Collaborative Pipe Robots

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INTRODUCTION

The UK's sewage infrastructure, with over 640,000 km of pipes, is prone to damage and is in frequent need of inspection and repair. Small autonomous pipe inspection robots have been developed to inspect and map unknow sections of pipes. When one autonomous pipe robot encounters an obstacle, It is inhibited from inspecting further. Swarm robots can be used in pipes to speed up inspections and by collaborating, overcome obstacles within pipes.

AIMS & OBJECTIVE

Design, manufacture and test a swarm of small collaborative robots to overcome obstacles in pipes.

1. Produce a design concept
2. Produce programs to control individual and combined robots to traverse a pipe network and overcome obstacles
3. Manufacture at least three identical robot prototypes for experimental testing
4. Build a virtual and physical pipe environment to test the robots
5. Produce a group report, a set of individual reports and a group presentation

DESIGN CONCEPT

Pipe Dimension Constraints

Sewage pipe networks have varied pipe sizes, with 150 mm pipes very common for general lateral residential use [1]. As such the individual robots are required to be designed with the ability to traverse these size pipe. To achieve this a maximum height and width dimension of 75 mm was imposed, ensuring that the individual robots sit low enough in the pipe.

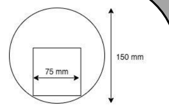

Figure 1 – Pipe and maximum robot dimensions

Obstacles

Obstacles within pipes are caused by pipe damage, which is especially common with in aging pipe networks. These obstacles can be characterised by steps caused by pipe misalignment and gaps caused by pipe damage or discontinuities. The designed robots must be able to link together and overcome these obstacles effectively and efficiently.

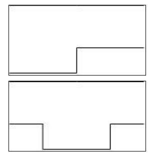

Figure 2 – Pipe obstacle Diagrams

Design Concept

The general design concept that was decided upon after considering the demands and wishes for the connected robot is that of an articulating scalable chain, with both up and down pivot rotational capability. This will be accomplished by a rear mounted, directly connected servo motor and complimentary male and female linkage halves mounted at the front and back respectively.

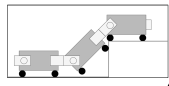

Figure 3 – Robot Design Concept

MECHANICAL DESIGN

Locomotion Method

Many locomotion methods have been utilised in traversal of pipe network environments. However, many of these methods encounter problems when obstacles are introduced. To overcome the required obstacles wheels and tracks pose the most well-rounded solution. Wheels hold the advantage of design and implementation simplicity over tracks, especially when the aim is to manufacture the majority of parts via 3D printing.

Wheel design features rounded profile complementary to pipe diameter (150 mm) to aid in maintaining centrality and straightness within the pipe. The wheel hub has been designed separate to the wheel tyre to allow for several tyre materials and geometries to be tested and utilised for different possible pipe environments. These include TPU and PLA or PETG with a smooth outer surface or with a tooth structure.

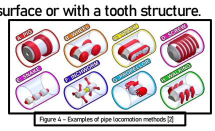

Figure 4 – Examples of pipe locomotion methods [2]

Linkage Design

The linkage of the robots is one of the most integral parts of the collaborative modular robot design. The linkages must be ridged and strong as to not sag under the applied load while remaining simple to operate and easy to align for autonomous connection. Another key consideration for the linkage method is power draw as power supply capacity is very limited due to robot and battery size and weight.

With these considerations in mind, an iterative process was carried out to yield a linkage mechanism capable of the necessary rigidity and strength in tandem with easy mating.

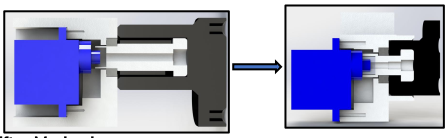

Figure 5 – Progression of linkage design from stage one to stage two

Lifter Mechanism

The lifter mechanism and servo motor are highly dependent on individual robot mass and the position of the centre of gravity. The stall torque of the servo motor determines the upper limit of the combination between these two parameters. Initial estimates suggested the maximum torque applied at approximately 0.8 Nm, being below the rated servo motor stall torque under operation at 6 V of approximately 1.1 Nm.

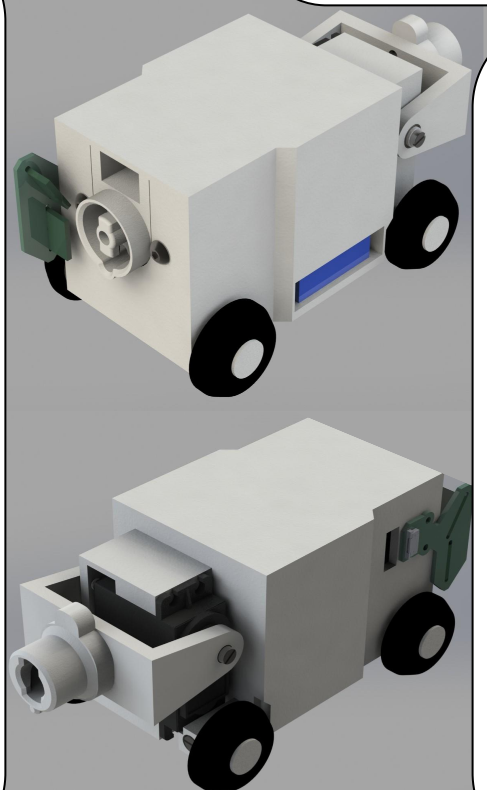

Figure 6 – Agent mechanical design concept

ELECTRICAL DESIGN

The electrical design of our robot balances compactness, performance, and reliability. Powered by a 7.4V battery, the system includes three power rails: 7.4V for the motors, 6V for driving the DC motors, and 3.3V for the ESP32 microcontroller and sensors. This ensures each component receives the proper voltage, with separation between motor and sensor power to avoid interference. The design is split into two boards connected via a flexible flat cable (FFC), maintaining a small form factor and allowing easy sensor replacement. Development modules for the MCU and sensors reduce costs and simplify future upgrades.

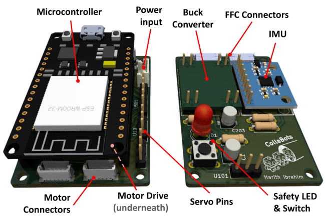

Figure 7 – PCB Gerber

Safety features include a fuse for overcurrent protection, capacitors at the power rails for noise filtering, a safety switch for easy shutdown, and an LED indicator for power status. Two TOF sensors are positioned at optimal angles for effective obstacle detection. The dual-layer PCB with a ground plane improves signal integrity and reduces noise, while step-down converters ensure each component receives the correct voltage. This layout and power management ensure reliable operation in a compact design.

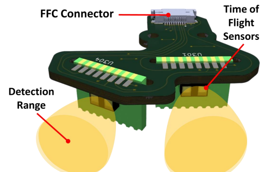

Figure 8 – Time of Flight Sensor

CONTROL FLOW

For obstacle detection, a LiDAR is used to find the obstacle and determine whether it is viable to cross or not. If not then a message is displayed accordingly, if it is then key points are recorded for the algorithm for traversing over the obstacle.

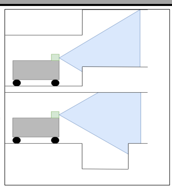

Figure 9 – Obstacle collision concept

A Mixed-integer non-linear programming algorithm is used to calculate the inverse kinematics of a feasible goal state while adhering to centre of mass, torque and collision constraints.

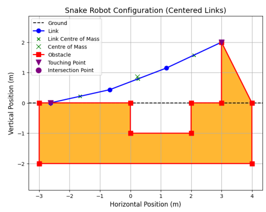

Figure 10 – Optimized joint angles for obstacle

A IMU sensor is used to position the robot in the centre of the pipe. The TOF Array is used to detect other robots. An IR Obstacle detection sensor is used to ensure alignment of robots.

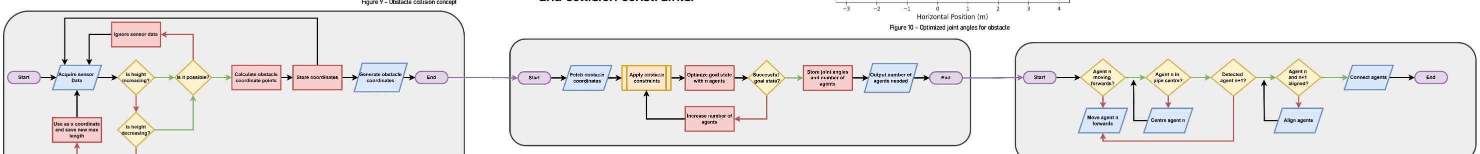

Figure 11 – Control logic flowchart

SIMULATION

Gazebo is used to simulate the agent's behaviour, including sensors, actuators, physics, communication and interaction with the world. This is due to its interfacing with ROS2, ease of porting logic to hardware and public plugins for simulating sensors and actuators. This allowed for the adding of all peripherals of the robot into the simulation.

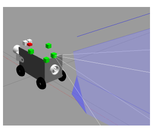

Figure 12 – Gazebo robot with sensors

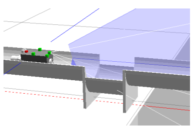

Figure 13 – Gazebo "gap" obstacle example

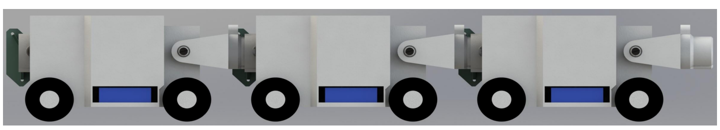

Figure 14 – Solidworks assembly of modular chain

MODULAR CONTROL

ROS2 MoveIt2 is used to plan the trajectory of the modular robots once they are connected. A model all the connected agents is created to represent a singular chain robot with multiple joints. A built in KDL inverse kinematics driver is used to plan the trajectory between the initial "state state" (Green) and calculated "goal state" (Orange) seen in Figure 10.

Model predictive control is then used to readjust the trajectory mid-execution with a resolution of 10 steps, to allow for more accurate control. The joint angles from the fake robot model are used to actuate the real robot

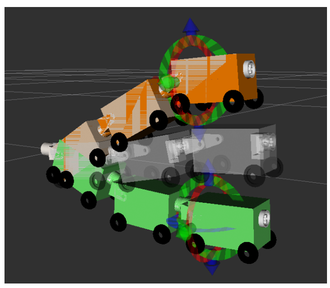

Figure 15 – MoveIt trajectory planning for modular robot

REFERANCES

[1] Dodds, P.E. and McDowall, W., 2013. The future of the UK gas network. *Energy Policy*, *60*, pp.305-316.
[2] Jackson-mills, G. 2020. Magnetic Locomotion for In-Pipe Inspection Robots. Ph.D. thesis, University of. Leeds