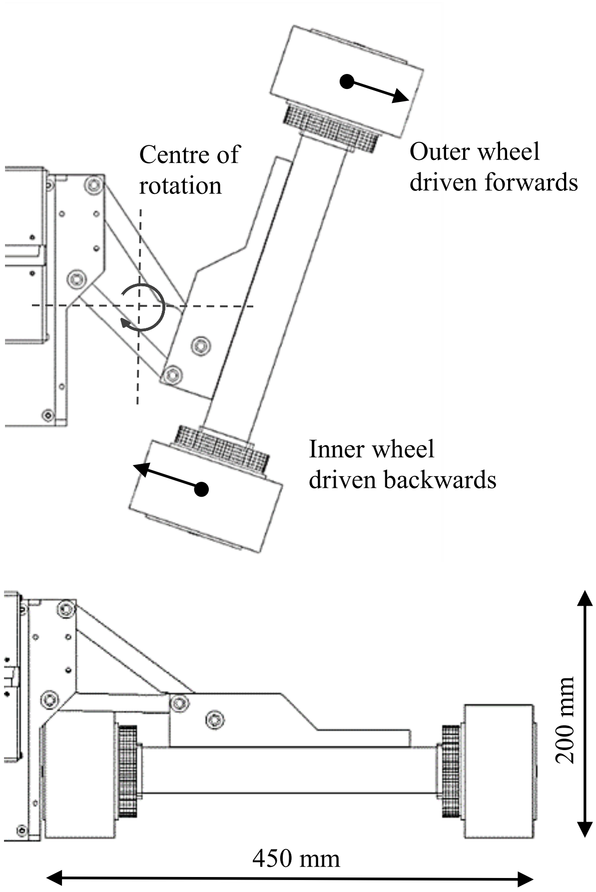

Figure 4: Final folding mechanism shown partially folded (top) and fully folded (bottom).

The use of two links also results in a stiffer structure with less deflection and as the rotation of the axle is controlled, an additional locking mechanism is not required. When in the normal operating position the axle can be locked in place with a simple solenoid and latch.

The control systems includes algorithms and techniques for sensor fusion, surveying and mapping, navigation and control of the robotics platform:Specific features of the control system include:

- Sensor fusion and control algorithms that allow accurate 3D maps to be constructed from inexpensive hardware using algorithms to fuse and register scans from different locations.
- Recognition of features within the void, e.g. floorboards, joists, sleeper walls and insulation, allowing maps to be built up, the coverage and depth of insulation to be calculated.
- Spray algorithms that govern the complex movement of the spray equipment to deliver even coverage across the ceiling taking into account the position and pitch of the robot, and nature of the environment.
- User interface and ability to overlay 3D information from the mapping systems on the control view providing real time feedback on the position of the gun, area to be covered and allowing the operator to select an area to be sprayed by pointing to the screen and the robot calculates the required actions.
- Low visibility navigation and control routines for complex 3D environments.

The final design is shown in Figure 5 in its normal operating mode (top left) and with the front axle fully folded (bottom right). The design also shows a spray gun for the application of treatments within the void. The prototypes were successfully tested on site in domestic and public buildings in the UK. The robot was inserted as planned through an external air vent, by removing the air vent and a few bricks.

4 Testing of the Final Design

The robot was tested both at Q-Bot's test cell and at a number of sites in London, UK with Peabody, a housing association who own approximately 4,000 period properties needing underfloor insulation. The process is shown below at the test cell.

3.1 Access

Figure 5: The air vent and surrounding brick work.

The air vent and surrounding brick work typical of older period properties in the UK and replicated in the test cell at Q-Bot is shown in **Figure 5**. The air vent is typically removed with power tools to form an opening and the robot is prepared in its folded position so as to minimise the cross sectional area as shown in **Figure 6**. Although the robot

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when folded has a cross sectional area of 150 mm by 200 mm the umbilical hose and connecting hoses require a little more space and so an additional brick was removed below the air vent to create an opening approximately 225 mm square. The robot could then be inserted into the void as shown in **Figure 7**.

Figure 6: The robot in its folded position outside.

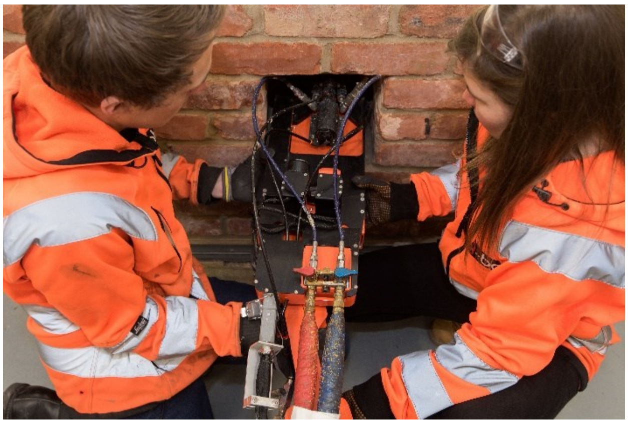

Figure 7: The robot being inserted through the opening.

3.2 Deployment

Once the robot is inserted into the void it needs to be deployed from its folded orientation as shown in **Figure 8** to its normal operational configuration as shown in **Figure 9** below.

Where the ground is relatively flat this could be achieved by driving the wheels as described in Section 3.1. Although the void surface is often covered in loose debris the power drive modules are powerful enough of exerting enough force to rotate the axles relative to the much heavier chassis (each can put out a torque of 10.5 N m and peak power of approximately 65 W).

However in some cases it was found that it was difficult to completely open or close the mechanism and so a cable release mechanism and ratchet was used to provide a secondary means of powering and closing the mechanism.

Once deployed the robot can apply insulation to the underside of the floor as shown in **Figure 10**. The robot can operate under manual control of the operator or semi autonomously navigating, mapping and applying insulation through autonomous routines but under the supervision of the operator.

Figure 8: The robot in its folded position inside the void.

Figure 9: The robot deployed within the void.

Figure 10: The robot after application of insulation to the underside of the floor above.

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5 Conclusions

A robot has been developed for applications such as spraying thermal insulation in building cavities. The resulting requirements were for a simple, robust and inexpensive platform that can be easily used by construction workers and can be applied across the wide range of buildings and applications. An articulated robot platform has been developed and deployed for access voids and confined spaces. The platform uses a four bar linkage and associated locking mechanism in order to reduce the cross sectional area of a chassis during the access phase of deployment. This folding mechanism enables reduction of the area in this application from 450 x 150 mm to 200 x 150 mm. Following accessing of a void the robot axles rotate through 90 degrees and lock into place. The mechanism has been demonstrated in a practical application for robot spraying of thermal insulation within underfloor voids.

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References

[1] A.Rock, I.R.Macmillan, The Victorian House Manual. Care and repair for all popular house types, Somerset, Haynes Publishing, 2005.

[2] English Heritage, Energy Efficiency and Historic Buildings: Insulation of suspended timber floors, 2012. https://content.historicengland.org.uk/images-books/publications/eehb-insulation-suspended-timber-floors/eehb-insulation-suspended-floors.pdf/

[3] Roman, H., Pellegrino, B., Pipe Crawling Inspection Robots: An Overview, IEEE Transactions on Energy Conversion, 1993.

[4] Nassiraei, A., Kawamura, Y., Ahrary, A., Mikuriya, Y., Ishii, K., Concept and Design of a Fully Autonomous Sewer Pipe Inspection Mobile Robot "Kantaro", 2007 IEEE International Conference on Robotics and Automation, 2007.

[5] Shao, L., Wang, Y., Guo, B., Chen, X., A review over State of the Art of In-Pipe Robot, Proceedings of 2015 IEEE International Conference on Mechatronics and Automation, 2015.

[6] Yamamoto, S., Development of Inspection Robot for Nuclear Power Plant, Proceedings of the 1992 IEEE International Conference on Robotics and Automation, 1992.

[7] Katrasnik, J., Pernus, F., Likar, B., A Survey of Mobile Robots for Distribution Power Line Inspection, IEEE Transactions on Power Delivery, 2010.

[8] Yao, W., Childs, P.R.N. Application of design rationale for a robotic system for single-incision laparoscopic surgery and natural orifice transluminal endoscopic surgery. Proceedings of the Institution of Mechanical Engineers, Part H, Journal of Engineering in Medicine, Vol. 207, pp. 821-830, 2013.

[9] Jayaram, K., and Full, R.J. Cockroaches traverse crevices, crawl rapidly in confined spaces, and inspire a soft, legged robot. PNAS Vol. 113 no. 8, 2016

[10] Dharmawan, A.G., Vibhute, A.A., Foong, S., Soh, G.S., and Otto, K. A survey of platform designs for portable robotic welding in large scale structures. Control Automation Robotics & Vision (ICARCV), 2014.

[11] Tadakuma, K., Masatsugu, M., Hirose, S., Mechanical Design of Joint Braking and Underactuated Mechanism of "Tri-Star3", Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robotics and Systems, 2006.

[12] Shao, L., Guo, B., Wang, Y., and Chen, X. An overview on theory and implementation of snake-like robots. IEEE International Conference on Mechatronics and Automation (ICMA), 2015.

[13] Childs, P.R.N. Mechanical engineering design handbook. Elsevier, 2013.

[14] Lee, Szu-Hung, Jiang, P., Childs, P.R.N. Functional Analysis Diagrams with the Representation of Movement Transitions. IMECE2013-63738, 2013.

[15] Childs, P.R.N., and Pennington, M. Industrial, and innovation design engineering. In Chakrabarti, A., and Lindemann, U. (Editors) Impact of Design Research on Industrial Practice, pp. 133-149, Springer, 2016.

[16] http://www.ros.org/